PROCEEDINGS OF THE 10TH SYMPOSIUM ON ACCELERATOR SCIENCE AND TECHNOLOGY
October 25-27, 1995, Hitachinaka, Japan

October 1995

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The 10th Symposium on Accelerator Science and Technology is held October 25-27, 1995 at Hitachinaka city. The symposium is organized by the KASOKUKI-DOKOKAI and is attended by 260 registered participants. Scientific contributions to the symposium included 54 oral presentations and 105 poster presentations.

The proceedings contain the manuscripts of 159 contributions to the symposium. The secretariat of the symposium is undertaken by members of KASOKUKI-DOKOKAI in Japan Atomic Energy Research Institute.

Keywords: Symposium, Accelerator
第10回加速器科学研究発表会報文集
1995年10月25日～27日、ひたちなか市

日本原子力研究所

(1995年10月2日受理)

第10回加速器科学研究発表会は1995年10月25日から27日までひたちなか市において開催される。この発表会は加速器同好会によって催され、280名の参加者があり、口頭54件、ポスター105件の発表がある。

この報文集は発表会で報告された159件の論文からなり、発表会の事務局は日本原子力研究所の加速器同好会員が担当した。

日本原子力研究所：〒319-11 茨城県那珂郡東海村白方白根 2 - 4
PREFACE

In 1989, an association named KASOKUKI-DOKOKAI, the Japanese Accelerator Researchers Association - JARA, was formed in order to promote the research activities on particle accelerator and their applications in Japan and decided to hold the Symposium on Accelerator Science and Technology under the auspices of this association from the 9th Symposium which was held in 1993.

The 10th Symposium on Accelerator Science and Technology is held on October 25-27, 1995 at Hitachinaka City of Ibaraki Prefecture by the members of Japan Atomic Energy Research Institute - JAERI. These Symposia have been held in almost every two years in series and organized by National Laboratory for High Energy Physics - KEK, Institute for Nuclear Study of Tokyo University - INS, Research Center for Nuclear Physics of Osaka University - RCNP and the Institute of Physical and Chemical Research - RIKEN cyclically. The first symposium was organized in 1975 by KEK.

The 10th Symposium, however, is newly prepared by members of JAERI, where the research and development on powerful accelerators are carried out actively and the number of researchers on particle accelerators and their applications are rapidly increasing recently, out of host institute - circle mentioned above.

The framework of the symposium program is similar to that of the previous one held in 1993 at KEK. Three plenary, ten parallel, and two poster sessions are opened, and technical bus tour to JAERI are programmed after the sessions. The three plenary sessions are allotted to two invited talks, status reports of major facilities, and future accelerator plans, respectively. The invited talks are composed of on HIMAC and the therapeutics by Dr. K. Morita, National Institute of Radiological Science and on the development of the high current negative ion source for nuclear fusion research by Dr. Y. Okumura, JAERI. As of September 14, 158 papers have been submitted and 260 participants have made pre-registration. These papers cover a vast scope of researches on particle accelerators and their applications in many branches of science and technology.

The present Symposium was prepared by Symposium Secretaries from JAERI under the Organizing Committee of JARA. I wish to express my appreciation to all the members of Symposium Secretaries and Organizing Committee in advance and I hope the Symposium will be conducted successfully through co-operation of all participants.

October 25, 1995

Yasuo Suzuki
Chairman

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Contents

Plenary Session Invited Talks
1a-1 Phase I/II Clinical Trial with Heavy Ion at National Institute of Radiological Sciences ......................................................... 1
K. Morita (NIRS)
1a-2 Development of High Power Negative Ion Sources for Fusion at JAERI ........... 2
Y. Okumura (JAERI)

Plenary Session Status Report
1a-3 Present Status of the Medical Accelerator HIMAC ........................................ 5
S. Yamada, N. Araki, M. Hosaka, A. Itano, M. Kanazawa, A. Kitazawa, T. Kohno,
M. Kumada, T. Murakami, M. Muramatsu, K. Noda, H. Ogawa, K. Sato, S. Sato,
T. Fukushima, Y. Ishikawa and T. Kimura (NIRS)
1a-4 Current Status of the RCNP Ring Cyclotron .............................................. 8
I. Miura, K. Hatanaka, K. Hosono, T. Itahashi, K. Sato, M. Sato, T. Saito,
A. Shimizu, K. Takahisa, K. Tamura, T. Yamazaki, S. Ano, M. Kibayashi, H. Tamura
and M. Uraki (RCNP)
1p-1 Status of the KEK-PS Main Ring .................................................. 11
H. Sato (KEK)
1p-2 Construction of SPring-8 Injector System ............................................ 14
H. Yokomizo, H. Abe, T. Aoki, K. Fukami, S. Hayashi, T. Hori, H. Hosoda,
M. Ichihara, Y. Itoh, T. Kaneda, M. Kodera, H. Kotaki, A. Kuba, A. Mizuno,
K. Okanishi, T. Oku, S. Ohzuchi, H. Oyatani, H. Sakaki, H. Suzuki, S. Suzuki,
N. Tani, T. Taniuchi, K. Yanagida, H. Yonehara and H. Yoshikawa (SPring-8)
1p-3 1.54 GeV ATF Injector Linac .................................................. 17
T. Naito and H. Matsumoto (KEK, *Tohoku-Gakuin Univ., **Yokohama National
Univ.)
1p-4 Present Status of the KEKB Project .................................................. 20
S. Kurokawa (KEK)

Poster Session Status Reports
PA01 The Operation of RIKEN Ring Cyclotron ........................................... 23
   M. Kase, N. Inabe, A. Goto, T. Kageyama, I. Yokoyama, M. Nagase, S. Kohara,
   T. Nakagawa, K. Ikekami, O. Kamigaito, I. Fujita and Y. Yano (RIKEN)

PA02 NNI-J-III Superconducting Compact Light Source Facility .......................... 26
   K. Emura, T. Naga, T. Shinzato and H. Takada (Sumitomo Heavy Industries)

PA03 Helium Beam Acceleration in the KEK Proton Synchrotron ........................... 29
   I. Sakai, A. Takagi, Y. Mori, S. Machida, M. Yoshii, T. Toyama, M. Shirakata,
   Y. Shoji and H. Sato (KEK)

PA04 Status Report on JEARI-AVF Cyclotron .............................................. 32
   and M. Fukuda (JAERI)

Poster Session E-Gun and Ion Sources

PA05 Pulse Response of Y-796 Electron Gun and Space Charge Effects ................... 35
   T. Kozawa, T. Kobayashi, T. Ueda, M. Uesaka, K. Miya, H. Shibata* and
   H. Kobayashi (NERL, *RCNST, **KEK)

PA06 Plasma Jet Emitter: Mechanism of Ion Beam Formation with Low Emittance ......... 38
   T. Sakae, K. Ogawa and T. Yamamoto (Kyushu Univ.)

PA07 Study of ECRIS for Highly Charged Ion Production -HiECR MK3- ..................... 40
   T. Katayose, H. Tomizawa, K. Isokawa and T. Hattori (RLNR)

PA08 Acceleration of Deuteron and Alpha Beams in the KEK-PS Injector .................... 43
   A. Takagi, K. Ikekami, C. Rubota, Z. Igarashi, M. Kinsho, K. Shiento*, S. Machida,
   M. Yoshii, E. Takasaki and Y. Mori** (KEK, *GUAS, **INS)

PA09 Development of a High Brightness Negative Hydrogen Ion Source .................... 46
   H. Oguri, Y. Okumura, N. Miyamoto, M. Mizumoto and J. Kusano (JAERI)

PA10 Development of JAERI 18-GHz ECR Ion Source ....................................... 49
   W. Yokota, T. Nara, Y. Saitoh, Y. Ishii, K. Arakawa and Y. Wu* (JAERI, *Nagoya Univ.)

PA11 Plasma Jet Emitter: Simulation Model for the Plasma in a Small Ion Source .......... 52
   K. Ogawa, T. Sakae, T. Yamamoto, Y. Uozumi, A. Nohtomi and M. Matoba
   (Kyushu Univ.)

Poster Session RF

PA12 RF Systems of Synchrotrons for Japanese Hadron Project ............................ 55
   T. Tanabe, Y. Tanabe and M. Yoshii* (INS, *KEK)
PA13 Development of a Compact Linac for FEL Oscillation ................................. 58
  T. Haga, K. Tsumori, T. Shinzato, K. Emura and T. Takada
  (Sumitomo Electric Industries)

PA14 Cold Test of a 25.5 MHz Double-coaxial $\lambda/4$ Resonator .......................... 61

PA15 Development of an RF Electron Beam Irradiation System ............................ 64
  T. Fujisawa, T. Hirasima, T. Katori, S. Wada and M. Odera (Denki Kogyo)

PA16 Cold Model Measurement of Biperiodic L-support DAW ............................... 67
  Y. Iwashita, A. Noda, H. Okamoto, T. Shirai and M. Inoue (ICR)

PA17 RF Characteristics of the Bullet-shape SiC Absorber for KEKB ..................... 70
  Y. Takeuchi (KEK)

PA18 RF System of SPring-8 Linac ........................................................................... 73
  S. Suzuki, H. Yoshikawa, T. Hori, T. Taniuchi, K. Yanagida, A. Mizuno, A. Kuba,
  Y. Itoh, H. Sasaki, M. Kodera, H. Kotaki, T. Okada and H. Yokomizo (SPring-8)

PA19 Modulators for SPring-8 Linac ........................................................................ 76
  A. Mizuno, T. Hori, H. Yoshikawa, M. Kodera, H. Misawa*, H. Teramura*,
  N. Akashige*, Y. Ohnishi*, S. Suzuki, K. Yanagida, H. Sakaki, Y. Itoh,
  T. Taniuchi, H. Kotaki, A. Kuba and H. Yokomizo (SPring-8, *Toshiba)

PA20 An Untuned Type RF Cavity using Multiple Power Feeding .............................. 79
  J. Hirota, M. Katane, K. Saitou, M. Tadokoro, F. Noda, Y. Iwashita*, A. Noda*
  and M. Inoue* (Hitachi, *ICR)

PA21 Construction of 100 MeV Electron Linac in Kyoto University ......................... 82
  T. Shirai, T. Sugimura, M. Kando, M. Ikegami, Y. Iwashita, H. Okamoto, S. Kakigi,
  H. Dewa, H. Tonguu, H. Fujita, A. Noda and M. Inoue (ICR)

Poster Session Vacuum

PA22 Conceptual Design Study for Aluminum Recycler Ring Vacuum Chamber
  in FERMILAB .......................................................................................................... 85
  H. Ishimaru (KEK)

PA23 Conditioning of Positive Inflector Voltage for the Injection of Negative
  Ions at TARN-II .................................................................................................... 88
  K. Chida, T. Tanabe, M. Yoshizawa, Y. Arakaki, T. Morimoto and I. Katayama (INS)

PA24 Development of a Bellows Assembly with an RF-shield for the KEKB .............. 91
  K. Ohshima, Y. Suetsugu* and K. Kanazawa* (Irie-Koken, *KEK)

Poster Session Magnets
PA25  A Design of the Injection Scheme and a Construction of Model Kicker Magnet for the High Brilliance Lattice of the Photon Factory ........................................ 94
   T. Mitsuhashi, M. Katoh and A. Ueda (KEK)

PA26  Magnet Alignment System of the SPring-8 Storage Ring using Laser ............... 97
   S. Matsui, C. Zhang, J. Ohnishi and Y. Chida (SPring-8)

PA27  Development of a Compact Steering Magnet with Eight-pole Structure ............ 100
   M. Ikegami and Y. Iwashita (ICR)

PA28  Alignment of Magnets for the SPring-8 Synchrotron .................................. 103
   T. Nagafuchi*, N. Suetake*, Y. Yoshiwara* and H. Itoh* (SPring-8, *Toshiba)

PA29  DCCTs for Magnet Power Supplies ............................................................. 106
   T. Ozaki (KEK)

PA30  Manufacture and Arrangement of Bending Magnets of SPring-8 Synchrotron ....... 109
   K. Fukami, H. Yonehara, H. Suzuki, T. Aoki, N. Tani, H. Abe, S. Hayashi,
   H. Ueyama, T. Kaneta, K. Okanishi, S. Ohzuchi, H. Tanaka, H. Yokomizo,
   T. Cyugun* and T. Nagahuchi* (SPring-8, *Toshiba)

PA31  Design of Solenoidal Magnets with Laminated Cores .................................. 112
   E. Tanaka*, S. Yamada, T. Murakami, A. Kitagawa, H. Ogawa, T. Fukushima,
   (NIRS, *Accelerator Engineering Co., **Sumitomo Heavy Industries Ltd)

PA32  Simulation of Power Supply for Rapid Cycling Accelerator .......................... 115
   FQ Zhang (GUAS)

PA33  Design of Magnet Power Supplies for KEKB Accelerator .............................. 118

PA34  Magnets for the High Brilliant Configuration at the Photon Factory
   Storage Ring ................................................................................................. 121
   Y. Kobayashi, M. Katoh and T. Kasuge (KEK)

Poster Session  Superconducting

PA35  Design Study of Sector Magnet for the RIKEN Superconducting Ring
   Cyclotron (I) .............................................................................................. 124
   T. Mitsumoto, A. Goto, T. Kawaguchi, Y. Tanaka, T. Kubo, H. Okubo, T. Tominaka,
   S. Fujishima and Y. Yano (RIKEN)

PA36  Design Study of Sector Magnet for the RIKEN Superconducting Ring
   Cyclotron (II) .............................................................................................. 127
   T. Kawaguchi, T. Kubo, T. Mitsumoto, T. Tominaka, S. Fujishima, H. Okuno,
Poster Session New Techniques

PA37 Frequency Up-shifts Observed in Microwave-plasma Interaction .................................. 130
X. Xu, Y. Nishida and N. Yugami (Utsunomiya Univ.)

PA38 Formation of Duct in Plasma by High Power Microwave and Self-focusing .......... 133
H. Ito, Y. Nishida and N. Yugami (Utsunomiya Univ.)

PA39 Experimental Demonstration of Vp×B Acceleration Scheme with Use of
Transverse Electromagnetic Waves .................................................................................. 136
S. Sanjo, N. Kirihiara, N. Yugami and Y. Nishida (Utsunomiya Univ.)

Poster Session Beam Handling

PA40 Continuous Beam Monitoring for Charged Particle Therapy ...................................... 139
T. Kohno** (NIRS, *Accelerator Engineering Co., **Tokyo Inst. of Tech.)

PA41 Development of an Analog Switch Gating a Single Bunch ........................................ 142
T. Ieiri, K. Tanimura* and M. Suzuki* (KEK, *NTT Electronics Technology Co.)

PA42 Analog Processor for Emittance Monitor in SPring-8 Linac ...................................... 144
K. Yanagida, Y. Itoh, H. Yoshikawa, T. Hori, S. Suzuki, A. Mizuno, H. Sakaki
(SPring-8)

PA43 Horizontal COD Measurement and Correction System in HIMAC Synchrotron ........ 147
M. Katane***, J. Sagawa***, T. Miyaoka****, E. Toyoda***** and T. Yagi*****
(NIRS, *Hyogo Pref., **RCNP, ***Hitachi, ****Toshiba)

PA44 Development of a Beam Pulse Monitor for the JAERI AVF Cyclotron ..................... 150
and K. Arakawa (SPring-8)

PA45 Radial and Vertical Betatron Oscillation Frequencies Observed by
a Scintillation Plate and a Three Wire Tomography Monitor ......................................... 153
T. Itahashi, K. Hosono, K. Hatanaka, I. Miura, T. Saito, A. Shimizu, K. Tamura,
K. Takahisa, T. Yamazaki, S. Ano, M. Kibayashi, H. Tamura and M. Uraki (RCNP)

PA46 Correcting Slanted Beam Profiles in Superconducting Storage Rings ...................... 156
K. Yamada, M. Nakajima and T. Hosokawa (NTT)

PA47 Refinement of Calibration Procedure for Beam Position Monitors .......................... 159
K. Tamura, S. Sasaki*, M. Shoji* and S. Takano* (Hiroshima Univ., *SPring-8)
PA48 Beam Position Monitor for an Orbit Feedback System .......................... 162
   M. Tejima, H. Ishii and Y. Funakoshi (KEK)

PA49 Development of a Single-bunch Selector for the Riken Ring Cyclotron .......... 165
   N. Inabe, M. Kase, I. Yokoyama, A. Goto and Y. Yano (RIKEN)

PA50 Single-pass Measurements of Injection-beam Position at the Photon Factory Storage Ring ......................................................... 168
   T. Honda (KEK)

PA51 Stability Study of ATF 80MeV Injector Linac .................................. 171
   T. Naito, H. Hayano, H. Matsumoto, J. Urakawa, M. Ross*, J. Jobe* and
   D. McCormick* (KEK, *SLAC)

Parallel Session Status Reports (I)
2a1-1 Present Status of NAR ................................................................. 174
   M. Nakajima, K. Yamada and T. Hosokawa (NTT)

2a1-2 Present Status of PNC High Power CW Electron Linac .......................... 177
   T. Emoto, I. Tanimoto, A. Ohomura, Y. Yamazaki, H. Takei, K. Hirano, M. Nomura,
   S. Toyama, Y. L. Wang, I. Sato*, J. Kobayashi* and A. Enomoto* (PNC, "KEK"

2a1-3 Generation of Subpicosecond Electron Single Pulse .......................... 179
   T. Kozawa, T. Kobayashi, T. Ueda, M. Uesaka and K. Miya (NERL)

2a1-4 Present Status of the Photon Storage Ring Project ............................ 182
   I. Sato*** and K. Shimoda (Ritsumeikan Univ., *Sumitomo Heavy Industries,
   **Russian Academy of Science, ***KEK)

Parallel Session Status Reports (II)
2a2-1 Present Status of the Accelerator Development at the ICR Kyoto University ... 185
   M. Inoue, A. Noda, Y. Iwashita, H. Okamoto, T. Shirai, S. Kakigi, H. Tonguu,
   H. Fujita, H. Dewa, M. Ikegami, V. Kapin, M. Kando, T. Sugimura and H. Fujisawa*
   (ICR, "Nissin Electric"

2a2-2 Construction of a New Pre-injector for the RILAC ............................. 188
   A. Goto, Y. Miyazawa, M. Hemmi, O. Kamigaito, T. Nakagawa, M. Kase, T. Chiba,
   N. Inabe, S. Kohara, T. Kageyama, Y. Battygin and Y. Yano (RIKEN)

2a2-3 Progress Report on the Construction of the Heavy-ion Linacs for
Radioactive Nuclei ................................................................................. 191
   M. Tomizawa, S. Arai, R. Arakaki, Y. Hashimoto, A. Imanishi, T. Katayama,
   H. Masuda, K. Niki, M. Okada, Y. Takeda, E. Tojyo, N. Tokuda, C. Velissaris,
K. Yoshida and M. Yoshizawa (INS)

2a2-4 Acceleration Tests of the JAERI Tandem Superconducting Booster ................................... 194
S. Takeuchi, T. Ishii, M. Matsuda, Z. Yan and T. Yoshida (JAERI)

Parallel Session Vacuum and Magnets

2a3-1 Vacuum Design for KEKB ........................................................................................................ 197
K. Kanazawa, Y. Suetsugu, H. Hisamatsu, M. Shimamoto, S. Kato, N. Terunuma,
M. Nakagawa, M. Sato and H. Ishimaru (KEK)

2a3-2 Dust Trapping Experiments at TRISTAN AR ........................................................................ 200
S. Kato, K. Kanazawa, T. Tsukamoto and S. Uno (KEK)

2a3-3 Measurement of Magnetic Field Center of the Quadrupoles and Sextupoles
for the SPring-8 Storage Ring ........................................................................................................... 203
J. Ohnishi, M. Kawakami and S. Matsui (SPring-8)

Parallel Session Power Supplies

2a4-1 High Stability, High Current DC-power Supplies ................................................................. 206
K. Hosono, K. Hatanaka, T. Itahashi, I. Miura, K. Sato, T. Saito, A. Shimizu,
K. Takahisa, K. Tamura, T. Yamazaki, S. Ano, M. Kiibayashi, H. Tamura and M. Uraki
(RCNNP)

2a4-2 Design of Magnets and Power Supplies of 3 GeV Booster for
Japan Hadron Project ......................................................................................................................... 209
T. Adachi and JHP Accelerator Design Group (KEK)

2a4-3 Development of High Duty Pulse Power Supply for S-band Klystron ............................... 212
K. Satoh, N. Kumazawa, O. Endoh, M. Imagawa, Y. Yamashita, Y. Suzuki,
M. Shinohara, A. Miura, K. Nagatsuka, N. Matsunaga, K. Suzuki, H. Matsumoto,
H. Baba, K. Shinohara, S. Katoh*, Y. Kamino*, T. Noguti* and N. Hisanaga*
(Nihon Koshuha, *Mitsubishi Heavy Industries)

2a4-4 Development of Long Pulse, High-flatness Pulse Modulator for an S-band
Klystron ............................................................................................................................................ 215
E. Oshita, S. Okuma, K. Wakita and T. Tomimasu (FELI)

Parallel Session Ion Sources

2p1-1 Manufacture of the 6-10 GHz Compact ECR Ion Source with a Variable Permanent
Magnet Mirror .................................................................................................................................... 218
E. Tojyo, Y. Shirakabe, Y. Ohshiro, M. Oyaizu, T. Yamazaki, M. Fujita,
N. Yamazaki, M. Nishiguchi and H. Muto (INS)
2p1-2 Production of Polarized Negative Deuterium Ion Beam with Dual Optical Pumping ................................................................. 221
  M. Kinsho, K. Ikegami, A. Takagi and Y. Mori* (KEK, *INS)

2p1-3 Development of RIKEN 18 GHz ECRIS .......................................................... 224
  T. Nakagawa, Y. Miyazawa, M. Hemmi, T. Chiba, N. Inabe, M. Kase, T. Kageyama,
  O. Kamigaito, E. Ikezawa, A. Goto and Y. Yano (RIKEN)

2p1-4 The New External Ion Sources and the New Axial Injection System at RCNP .............. 227
  M. Sato, K. Hatanaka, K. Hosono, T. Itahashi, T. Saito, K. Takahisa, H. Tamura,
  K. Tamura and I. Miura (RCNP)

2p1-5 RF Beam Chopping in a Surface-plasma Type Negative Ion Source ....................... 230
  K. Shinto, A. Takagi, M. Kinsho, K. Ikegami, Z. Igarashi, S. Machida, M. Yoshii
  and Y. Mori (KEK)

Parallel Session RF

2p2-1 R&D Status on the High Intensity Proton Accelerator in JAERI ......................... 233
  K. Hasegawa, M. Mizumoto, J. Kusano, N. Ito, H. Oguri, Y. Touchi, H. Ino and
  K. Mukugi (JAERI)

2p2-2 Development of a Variable-frequency RFQ Linac for the RILAC ......................... 236
  O. Kamigaito, A. Goto, Y. Miyazawa, T. Chiba, M. Hemmi, S. Kohara, M. Kase,
  Y. Batyggin and Y. Yano (RIKEN)

2p2-3 High Power Test of a Damped Cavity for High-brilliant Synchrotron Radiation
  Source ........................................................................................................... 239
  T. Koseki, M. Izawa, S. Tokumoto, K. Shinoe, Y. Kamiya, T. Miura, K. Sato, T. Naba,
  Y. Ohnishi and S. Fujii (ISSP)

2p2-4 Study on Tuning-free Network for RF Accelerating Cavity ................................. 242
  (KEK, *Toshiba)

2p2-5 Conceptual Design of Compact HIF Driver by RF Linac with High Acceleration
  Rate .............................................................................................................. 245
  T. Hattori, K. Sasa, M. Okamura, T. Ito, H. Tomizawa, T. Katayose, N. Hayashizaki,
  T. Yoshida, K. Isokawa, M. Aoki, N. Fujita and M. Okada* (RLNR, *INS)

Poster Session Beam Handling

PB01 Longitudinal Emittance Measurement for 433 MHz Proton Linac .......................... 248
  H. Dewa, T. Sugimura, M. Kando, M. Ikegami, V. Kapin, H. Tonguu, T. Shirai,
PB02 Calibration of Beam Position Monitor for the SPring-8 Synchrotron
T. Aoki, H. Yonehara, H. Suzuki, N. Tani, H. Abe, K. Fukami, S. Hayashi, Y. Ueyama,
T. Kaneta, K. Okanishi, S. Ohzuchi, T. Miyaoka*, K. Sato*, E. Toyoda*, H. Ito* and
H. Yokomizo (SPring-8, *Toshiba)

PB03 The Effect of the Aberration on the Emittance Growth Revealed in
Design Study of LEBT using Magnetic Lenses for the JHP RFQ
S. Fujimura, A. Ueno and Y. Yamazaki (KEK)

PB04 Beam Position Dependence of a Wall-current Monitor
K. Tamiya, A. Asami, T. Suwada*, T. Urano* and H. Kobayashi*
(Naruto Univ. of Education, *KEK)

PB05 Fast Wire Scanner at the KEK-PS
K. Koba, D. Arakawa, J. Kishiro, K. Mikawa, H. Sato, M. Shirakata, T. Toyama and
M. Yoshii (KEK)

PB06 3D Visualization of Fast Light Emission Phenomena by Dynamic CT
M. Aida, T. Kozawa, T. Ueda, T. Kobayashi, M. Uesaka and K. Miya (NERL)

PB07 Non-destructive Beam Profile Monitor at HIMAC
S. Sato, N. Araki, M. Hosaka, Y. Sano*, H. Takagi*, M. Torikoshi, K. Noda,
(NIRS, *Accelerator Engineering, **CYRIC, ***Mitsubishi Electric,
****Toshiba)

PB08 Numerical Calculation of the Electromagnetic Coupling Strength between
the Electrodes of a Beam-position Monitor
T. Suwada (KEK)

PB09 A Beam Spill Control System at HIMAC
N. Araki, K. Noda, E. Takada, K. Sato*, A. Itano**, M. Kanazawa, M. Kumada,
Y. Yamamoto***, S. Sato, M. Torikoshi, Y. Sato, S. Yamada and H. Ogawa
(NIRS, *RCNP, **Hyogo Pref., ***Hitachi Zosen)

PB10 A Design of the Beam Profile Monitor for the High Brilliance Lattice of
the Photon Factory
T. Mitsushashi (KEK)

PB11 Development of a Two-tap FIR Filter for Bunch-by-bunch Feedback Systems
M. Tobiyama, E. Kikutani, T. Taniguchi and S. Kurokawa (KEK)

PB12 Longitudinal Bunch Feedback System with a Two-tap FIR Filter Prototype

PB13 Recent Improvement of Ripple Performance in HIMAC Synchrotron Power Supply
Poster Session: Operation and Control

PB14 Control System for RCNP Cyclotron
K. Tamura, K. Hosono, K. Hatanaka, I. Miura, T. Saito, T. Yamazaki, T. Itahashi,
A. Shimizu, K. Nagayama, M. Kibayashi, M. Uraki and H. Tamura (RCNP)

PB15 Team Development System for Accelerator Control Software on the WAN
Y. Shibasaki, M. Mutoh, I. Abe and K. Nakahara (LNS, KEK)

PB16 Graphical Representation of Objects' States for the PF Linac Control System
I. Mejuev, I. Abe and K. Nakahara (KEK)

PB17 High Accurate Timing System for the SPring-8 Synchrotron
H. Suzuki, H. Yonehara, T. Aoki, N. Tani, S. Hayashi, T. Miyaoka, Y. Shimouchi,
T. Yagi and E. Toyoda (SPring-8, Toshiba)

PB18 VME Based Control System for the TRISTAN Correction Dipole Power Supply
H. Fukuma, K. Endo, A. Kabe, H. Koiho and T. Kubo (KEK)

PB19 Control System of SPring-8 Injector Linac
H. Sakaki, H. Yoshikawa, Y. Itoh, A. Kuba, T. Taniuchi and H. Yokomizo (SPring-8)

PB20 Analysis of the PLC Object Model in the PF Linac
I. Abe, A. Shirakawa, K. Nakahara and M. Tanaka (KEK)

PB21 Control System of a High Energy Beam Transport System of HIMAC
M. Torikoshi, E. Takada, S. Yamada, H. Ogawa, K. Noda, T. Kohno, J. Matsuura,
S. Kobayakawa, F. Sasaki, K. Okumura, S. Namai and Y. Ishikawa
(NIRS, *TIT, **Mitsubishi Electric, ***Accelerator Engineering)

PB22 Present Status of HIMAC Synchrotron Control System
B. Takada, S. Sato, K. Noda, M. Kumada, M. Kanazawa, A. Itano, N. Araki, Y. Sano,
T. Togashi, H. Takahashi, M. Ogata, M. Mori and T. Gushiken (NIRS)

PB23 Development of Dynamic Pattern I/O Modules for Advanced Accelerator Operation
E. Takada, N. Araki, A. Itano, M. Kanazawa, M. Kumada, K. Noda, S. Sato,
E. Hishitani, S. Arai and H. Nakagawa (NIRS, *Hyogo Pref.,
**Hitachi Zosen)

PB24 Construction of a Remote Controlled Monitoring System with GPIB Devices and EPICS
T. Yoshikawa and N. Yamamoto (Hitachi Zosen, KEK)
Poster Session Orbit Analysis

PB25 Beam Current Limitations due to Single-beam Collective Effects in the Ion Storage Ring of RIKEN RI Beam Factory Project .............................................. 318
M. Takanaka and T. Katayama* (RIKEN, *INS)

PB26 A Resonant Extraction Technique for a Compact Synchrotron; Asymmetric Driving of two Sextupole Magnets ................................................................. 321
K. Matsuda and K. Hiramoto (Hitachi)

PB27 Particle Orbit Simulation for High Energy Heavy Ion Implanter ................. 324
T. Ito, T. Hattori, Y. Oguri, K. Sasa, N. Hayashizaki and E. Osvath*
(RLNR, *Institute for Nuclear Physics, Romania)

PB28 Lattice Design of JHP Circular Accelerators .................................................. 326
Y. Ishi and JHP Synchrotron Design Group (INS)

PB29 Bunch Lengthening of the NIJI-IV ................................................................. 329
M. Yokoyama, M. Kawai, K. Yamada*, N. Sei*, S. Hamada, S. Sugiyama*,

PB30 Basic Design of an Asymmetric Double Slow Extraction System for the KEK-PS ... 332
Y. Shoji, K. Marutsuka, T. Toyama and H. Sato (KEK)

PB31 Low-emittance Slow Extraction using Half-integer Resonance ...................... 335
Y. Shoji, K. Marutsuka, T. Toyama and H. Sato (KEK)

PB32 Ion Trapping Effect Observed in NAR ............................................................. 338
M. Nakajima, K. Yamada and T. Hosokawa (NTT)

PB33 Beam Test of the RF Feedback for KEKB in TRISTAN MR .............................. 341
S. Yoshimoto, E. Ezura, K. Arai, K. Ebihara and M. Suetake (KEK)

PB34 New Concepts for the Simulation of Beams in Cyclotrons .............................. 344
M. Fukuda and S. Adam (JAERI)

PB35 Bunch Deformation of a Multi-bunched Beam in TRISTAN Accumulation Ring .... 347
T. Obina*, Y. Funakoshi, M. Tobiyama, K. Satoh and T. Kasuga (GUAS, KEK)

PB36 Design Parameters of a Spiral Inflector for Axial Injection Project of the CYRIC Cyclotron .......................................................... 350
M. Fujioka, T. Honma, T. Shinozuka, O. Morishita* and T. Tachikawa*
(CYRIC, *Sumitomo Heavy Industries)

PB37 Hollow Beam Formation in the Extraction Region of BCRIS ........................... 353
Y. Batygin, A. Goto and Y. Yano (RIKEN)

PB38 Study of Incoherent Beam-beam Effects at Radioactive Isotope Beam Factory ... 356
Y. Batygin and T. Katayama* (RIKEN, *INS)
PB39 Effect of Field Variation on Beam Parameters in RIKEN RFQ Linac ........................ 359
    Y. Batygin, A. Goto, O. Kamigaito and Y. Yano (RIKEN)

Poster Session Radiation Protection

PB40 Comparison of Calculated Shielding Effects for 8 Materials ................................. 362

PB41 Nonlinear Resonances in a Multi-stage Free-electron Laser Amplifier ...................... 365
    S. Hashimoto and K. Takayama* (GUAS, *KEK)

PB42 X-band Prebunched FEL Amplifier .............................................................................. 368
    K. Saito, K. Takayama*, T. Ozaki*, J. Kishiro*, K. Ebihara* and S. Hiramatsu*
    (Hitachi, *KEK)

PB43 Development of Infrared Free-electron Laser System Using Compact Linac ............... 371
    T. Shinzato, K. Emura, T. Haga and H. Takada (Sumitomo Electric Industries)

PB44 Experiments of Beam-induced-plasma for Basic Study of HIF by RFQ-linac ............... 374
    K. Sasa, T. Ito, N. Hayashizaki and T. Hattori (RLNR)

PB45 Particle Orbit Simulation of Decelerator Cyclotron for RI Production .................... 377
    T. Nakamura, T. Hattori, H. Morinaga*, Y. Oguri, S. Yamaki**, K. Isokawa and
    N. Hayashizaki (RLNR, *Technischen Universitat Munchen, **Japan Steel Works)

PB46 A Novel Technique for Constructing a Plasma Micro-undulator and a Compact
    Soft X-ray Source ........................................................................................................ 378
    (Ibaraki Univ., *JAERI)

PB47 Study of Differential Pumping System for Beam-pumped Laser by TIT Heavy-ion
    RFQ Linac .................................................................................................................. 381
    H. Tomizawa, T. Hattori, Y. Oguri, M. Okamura, M. Okada, K. Sasa and T. Katayose
    (RLNR)

PB48 Operation of Linac Based FELs in IR- and Visible-range at the FELI ...................... 383
    T. Tomimasu, K. Saeki, Y. Miyauchi, E. Oshita, S. Okuma, K. Wakita, A. Kobayashi,
    T. Suzuki, A. Zako, S. Nishihara, A. Koga, K. Wakisaka, E. Tongu, A. Nagai and
    M. Yasumoto* (FELI, *Osaka National Research Inst.)

PB49 Novel X-ray Source Using Collisions of Circulating Relativistic Electrons
    and a Wire Target ........................................................................................................ 386
    H. Yamada (Ritsumeikan Univ.)

PB50 Study of Infrared Free Electron Laser Oscillator with Tohoku Linac ...................... 389
    B. Feng, T. Nakazato, M. Oyamada, S. Urasawa and T. Yamakawa (LNS)

PB51 A Design Study of an FEL-SR at the FELI ............................................................. 392
Y. Miyauchi, T. Takii and T. Tomimasu (FELI)

PB52 Time-of-flight Measurements of Positron-annihilation Induced Auger Electrons ................................................................. 395
  T. Ohdaira, R. Suzuki, T. Mikado, H. Ohgaki, M. Chiwaki and T. Yamazaki (ETL)

Poster Session Future Plans
PB53 Heavy Ion Medical Accelerator Project by Hyogo Prefectural Government ...... 398
  A. Noda**** and S. Yamada* (Hyogo Pref., *NIRS, **INS, ***ICR)

PB54 Status of the Emittance Upgrade Program at the Photon Factory Storage Ring ... 401
  M. Katoh and Y. Hori (KEK)

Parallel Session Orbit Analysis
3a1-1 Calculation of Electron Orbital for the Design of the X-band LINAC ............ 404
  A. Takeshita, T. Kozawa, M. Uesaka, T. Kobayashi, T. Ueda and K. Miya (NERL)

3a1-2 Beam Dynamics Issues in the Japanese Hadron Project Circular Accelerators ... 407
  S. Machida and JHP Synchrotron Design Group (KEK and INS)

3a1-3 The Optical Design of HIMAC Secondary Beam Course .............................. 410
  M. Hosaka, K. Noda, T. Murakami, M. Kanazawa, A. Kitagawa, Y. Sato, E. Takada,
  M. Torikoshi and S. Yamada (NIRS)

3a1-4 Design of a Compact Proton Accelerator Facility Dedicated for Cancer
  Therapy ........................................................................................................... 413
  A. Noda, M. Inoue, Y. Iwashita, T. Shirai, M. Nishi*, K. Hiramoto* and J. Hirota*
  (ICR, *Hitachi)

Parallel Session Applications and Future Plans
3a2-1 X-ray Leakage around 1.7 MV Tandetron Accelerator .................................. 416
  N. Sugiura, T. Kawanishi and T. Kosako (RCNST)

3a2-2 Study on Quantum Beam Science by using Ultra Short Electron Pulse, FEL, and
  Slow Positron Beam at ISIR, Osaka University .............................................. 419
  Y. Yoshida, S. Tagawa, S. Okuda, Y. Honda, N. Kimura, T. Yamamoto and G. Isoyama
  (ISIR)

3a2-3 Present Status of the Positron Factory Project and Development of Positron
  Beam Techniques ............................................................................................ 422
  S. Okada, H. Kaneko, A. Kawasuso, S. Masuno, H. Sunaga, H. Takizawa and
JAERI-Conf 95-021

K. Yotsumoto (JAERI)

3a2-4 VUU•SX High Brilliant Light Source ................................................................. 425
Y. Kamiya (ISSP)

Parallel Session  Beam Handling and Control

3a3-1 Design of a Beam-position Monitor Circuit for the KEKB Injector ................. 428
Y. Hosono, H. Kobayashi*, T. Suwada*, T. Urano* and A. Lazos*
(Univ. of Tokyo, *KEK)

3a3-2 Development of an Ion Implanted Thin Alumina Beam Profile Monitor .......... 431
S. Okada*, S. Masuno* and Y. Aoki* (KEK, *JAERI)

3a3-3 Development of Visual Beam Adjustment Method for Cyclotron ...................... 433
T. Agematsu, K. Arakawa and S. Okumura (JAERI)

3a3-4 Control System for the JAERI Tandem Accelerator ........................................... 436
S. Hanashima (JAERI)

Parallel Session  Medical Applications (HIMAC)

3a4-1 A Treatment Beam Control System for Irradiation Gated by Respiration of
a Patient ......................................................................................................................... 439
A. Itano**, K. Sato***, H. Ogawa and S. Yamada
(NIRS, *ICR, **Hyogo Pref., ***RCNP)

3a4-2 Development of 3-dimensional Irradiation System for Heavy-ion Radiation
Therapy ......................................................................................................................... 442
Y. Futami, H. Tomura, N. Matsufuji and T. Kanai (NIRS)

3a4-3 Physical Studies of Beam Delivery System for Proton and Heavy Ion Treatment... 445
A. Higashi, T. Kanai*, H. Tomura*, M. Endo*, A. Itano, H. Karashima and
Y. Hishikawa (Hyogo Pref., *NIRS)

3a4-4 Dosimetry System for Heavy-ion Radiotherapy ................................................... 448
T. Kanai, Y. Futami, H. Tomura and N. Matsufuji (NIRS)

3a4-5 Beam-quality Measurements on Heavy Ion Therapeutic Beam of HIMAC ............. 451
N. Matsufuji, T. Kanai, H. Tomura, Y. Futami, A. Fukumura, T. Kohno* and
K. Kawachi (NIRS, *TIT)

Plenary Session  Future Plans

3pl-1 Outline of JHP Synchrotron Design ................................................................. 454

xviii
Y. Mori and JHP Synchrotron Design Group (INS)

3p1-2 RIKEN RI Beam Factory Project ............................................................... 457
Y. Yano, A. Goto, T. Katayama* and RIBF Group (RIKEN, *INS)

3p1-3 Femtosecond Ultrafast Quantum Phenomena Research .................................... 460
M. Uesaka, T. Kozawa, A. Takeshita, M. Aida, T. Kobayashi, T. Ueda and K. Miya
(NERL)

3p1-4 The Tohoku University Stretcher-booster Ring ........................................... 463
M. Oyamada, J. Kasagi, O. Konno, A. Kurihara, M. Mutoh, T. Nakazato, M. Nanao,
T. Oonuma, Y. Shibasaki, M. Sugawara, S. Takahashi, T. Tamae, S. Urasawa,
T. Yamakawa, M. Kato*, T. Momose** and G. Isoyama***
(LNS, *KEK, **Miyagi National College of Technology, ***ISIR)

PD-01 Next-step ECRIS and 2m Length 4.52 GeV Advanced Accelerator:
Novel Extraction of Trapped Ions and their Acceleration-final Focusing
by Nonneutral and Neutral Plasmas ................................................................. 466
M. Niimura, T. Nakagawa, A. Goto and Y. Yano (RIKEN)
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYRIC</td>
<td>Cyclotron and Radioisotope Center, Tohoku University</td>
</tr>
<tr>
<td>ETL</td>
<td>Electrotechnical Laboratory</td>
</tr>
<tr>
<td>FELI</td>
<td>Free Electron Laser Research Institute, Inc.</td>
</tr>
<tr>
<td>GUAS</td>
<td>Graduate University for Advanced Studies</td>
</tr>
<tr>
<td>ICR</td>
<td>Institute for Chemical Research, Kyoto University</td>
</tr>
<tr>
<td>INS</td>
<td>Institute for Nuclear Study, University of Tokyo</td>
</tr>
<tr>
<td>ISIR</td>
<td>Institute for Scientific and Industrial Research, Osaka University</td>
</tr>
<tr>
<td>ISSP</td>
<td>Institute for Solid State Physics, University of Tokyo</td>
</tr>
<tr>
<td>TIT</td>
<td>Tokyo Institute of Technology</td>
</tr>
<tr>
<td>JAERI</td>
<td>Japan Atomic Energy Research Institute</td>
</tr>
<tr>
<td>KEK</td>
<td>National Laboratory for High Energy Physics</td>
</tr>
<tr>
<td>LNS</td>
<td>Laboratory of Nuclear Science, Tohoku University</td>
</tr>
<tr>
<td>NERL</td>
<td>Nuclear Engineering Research Laboratory, University of Tokyo</td>
</tr>
<tr>
<td>NIRS</td>
<td>National Institute for Radiological Science</td>
</tr>
<tr>
<td>PNC</td>
<td>Power Reactor and Nuclear Fuel Development Corporation</td>
</tr>
<tr>
<td>RCNP</td>
<td>Research Center for Nuclear Physics, Osaka University</td>
</tr>
<tr>
<td>RCNST</td>
<td>Research Center for Nuclear Science and Technology, University of Tokyo</td>
</tr>
<tr>
<td>RIKEN</td>
<td>Institute of Physical and Chemical Research</td>
</tr>
<tr>
<td>Spring-8</td>
<td>JAERI-RIKEN Spring-8 Project Team</td>
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</table>
PHASE I/II CLINICAL TRIAL WITH HEAVY ION AT
NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES

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In Japan the heavy particle therapy started already at NIRS in 1971. At first, the fast neutron beam was used in anticipation of its biological advantages. In some tumors, fast neutron therapy was more effective than conventional photon and electron therapy. But generally, the treatment results of fast neutron therapy were not satisfactory, because of its inadequate dose-distribution. Recently, the proton beam with high energy is going to get into the spotlight. Its dose localization is excellent and the biological effect is almost the same as that of the photon beam. Therefore, radiation oncologists can easily become experienced in applying it to daily routine treatment.

High-LET charged particle radiotherapy has particular appeal for therapy of radioresistant neoplasms. The physical and biological properties secondary to heavy ions include, 1) advantageous dose localization at depth, 2) increased effect on hypoxic tumor cells by high-LET radiations, 3) less repair of sublethal and potentially lethal radiation damage, and 4) less variation of radioresponse in the different phases of the mitotic cell cycle. Since June last year our challenge has been to translate these theoretical advantages into significant clinical gains in the treatment of cancer. The objects of Phase I/II clinical trial using carbon-ion beam include the brain tumor, head and neck cancer, lung cancer, hepatoma, cervical cancer and cancer of the prostate. Fifty-five patients has been already treated. It takes long time to evaluate the usefulness of heavy ion therapy, because it is very important to observe the treated patients at least several years after treatment. The preliminary results are encouraging. Although much has been learned regarding the potential of heavy charged particles, there is still a need for further research into their biology, physics and clinical applications.
DEVELOPMENT OF HIGH POWER NEGATIVE ION SOURCES FOR FUSION AT JAERI

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ABSTRACT

Technologies producing high power negative ion beams have been highly developed in these years at JAERI for use in neutral beam injectors for heating the thermonuclear fusion plasmas. At present, it is possible to produce multi-ampere H-/D- ion beams quasi-continuously at energies more than a few hundred keV with a good beam optics of beamlet divergence of a few mili-radian. Based on these technologies, two R&D projects have been initiated; one is to develop a 22A/500keV/10s D- ion source for the neutral beam injector for JT-60U, and the other is to develop a 1A/1MeV/60s H- ion source to demonstrate high current negative ion acceleration up to the energy of 1MeV, the energy required for the neutral beam injector for International Thermonuclear Experimental Reactor (ITER).

1. INTRODUCTION

Negative ion based neutral beam injector (N-NBI) is one of the most promising candidates for the current drive and heating system in steady state operation of reactor-grade tokamak fusion devices, such as the International Thermonuclear Experimental Reactor (ITER) [1]. The most crucial issue in realizing the injector is to develop a high power negative ion source which can produce negative deuterium ion beams with a current of several tens of amperes at an energy of 0.5-2 MeV. The ion source required for ITER, for example, has to produce 40A D- ion beams at an energy of 1MeV for a pulse duration of more than 1000s with a beam divergence of less than 5mrad [1,2]. The current density should be more than 20mA/cm^2 to make the size of the N-NBI system reasonable. In addition, the source should be operated at a low operating gas pressure of less than 0.3Pa to reduce the stripping loss of negative ions in the accelerator and to have a reasonable acceleration efficiency.

Although these specifications are far beyond the specifications of existing negative ion sources, basic performances have already been achieved individually by the negative ion sources developed at JAERI. Namely, H- ion beams of 10A, 50keV were extracted with an enough current density of 37 mA/cm^2 [3], and D- ion beams of 2.2A, 100keV, 5s (10 mA/cm^2) was produced in JAERI/CEA Joint Experiment at an low operating gas pressure of 0.3Pa [4,5]. Long pulse operation was demonstrated at 50keV, 0.3A (>10mA/cm^2) for a pulse duration of 24 hours in a small H- ion source [6], which has a same design concept as the 10A source. High energy H- ion beams of 350keV, 0.5A were produced using a three-stage electrostatic accelerator [7]. Beamlet divergence of as low as 5mrad was obtained at 400keV with a current density of 13mA/cm^2 [7].

Based on these successful results, two R&D projects have been initiated at JAERI. One is to develop a 22A, 500keV, 10s D- ion source for the N-NBI system for JT-60U [8]. The other is the development of a 1MeV negative ion source/accelerator for the demonstration of high energy acceleration of ampere-class negative ion beams to 1MeV [9], the energy required for ITER.

In the present paper, after a brief description of these two R&D projects, present status of the development is reviewed together with a future plan of the development.

2. D- ION SOURCE FOR JT-60U

A 500keV, 10MW N-NBI system has been constructed for studying of mega-ampere level NB current drive and plasma core heating experiments with a high density reactor-like plasma in JT-60U. It is the first neutral beam injector in the world using negative ions as the primary ions. The system is designed for injecting 10MW deuterium or hydrogen neutral beams for 10s beam duration with a duty cycle of 1/60. The N-NBI system consists of a beamline equipped with two ion sources, a power supply, a control system, and an auxiliary sub-systems that includes a cooling water system, cryogenic refrigeration system, and auxiliary pumping system. Each ion source has a cesium-seeded volume negative ion generator, a multi-aperture extractor and a three-stage electrostatic accelerator. Figure 1 shows a cross-sectional view of the ion source. The source is designed so as to produce 22A, 500keV, 10s D- ion beams with a current density of 13mA/cm^2 [10,11]. The dimensions of the plasma generator are 64cm in diameter and 122cm in length. Produced negative ions are extracted from 1080 apertures of 14mm in diameter, which distributed within the area of 45cm x 110cm.

Out of the two ion sources, first ion source has been
designed and fabricated. After successful performance tests in test stands, the ion source was installed in the beamline of the N-NBI system and full power test has just started. Up to now, the source has been successfully operated and produced a 400keV, 5.9A, 0.1s D- ion beam [12], the world highest D- current and beam power.

The full power test will be finished by the end of October 1995, and the second ion source is to be installed in the beamline by January 1996. NB injection experiment is scheduled to start from April 1996.

3. PROTOTYPE ACCELERATOR FOR ITER

The negative ion beam energy required for ITER is as high as 1MeV to penetrate the beam into the high density, large core plasma of ITER. Although multi-MeV beams have been produced in the electrostatic accelerators used for high energy physics, the current is less than an order of mA. There is no experiment to accelerate ampere-class particle beams, including positive ion beam and electron beam, above the energy of several hundred keV. A demonstration of the ability to accelerate the ampere-class negative ion beams is, therefore, the most critical and urgent R&D item for ITER. Electrostatic acceleration will be employed because of its high electrical efficiency.

To develop the 1MeV negative ion accelerator, we have constructed a new test stand called MeV Test Facility (MTF) [9]. MTF has an acceleration power supply which has a capacity of 1MV, 1A, 60s, the world biggest Cockcroft-Walton circuit, and the power supplies for negative ion production and extraction. These high potential power supplies are installed in the SF6 gas vessel with the a 1MeV prototype accelerator for ITER.

In the prototype accelerator, negative ions created in the 'KAMABOKO' type negative ion generator [13] are accelerated by five-stage electrostatic accelerator.

Up to now, the accelerator was conditioned up to the voltage of 750 kV. Hydrogen negative ion beams were accelerated after the accelerator conditioning. The H- beam was successfully accelerated up to an energy of 700 keV with an acceleration drain current of 230 mA for a duration of 1s. The highest drain current of 360 mA was obtained at 600 keV.

4. SUMMARY

Figure 2 shows the negative ion beam currents and energies achieved in the existing ion sources. Specifications at which the N-NBI system for JT-60U and MTF aim are also shown in the figure together with the final target for ITER. The large negative ion source for JT-60U and the prototype accelerator in MTF are the two critical steps for 1MeV, 40A, CW ion source/accelerator for ITER.

REFERENCES

Fig. 1  Cross-sectional view of D- ion source for JT-60U N-NBI

Fig. 2  Status of high power negative ion beam development
Present Status of the Medical Accelerator HIMAC


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Abstract

Clinical study of cancer treatment has been going on since June 21, 1994 with HIMAC at NIRS. More than 50 patients have been treated with high energy carbon beams until August 4, 1995. The preliminary results look excellent as expected: very light damage on skin surface and remarkable effects on cancer cells.

HIMAC is operated day and night from 7 p.m. on Monday till 7 p.m. on Saturday for the clinical treatment and for basic experiments. About 1,500 hr. per year are used by clinical trials and 2,500 hr. is open for physical and biomedical users including researchers outside NIRS.

1. Introduction

Clinical trials and biomedical experiments at LBL[1] strongly suggest that the heavy ion therapy is very powerful especially in treating deeply seated tumors. The advantage of the therapy comes from the well known characteristics of heavy ions: a very good three dimensional dose localization in a human body. In a longitudinal dose distribution, a very sharp Bragg peak is observed around the end point of heavy ions. A high value of LET at the Bragg peak is also attractive in the treatment of radio-resistant tumors. Based on the long experience of radiotherapy with protons and fast neutrons, NIRS adopted heavy ion therapy because of these excellent characteristics of heavy ions.

The maximum energy of HIMAC is designed to be 800 MeV/u for light ions with \( q/A = 1/2 \) so that silicon ions reach 30 cm deep in water[2],[3]. Two ring structure of the main accelerator of HIMAC will allow further development of the beam quality and performance. Ion species ranging from He to Ar are required for the clinical treatment. In the facility, there are three treatment rooms one of which has both vertical and horizontal beam lines. The other two treatment rooms are equipped with a vertical and a horizontal beam lines, respectively.

2. Commissioning

The HIMAC project was approved in 1987 as one of the major project of “Comprehensive 10 year Strategy for Cancer Control” promoted by Japanese government since 1984. The first beam from the injector was obtained in late March 1993 with singly charged He ions. For the dual synchrotron rings, beam tests were begun in November 1993 with doubly charged He ions. The ions were accelerated to 230 MeV/u with a repetition rate of 1/2 Hz for each ring. Tests of the slow extraction from both rings were successfully completed in December and the extracted beams were transported to three treatment rooms within a few days. The length of the extracted beam spill was typically 300 ms.

After careful tuning of the accelerator system, biomedical and physical experiments were performed for a few months. Final check of the reliability of the total system was done with the carbon beam irradiation on a monkey. Clinical trials of the heavy ion cancer therapy started on June 21, 1994 with 290 MeV/u carbon ions. The first series of the treatment was successfully completed for three patients in August 1994. It takes about 90 seconds for a single fractional treatment, while the precise patient-positioning procedure requires about 20 min. Three treatments per week and total of 18 treatments for each patient were adopted as a protocol of the clinical trial.

The interim diagnosis shows excellent results: radiation damage on the mucous membrane seems very light in spite of the perfect damage of tumors. All of the first three patients got good recovery and already out of hospital. For some other patients, however, no remarkable improvements were observed.

In the second and the third series of the clinical trials, heavy ion treatment was applied to cancers at the head or neck, the lungs, the central nerve system, the uterus, the liver, the prostate etc. More than 50 patients are already treated with 290, 350 and 400 MeV/u
carbon ions. Total of 100 patients will be finished by the end of the fiscal year 1995.

3. Operation of HIMAC

In the early stage of the accelerator operation, all devices were turned off overnight except for the vacuum system and the control system. After turning on in the morning, it took only 4 hr. to get the accelerated beam in a treatment room. Most part of the time are spent in tuning of the ion source and LEBT elements. After October 1994, HIMAC is operated day and night from Monday 7 p.m. to Saturday 7 p.m. In the day time of every Monday, weekly maintenance is scheduled. Accelerator Engineering Corporation (AEC) is responsible for the machine operation and the weekly maintenance. Major activities of the accelerator group of NIRS are set toward the improvements of the beam performance.

The machine time from 9 a.m. to 7 p.m. of the weekday is scheduled for the clinical trials and from 7 p.m. to the next 7 a.m. is open for users with carbon ions. From Friday 7 p.m. to Saturday 8 p.m., various kind of ion species are accelerated for users in physics and other fields of researches.

An energy change of the synchrotron is required once in a daytime to select the optimum residual range for different patients. After changing the beam energy, the dose uniformity in the irradiation field is checked. Before and after the daily treatments, energy and beam course is changed for the basic experiments.

Total of 37 weeks per year are available as machine time, other 2 weeks are for beam tuning and 13 weeks are scheduled shut down for machine maintenance etc. About 1,500 hr. per year was spent by the clinical trials and about 2,500 hr. of machine time is assigned to the basic experiments and beam tuning.

All devices of HIMAC are controllable through a digital computer system. Optimized set of the operation parameters are saved in a specified file and usable in the next operation. With a well established operation file, it takes only 20 or 30 min. to tune a pair of the synchrotron rings. It requires nearly the same time to fix the HEBT parameters including the tuning time for the beam switching. The injector, however, needs more than one hour, because it takes about 30 min. for an ion source to get stable.

The reproducibility of the beam performance is excellent without manual tuning of the magnetic fields. In order to minimize the field variation due to a hysteresis loop, an initializing technique is introduced before setting the magnet currents. During the initializing process, all magnets are excited with the maximum currents of the power supplies. By following the same path of the hysteresis loop, the magnetic fields well reproduces the previous values with only setting the magnet currents.

4. Beam Performance

We have two types of ion sources: a PIG and an ECR sources installed independently on high voltage decks of 60 kV max. The output beam intensities and emittance of both sources are satisfactory for the treatments[4],[5]. The beam transmission efficiencies through the low energy transport line and the RFQ are attained to be around 80% and 90%, respectively, in daily operation. An example of the output beam signal of the injector is given in Fig.1 together with rf pulses for RFQ and DTL.

The two synchrotron rings are operated independently from each other except that the magnets must be excited 180° out of phase. The dipole field changes from 0.11 T at injection energy to 1.5 T at maximum with a ramping rate of 2 T/s (max). The betatron tunes are chosen typically at 3.68 and 3.13 for horizontal and vertical directions, respectively. A typical operation pattern of the ring magnets is 200 ms for a flat base, 700 ms for rise and falling time and 400 ms for a flat top. In Fig. 2, an example of oscilloscope signals is given for a bending magnet excitation pattern (top), a bump magnet for beam extraction (2nd), beam signal in the synchrotron ring (3rd) and the extracted beam signal (bottom). In the signal of the extracted beam, very big intensity fluctuation can be observed. This fluctuation is due mainly to a current ripple of the synchrotron magnets, because no feedback system is applied to stabilize the extracted beam intensity.

High frequency components of the beam ripple are suppressed appreciably after careful tuning of the synchrotron magnet power supplies. At the flat top, voltage ripples of the power supplies of QF and bending magnets are kept extremely low values of less than 1x10^-6 and 1x10^-5, respectively (50 Hz). A beam ripple, however, remains at high level. By reducing the sextupole fields for chromaticity correction, satisfactory beam spill is obtained as shown in Fig. 3. This fact means that the fluctuation of the bending field may affects strongly on the beam ripple through the sextupole fields.

The whole control system works very well and even a very low intensity beam of a few hundred particles per second can be stably accelerated without Δϕ and Δr feedback loops.

In order to get a high efficiency of the treatment room usage, it is required to switch the accelerated beam from one treatment room to the other room in a very short time. The beam switching must be done
without introducing the beam into the treatment room. The reproducibility of the beam position should be better than ±2.5 mm at the iso-center. Such precise beam positioning is realized with a special sequence in the switching magnet excitation. The new technique for beam switching takes only 5 min. and will be adopted in the actual treatment in near future.

5. Future Developments

HIMAC facility is open for many researchers who are interested in the heavy ion science as well as heavy ion therapy. In many researches, HIMAC is required to accelerate heavier ions with a variety of energies and with high quality. In order to meet these demands, third ion source of 18 GHz ECR source is now under development. Ions from these three ion sources will be accelerated simultaneously with so called time sharing acceleration scheme and delivered to a medium energy experimental room, the upper synchrotron ring and the lower synchrotron ring.

A secondary beam will be available within a few years to investigate the possibility of precise check of the ion stopping position in a human body. The positron emitters, such as $^{13}$C, are considered to be effective for this purpose. The beam course will be open for other scientific fields.

Further sophisticated irradiation schemes, such as a spot scanning method or a three dimensional irradiation method, are also important in improving the effectiveness of the heavy ion therapy. An irradiation treatment synchronized with human breathing is our first target to reduce the unwanted dose to the normal cells around the tumor. The treatment will be realized with a quick response of the rf-knockout beam extraction from the synchrotron ring[6].

6. Acknowledgments

The authors express their sincere gratitude to Drs. Y. Hirao and K. Kawachi for their continuous encouragement and fruitful discussions. They are also grateful to other members of AEC for their skillful assistance.

7. References

CURRENT STATUS OF THE RCNP RING CYCLOTRON


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Abstract

Experimental studies with the RCNP Ring Cyclotron were started from 1992. Energy resolution of 25 keV was obtained with high resolution spectrograph Grand Raiden for 300 MeV proton beam of 80 keV energy width by using dispersion matching. A very short polarized proton beam pulse of 150 ps was achieved for neutron TOF experiment. A new high intensity polarized proton and deuteron ion source, a new axial injection system and injection beam line for polarized ion source and Neomafios were installed in August 1994. The old RCNP AVF cyclotron has been used as injector cyclotron without any modification. On this scheduled summer shutdown, the control system and the main magnet power supply of the AVF cyclotron were replaced by a new one. Many improvement on the stability and the controllability of the AVF cyclotron can be expected. On January 17th, 1995, the Ring Cyclotron was displaced about 5 mm by the earthquake. The realignment of the system had been made and experimental studies are started in May.

I. Introduction

The construction of the RCNP ring cyclotron was started in 1987. The first extracted beam was obtained in 19911. The ring cyclotron is energy quadrupler of the RCNP AVF cyclotron. Proton and alpha particles can be accelerated up to 400 MeV. The K value for light-heavy ions acceleration is 400. Table 1 shows the accelerated ions and the energies by the ring-cyclotron2). For 400 MeV proton beam acceleration, 30-50% of accelerated beam was lost by axial oscillation driven with median plane error near \( \nu_e = 1 \) resonance for improper setting of the trim coil currents3). However no beam loss was observed for smooth surface current density distribution of the trim coil4).

Plan view of the ring cyclotron is shown in Fig.1. Three single gap acceleration cavities are used in the ring cyclotron. Frequency range of the cavity is 30-52 MHz. An additional single gap cavity is used for flat-topping with 3rd harmonic of acceleration frequency to get good energy resolution and wide phase acceptance for single turn extraction mode5).

The phase acceptance is 20° for energy deviation with flat-topping within \( 10^{-4} \). A 180°-single-dee acceleration cavity is used in the injector cyclotron. The frequency range of the cavity is 5.5-19.5 MHz. The phase acceptance of the injector cyclotron is \( 7^\circ \) and \( 4^\circ \), since the ratio of acceleration frequency of the ring cyclotron to the injector cyclotron is 3 and 5 for proton and alpha, respectively. In order to get high quality injection beam for the ring cyclotron, the six dimensional phase space volume of the injection beam is limited by various slits between the ion source and the ring cyclotron. The beam intensity reduction about \( 10^{-2} \) with these slits is very serious for polarized beam and heavy ion beam. The beam intensity upgrade project had been done in 19945,6,7). Many efforts are being continued to improve beam quality, stability and intensity of the ring cyclotron. Injection beam instabilities caused by main coil and trim coil power supply of the injector cyclotron was serious problem. The beam stability upgrade project of the injector cyclotron was done in this summer8,9,10).

<table>
<thead>
<tr>
<th>Table 1 Accelerated Ions and the energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
</tr>
<tr>
<td>Deuteron</td>
</tr>
<tr>
<td>(^3)He</td>
</tr>
<tr>
<td>Alpha</td>
</tr>
<tr>
<td>(^{14})N(^{7+})</td>
</tr>
</tbody>
</table>

II. BEAM INTENSITY UPGRADE PROJECT

1. New axial injection system

Old axial injection line with electrostatic quadrupole lenses was replaced by new system with Glaser lenses, sawtooth buncher and spiral inflector to get a high-transmission and stable operation. Fig.2 shows layout of the injection line. The direction of magnetic field in the Glaser lenses is excited alternately to cancel the depolarization effect of the lens. The obtained injection efficiency for 65 MeV proton is 14%5,7).
2. High intensity polarized ion source

A new atomic beam type polarized proton and deuteron source with cold (30K) nozzle, NEOMAX sextuple magnets and ECR ionizer. A maximum proton current of 8μA was obtained for 65MeV. The polarization is about 0.75. The polarized ion source is horizontal type and easy for maintenance. The polarized protons and deuterons are deflected upward by 6.7 and 15 degrees respectively with electrostatic deflector and deflected downward by 96.7 and 105 degrees with a following dipole magnet to get longitudinally polarized beam in the vertical beam line5,7).

3. NEOMAFIONS

A 10GHz ECR ion source NEOMAFIOS is used as external ion source of the injector cyclotron from last September. Table 2, shows the beams accelerated for experimental studies6,7).

III. BEAM STABILITY UPGRADE PROJECT

1. Control system of the injector cyclotron

It became difficult to maintain the old control system of AVF cyclotron. A new control system was needful to install a new high resolution high stability reference voltage for every power supplies of the AVF cyclotron. The main computer of the ring cyclotron control system was upgraded from micro VAX 4000/200 to micro VAX 4000/500. The control and monitor functions of the AVF cyclotron were concentrated to the ring cyclotron control system8).

2. DC power supplies for the injector

The achieved long-term current stability of the new main magnet power supply is 4 x 10^-8. The long-term current stability better than 10^-5 was obtained for the trim coil power supply by using HOLEC-DCC(TOPACC). The remained old DCCT of the trim coil power supplies will be replaced soon by the new DCCT9).

3. RF system of the ring cyclotron

Many efforts were made to improve stability of RF system. Typical phase excursion between acceleration and flat-topping voltages are 0.1deg/week. The voltage stabilities are 0.01% and 0.1% for the acceleration and flat-topping voltage respectively10). The development to improve stability of the RF system is being continued.

4. RF system of the injector cyclotron

The low-level RF system was replaced by new system very similar to the ring cyclotron RF system. Improvement on the stability is expected.

IV. DAMAGE AND IMPROVEMENT

1. Utility

Old chillers of the cooling water system and old air conditioning system for the AVF cyclotron were replaced by new one. PID temperature regulator of the cooling water was appended.

2. Repair of the cooling pipes

The Dee-electrode of the AVF cyclotron was overhauled to repair perfectly the cooling water leakage to vacuum.

3. The earthquake

The estimated maximum acceleration of the earthquake(January 17th,1995) on the RCNP is more than 300gal. About 5mm slip to north was occurred between the rest and the base-plate of the ring cyclotron. No damage of the elements was occurred. The rests and the base-plates were welded together after the realignment of the ring cyclotron system2).

4. RF current contact of the ring cyclotron

After long exposure to the atmosphere during two months realignment of the ring cyclotron, the sliding RF current contacts (made of graphite admixed silver) failed on 300MeV proton acceleration position. The cavity wall was polished and the contacts were replace by pure silver contacts in this summer. The leaf springs of the RF current contacts of the acceleration cavity were degraded by three years operation on high temperature(~ 300°C). The leaf spring is silver plated and made of Be-Cu alloy having electric conductivity about 20% IACS. The thermal conductivity of metal is nearly proportional to the electric conductivity. Cr-Zr-Cu alloy (85% IACS) leaf springs will be installed soon.

| Table 2 Accelerated ions from Neomafios |
|----------------|----------------|----------------|
| Energy AVF (MeV) | Beam current at exit (μA) |
|----------------|----------------|----------------|
| 3 d            | 43.5           | 9              |
| 3 H^1+        | 32             | 4              |
| 3 He^2+       | 92.6           | 7.4            |
| 4 He^2+       | 120            | 3.2            |
| 6 Li^2+       | 64             | 0.042          |
| 6 Li^2+       | 131.1          | 0.088          |
| 7 Li^3+       | 114.0          | 0.242          |
| 14 N^4+       | 130.3          | 4.4            |
| 14 N^5+       | 210            | 2.3            |
Reference


Fig. 1 Plan view of the ring cyclotron.

Fig. 2 Layout of the injection line.
Status of the KEK-PS Main Ring

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Abstract

The KEK-PS has been operated successfully to serve an intense proton beam for the past two decades. To meet the need of new physics research, there are several objectives for the PS upgrade, such as, to increase the proton intensity in the main ring, to accelerate the various ions and then the multifunctional operation of PS. Especially, an intensity upgrade is coming to the urgent problem for the long baseline neutrino oscillation experiment and the rare event experiment. Machine study to make clear the machine parameters and to find the curing of the difficulty to increase the beam intensity has been under going. In this article, the brief history of KEK-PS, an operation status and an upgrade subjects will be described.

1. Brief History and an Operation Status

The KEK-PS consists of four accelerator complex, 750KeV Cockcroft Walton pre-injector, 40MeV injector linac, 500MeV booster synchrotron and 12GeV main ring. Brief history of the KEK-PS is shown in Table 1. Counter experiment started on July, 1976 using the secondary beam from an internal target and the fast extraction for bubble chamber experiment[1] and the slow extraction at 12GeV[2] started on January and November, 1977, respectively. Booster Synchrotron Utilization Facility to utilize surplus 500MeV proton beam started on October, 1980. In those days, beam intensity at the booster extraction and in the main ring were 6x10^11 ppp and 2x10^12 ppp, respectively. In order to aim the intensity upgrade, booster injection system was changed to H' injection one[3] from former positive ion multi-turn injection and the linac was subsequently upgraded to 40MeV after the long shut down on 1984. As the results of much effort, the beam intensity was increased to 5.4x10^12 ppp in the main ring on June 1989 and 2.4x10^12 ppp for BSF on May 1990. On the other hand, a polarized proton beam acceleration (typically 40% polarization at 3.5GeV) was performed during those days.4)

Newly second slow extraction line (EP1) and North Counter Hall were established on 1990 at the terminated bubble chamber experimental area besides the EP2 line for the East Counter Hall. Since then, the slow beam is extracted to both counter halls independently. Simultaneous extraction has been desired but the feasibility study is still under progress. Figure 1 shows a layout of the KEK-PS complex.

Main ring power supply and equipment for the slow extracted beam spill is 1.7-2.0 seconds. The spill servo controller was improved as a consideration of the frequency response analysis of the slow extraction process using the measured beam transfer function and the frequency response of the servo control devices.7) This contributed to reduce a spill fluctuation about 10-db and the extracted beam spill efficiency is maintained about 90%. However, the extracted beam spill has been sometimes getting an uncharacteristic frequency due to an incoming disturbance in the commercial AC line.8)

Figure 1. Layout of the KEK-PS Complex.

After successive operation of switching between polarized proton beam acceleration for main ring and high intensity proton beam for BSF, research and development for effective use of PS have been performed, such as deuteron and alpha beam acceleration9) and also beam was extracted at various energies. Especially, newly developed septum-bump injection system, which is the magnet system available for both negative ion charge exchange injection and positive ion multi-turn injection.10) This is very noble system and contribute to avoid much troublesome changing the injection system with a large scale evacuating process.

Although the highest beam intensity in the main ring was upgraded to 5.4x10^12 ppp on 1989 and increased to 5.95x10^12 ppp on November of 1994, we do not find and fixed yet the machine parameters for reproduction of this condition and an average intensity during operation has been still 3-4 x10^12 ppp.

For reliable acceleration of low intensity beam such as alpha beam and polarized beam, high sensitive beam monitors are going to install in the booster and the main ring.

One of the most effective upgrades for stable acceleration of intense beam and ions is an improvement of rf system,11) such as a voltage-controlled oscillator,
phase detectors, function generators, feedback loops and so forth.

Total operation time was more than 4500 hours per year for a recent few years, and 70-77% was dedicated to physics experiment and about 15% was used for accelerator study and tuning. The accelerator was operated in fairly good condition with less than 5% machine failure.

Data $V_{aperture\_Overlap}$

Figure 2. Results of the local aperture survey using local bump method. First and second cells are missing bend ones.

2. Intensive Machine Study for the Main Ring Intensity Upgrade

As described above, every effort to realize the upgrade of KEK-PS have been devoted. Booster synchrotron accelerates $1-2 \times 10^{12}$ ppp for Booster Synchrotron Facility. If the main ring can accept and accelerates the beam of this intensity with no beam loss, $10^{13}$ ppp beams could be expected for main ring utility. However, the circulating beam intensity is limited to about $6 \times 10^{12}$ ppp for some reasons which is not still understood. An intensive machine study has been performed to make clear the machine parameters and to find the cause and curing of the difficulty in order to realize the beam intensity upgrade.

First of all, several tools for the machine study were developed, such as an upgraded injection error monitor, a fast beam loss monitor which can observe it turn by turn using computer workstations and so forth.\(^\text{12}\)

After several times brain storming, the aim of the first study was decided to concentrate the main ring beam injection problem. The local aperture measurements of the main ring were performed to make clear the real orbit center in the vacuum chamber using a small size beam scraped in the booster synchrotron. The twenty eight steering dipoles were excited independently to make a local bump orbit at each section in the main ring. The vertical aperture seems to be determined by the diameter of the vacuum chamber in the bending magnet as shown in Figure 2.

The orbit was set to the center of the vacuum chamber as decided above, then the beam survival were measured to make clear and maximize the acceptance with dependence on the injection error made by injection kicker and septum magnet for the horizontal plane and by steering magnet in the transport line for the vertical plane. Data analysis is under consideration since there are some problems to make sure the systematic errors of twiss parameters and beam position monitors.

The usual operating point of PS main ring is at around $v_x=7.12$ and $v_y=7.25$ and the average beam intensity from the booster is $4.5 \times 10^{11}$ ppp. In order to avoid beam loss due to the space charge detuning for a high intensity beam, it should be select rather higher operating point. However, a third order resonance, $v_x + 2v_y = 22$, and fourth order resonances, particularly $4v_y=29$ and $2v_x + 2v_y = 29$ seem to be obstacles. After these resonances were corrected as established using rather low intensity beam, high intensity beam, $1.3 \times 10^{12}$ ppp, were injected from booster and measured the tune mapping of beam survival as shown in Figure 3. There is no region where more than 70% of the beam survives. A fast beam loss is brought at around an operating point with smaller tunes, on the other hand a slowly beam loss is brought at around an operating point with larger tunes. Further studies should be necessary to make clear these effect and how to cure.

Summary of the spring studies, which includes also some results at the studies performed before summer shut down, will be reported soon in KEK Report.

Figure 3. Tune mapping of the beam survival injected the intensity of $1.3 \times 10^{12}$ ppp from booster. Intensity ratio of the beam survival until 350ms after injection to that from the booster.

3. Design status for the fast extraction system

Fast extraction had been operated until July, 1981, for the bubble chamber experiment as a shaving extraction.\(^\text{13}\) At this time, full beam which is circulating in the main ring, should be extracted instantaneously for the neutrino oscillation experiment. Then, several research and development have been done.
Construction of 12.5Ω kicker magnet and Blumlein system are advantage from the view point of economy and saving the space of magnet setting. Prototype one has just constructed and is facing on the exciting test.

Orbit analysis for the feasibility using existing slow extraction devices, such as bump and septum magnets system is under consideration. This is important for the switching the fast extraction and the slow extraction for multi user request. We are considering now the changeable system of the extraction kicker and electro-static septum in the vacuum chamber. A large orbit excursion is the problem since the extracted beam passes through non linear magnetic field region of both bending and quadrupole magnets. In order to construct economically, reconstruction of these magnets should be avoided. Detailed analysis of the magnetic field and orbit calculation using this data are under going.

### 4. Summary

Acceleration of 5.95x10^{12} ppm intense beam has achieved, however, an average intensity during normal operation has been still 3.4x10^{12} ppm.

Although the spring studies were concentrated to the problem during injection period, the reason of the beam loss was not still understood yet. Further we should make clear the problems at acceleration start and transition crossing to realize the beam intensity upgrade.

Twenty years has passed since the KEK-PS constructed, then several equipments and parts become decrepit, then taking into consideration for this problem is also important subject for the reliability of machine operation.

The author would like to thank all of the PS members for useful suggestions and discussions. He thanks also to Beam Channel and Experimental Planning Coordination members and users for their encouragement.

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Table 1. History of KEK Proton Synchrotron

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 1971</td>
<td>Construction started</td>
</tr>
<tr>
<td>June 1974</td>
<td>Pre-injector accelerated protons to 750 KeV</td>
</tr>
<tr>
<td>August 1974</td>
<td>Injector linac accelerated protons to 20 MeV</td>
</tr>
<tr>
<td>December 1974</td>
<td>Booster synchrotron accelerated protons to 500 MeV</td>
</tr>
<tr>
<td>December 1975</td>
<td>Commissioning of main ring operation</td>
</tr>
<tr>
<td>March 1976</td>
<td>Main ring accelerated protons to 8 GeV</td>
</tr>
<tr>
<td>December 1976</td>
<td>Main ring accelerated protons to 12 GeV</td>
</tr>
<tr>
<td>May 1977</td>
<td>Bubble chamber experiment started</td>
</tr>
<tr>
<td>June 1977</td>
<td>Beam intensity of booster was 6x10^{11} ppm</td>
</tr>
<tr>
<td>November 1977</td>
<td>Counter experiments with slow extracted beam started</td>
</tr>
<tr>
<td>July 1978</td>
<td>Beam intensity of main ring was 2x10^{12} ppm</td>
</tr>
<tr>
<td>June 1980</td>
<td>Experiment with Booster Synchrotron Utilization Facility started</td>
</tr>
<tr>
<td>July 1981</td>
<td>Bubble chamber experiment was terminated</td>
</tr>
<tr>
<td>May 1984</td>
<td>Pre-injector acceleration duct was renewed</td>
</tr>
<tr>
<td>June 1985</td>
<td>Booster injection system was changed to H injection</td>
</tr>
<tr>
<td>November 1985</td>
<td>Linac upgraded to 40 MeV</td>
</tr>
<tr>
<td>May 1987</td>
<td>Experiment using polarized proton beam started</td>
</tr>
<tr>
<td>May 1988</td>
<td>Accelerator control was upgraded to MAP</td>
</tr>
<tr>
<td>June 1989</td>
<td>Beam intensity of main ring upgraded to 5.4x10^{12} ppm</td>
</tr>
<tr>
<td>May 1990</td>
<td>Beam intensity of booster upgraded to 2.4x10^{12} ppm</td>
</tr>
<tr>
<td>August 1990</td>
<td>Main ring power supply was upgraded</td>
</tr>
<tr>
<td>January 1991</td>
<td>Counter experiment at the North counter hall started</td>
</tr>
<tr>
<td>February 1992</td>
<td>Deuteron beam was accelerated to 11.2 GeV</td>
</tr>
<tr>
<td>April 1992</td>
<td>Experiment with deuteron beam started</td>
</tr>
<tr>
<td>April 1994</td>
<td>Septum-bump injection system was developed</td>
</tr>
<tr>
<td>April 1994</td>
<td>Alpha beam accelerated to 23 GeV and experiment started</td>
</tr>
<tr>
<td>August 1994</td>
<td>Realignment of the booster magnets</td>
</tr>
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</table>
Construction of SPring-8 injector system


JAERI-RIKEN SPring-8 Project Team
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Abstract

The SPring-8 injector system composed of a linac and a booster synchrotron is under construction on schedule. The performances of the linac preinjector were proved to satisfy the requirements. Many components were fabricated and tested their performances. Construction of the injector building was completed in April 1995 and installation of the accelerators was started from May 1995.

1 INTRODUCTION

The SPring-8 is a third generation synchrotron radiation X-ray facility with a main accelerator of 8 GeV storage ring. The injector for SPring-8 consists of a 1 GeV linac and a 8 GeV booster synchrotron, as shown in Fig. 1. The positrons are used for the operation particle in the storage ring as well as the electrons. Fabrication of the accelerator components began in 1990. Construction of the injector building began in 1992 and was completed in 1995. Installation of the accelerator was started in 1995. General feature of the injector system will be explained in section 2, and status of the linac and the booster synchrotron will be presented in sections 3 and 4.

2 GENERAL FEATURES

The 1 GeV linac consists of a 250 MeV high current linac and electron/positron converter, and a 900 MeV main linac. The electron beam is able to be accelerated up to 1.15 GeV by means of extracting the target of the electron/positron converter from the beam line. The linac is able to produce various kind of the pulse width from 1 ns to 1 μsec, which are requested by the storage ring operation modes; a multi-bunch operation and a single-bunch operation. The linac rf-frequency is 2856 MHz and its operation rate is 60 Hz at the maximum. The total length from the electron gun to the end of the linac is 140 m followed by a 39 m long beam transport line to the synchrotron.

The booster synchrotron is able to accelerate the beam injected from the linac from 1 GeV to 8 GeV which is the operation energy of the storage ring. The operation rate is 1 Hz. The synchrotron has a racetrack shape with a FODO lattice containing 40 cells, which consists of 30 normal cells and two straight sections including 5 cells each. This straight section has 3 dispersion-free cells and 2 dispersion-suppressing cells with missing bending magnets. One cell is ~10 m long, and circumference of the synchrotron is 396.12 m. The natural emittance is 2.3 x 10^-6 m·rad at 8 GeV, and that is expected to be satisfactory for subsequent injection into the storage ring. The horizontal and vertical tunes are 11.73, and 8.87, and the natural chromaticities are -14.4 and -11.5 for the horizontal and vertical direction, respectively. The beam transport line between the synchrotron and the storage ring is 310 m in length, climbing up by 9 m in height.

3 LINAC STATUS

3.1 Preinjector

The preinjector of the linac consists of the electron gun, two prebunchers, a buncher, several beam monitors, etc. This was fabricated in 1992 and temporarily installed in Tokai site to examine its performances. The performances of a thermionic cathode assembly were observed in many cases of changing parameters such as the high-voltage, grid-voltage, heater-power. The maximum beam current was obtained 22 A at the condition of the high voltage of 200 kV. The stability of the beam current was measured to be less than ± 1.5%. The pulse shape was adjusted by changing the three different types of the grid pulsers. The pulse width less than 1 ns was achieved by means of using a 4 kV rapid rise-time
pulser with a short circuit. The pulse transmission line between grid pulser and the electron gun was designed to have an impedance matched with the 1ns/μsec grid pulser to prevent deformation of the 1ns/μsec pulse. The bunching efficiency of the prebunchers and the buncher were 65% which is agreed with the calculation. The beam energy is 9MeV at the exit of the buncher and the energy spread was obtained to be less than ± 2%. The normalized emittance was measured to be about 130mm • mrad at the exit of the buncher.

3.2 Accelerator column

The linac has 26 accelerator columns. One accelerator column is 2.835m long containing 81 cells, and 2π/3 traveling-wave constant-gradient type. They have three different type in a borediameter of an exit iris, which are 20.0mm, 20.5mm and 20.95mm, respectively. They are arranged in a manner to prevent multisection beam-breakup. The rf power is fed 26MW to each column, so that the average accelerating field is ~16MV/m, and the energy gain per each column becomes ~45MeV. The accelerator columns are designed to operate in the constant temperature of 30 °C. The water cooling system is planned to have a capability of adjusting the temperature within an accuracy of ± 0.1 °C. The disks and cylinders of the accelerator column are carefully machined with high precision and brazed in the vacuum furnace. The phase deviation of each cell, as shown in Fig. 2, are low enough within the specification of 2 degrees. The whole of the accelerator columns are already fabricated and stored on site enclosed with the dry nitrogen.

3.3 Magnet

The beam focusing magnets are composed of triplet-quadrupole magnets, which are placed in between accelerator columns. The steering magnets are utilized for beam position adjustment, which are used with the combination of the beam position monitors. These magnets were all fabricated and quadrupole magnets were already installed in the machine room.

3.4 Klystron

13 klystrons are used for high power microwave amplifiers [2]. The klystron used in SPring-8 has the capabilities of the output-power 80MW, the pulse width 4μsec, the repetition rate 60pps. The klystron normally operates at the beam condition of 391kV and 474A. One klystron feeds the microwave to two accelerator columns. The fabrication of klystrons are under way and now 8 klystrons were completed.

3.5 Modulator

The 190MW pulse modulator has a line type PFN with 4 parallel and 14 series condensors and inductors [3]. The ratio of the pulse transformer is 1:16, so that this modulator is required to produce the high-voltage pulse with 49kV. The voltage fluctuation was achieved to be less than ± 0.5% during the flat-top of 2μsec among the full width of 5μsec. The reproducibility of the output voltage was obtained to be good within ± 0.5%. The thyratron was selected F351; peak voltage 55kV and peak current 10,000A after the careful examination of several candidates.

4 SYNCHROTRON STATUS

4.1 Magnet

The magnets of the synchrotron are 64 dipole magnets, 80 quadrupole magnets, 60 sextupole magnets and 80 correction magnets. The core of these magnets is stacked with 0.5mm thick, silicon steel laminations. The dipole magnet has C-type core. The pole length is 2.870mm, and the maximum field strength is 0.9T. The pole width is 140mm with lateral shims 7.5mm wide by 1mm high. The good field region was obtained in the area of ± 40mm as shown in Fig. 3. The dipole magnets were all fabricated and started to be installed in the synchrotron tunnel since August 1995. The bore radius and the length are 70mm and 0.57m for the quadrupole magnets, and the maximum field strength is 15T/m. The bore radius and the length are 100mm and 0.15m for the sextupole magnets, and the maximum field strength is 200T/m². These magnets were all fabricated and measured their performances [4].

4.2 RF cavity

508.58MHz RF system for the synchrotron includes two 1MW klystrons and eight 5-cells cavities. The required RF voltage is 8MV at injection and 18.7MV at extraction, and the maximum RF power is 1.69MW. The effective RF voltage is changed by controlling the microwave phases between two klystrons.
from 131 degrees to zero degree, keeping the output power of the each klystron constant:845kW. The 5-cells cavity was selected to realize a high shunt impedance to reduce the wall losses. The effective shunt impedance was obtained to be \( \sim 21 \text{M}\Omega/m \). The cavity has inductive coupling slots. A large coupling factor is required to stabilize the accelerating field against disturbances of the temperature rise. The total length 1640mm and the outer diameter is 492mm. Each cell of the cavity has a fixed tuner and a movable tuner to adjust the resonant frequency. The field distribution of 5 cells was adjusted to be constant as shown in Fig. 4.

**4.3 Beam monitor**

The synchrotron has several kinds of beam monitors: 3 current monitors, 80 position monitors, 14 screen monitors, a photon monitor, a RF-KO, 5 loss monitors. The beam position is measured at every quadrupole magnet by using a set of four button electrodes (BPM) mounted on the vacuum chamber. The signals from each BPM are transmitted through low-loss, high-frequency response cables to the detector circuits via fast pin-diode switches. For real time measurements of the beam position during ramping, 4 electric circuits are independently processing data from 4 electrodes. BPMs were calibrated to obtain the exact beam position using the rf-antenna simulating the beam current [5].

**4.4 Timing system**

The integrated timing system is necessary to operate the accelerator complex such as SPring-8. Since the time width of each RF bucket is 2nsec, the timing accuracy required for beam transfer between two accelerators must be less than 100ps to suppress the beam loss due to the synchrotron oscillation at injection. Optical fiber of the transfer line, EO/OE transmitter and receiver and other components are required to be low jitter and low temperature dependence [6]. Several components were tested and the jitter of the electron beam produced by the linac preinjector was achieved to be less than 30ps using the high performance timing system.

**5 CONCLUSION**

The construction of the SPring-8 injector system is in progress, and many components were fabricated and tested to confirm their performances. The installation of the machine was started in the accelerator tunnel from May 1995.

**6 REFERENCES**


1.54 GeV ATF Injector Linac

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Abstract
This paper describes the present status of 1.54 GeV S-band injector linac of the ATF (Accelerating Test Facility) for JLC.

1 INTRODUCTION

The ATF (Accelerator Test Facility) project was started in 1988 in order to stimulate the R&D work for the JLC project [1]. On the first stage, the accelerating gradient of 93 MeV/m has been achieved by an S-band linac [2, 3]. The project has been extended to construct an accelerator system as a prototype machine of the JLC [4].

As shown in Figure 1, ATF consists of five major accelerator-parts: an S-band injector linac [5], a beam transport-line [6], a damping ring [7], a bunch compressor, and electron/positron sources. ATF generates, accelerates, damps, and compresses a train of 20 bunches with $2 \times 10^{10}$ electrons/bunch and 2.8 ns bunch spacing. The amount of total number of electrons in a bunch-train is approximately half that of the JLC-I machine. The amount of total number of electrons in a bunch-train is $3 \times 10^{-8}$ m-rad and $5 \times 10^{-6}$ m-rad, respectively. The goal of the bunch length is 100 $\mu$m with a one-stage compression ratio. The amounts of both the beam emittance and the bunch length are same those of the JLC-I machine. ATF will verify the multi-bunch scheme of linear colliders in all parts from the injector linac to the bunch compressor.

2 1.54 GeV ATF Linac

The 1.54 GeV ATF injector linac was designed to accelerate multi-bunch electrons for the injection to a low-emittance damping ring [8]. The injector linac consists of an 80 MeV preinjector linac, 8 units of regular accelerator section, and an energy compensation system. The parameters of the 1.54 GeV ATF injector linac are summarized in Table 1.

3 80 MeV Preinjector Linac

The required specification of preinjector results from the energy acceptance and dynamic aperture of the damping ring [9]. Although the energy spread among the bunches will be compensated by a special accelerating structure in the 1.54 GeV ATF Linac, the energy spread within a bunch is determined by the bunch length at the exit of the preinjector. Also, the dynamic aperture of the damping ring determines the maximum emittance of the Linac beam. Assuming no emittance growth in the linac, the specification of the maximum emittance will be applied to the preinjector. As shown in Figure 2 the preinjector consists of a thermionic electron gun, two sub-harmonic bunchers, four single-cell bunchers, an accelerating structure, a matching section of beam lattice, an energy analyzer and beam instrumentations.

The role of the accelerator section of the injector linac is the acceleration of multi-bunch from 80 MeV to 1.54 GeV with a minimum energy spread and a minimum emittance growth. It consists of eight rf units, two energy compensation units, a linac lattice, and beam monitors. The beam transport line is located between the 1.54 GeV ATF linac and an injection kicker of the damping ring.
4.a RF System
The rf unit of regular section consists of an E-3712 klystron, a modulator [12], a dual-iris SLED cavity [13], rf waveguides, two 3 m-long accelerating structures [14] and rf dummy-loads as shown in Figure 4. The klystron produces the rf peak power of 80 MW with a pulse duration of 4.5 $\mu$s and supplies to a dual-iris SLED cavity. The rf phase is reversed at 3.5 $\mu$s and the peak power of 400 MW is extracted from the SLED cavity with a pulse duration of 1.0 $\mu$s . The rf power is divided into two rf waveguides in order to supply a peak power of 200 MW into a 3 m-long accelerating structure.

The accelerating field distributes from 52 MV/m at the downstream of the accelerating structure to 42 MV/m at the upstream of the structure. The energy gain of the first bunch among twenty bunches is 119 MeV in an structure. The energy spread is evaluated to be ±2.6% at the bunch population of $2.0 \times 10^{10}$, since the energy gain of the last bunch is 112.54 MeV in an structure with beam-loading.

4.b Alignment System
In order to avoid any emittance growth in the linac, the accelerating structures should be aligned to less than 200 $\mu$m r.m.s. of the vertical and horizontal directions. The support tables of the accelerator section of the linac have an active mover mechanism and wire-position sensors to align the linac components with a tolerance of less than 20 $\mu$m r.m.s. of the vertical and horizontal directions. The 91 m-long wires are stretched in both sides of the linac from the preinjector stage to the end of the linac. One end is fixed to the preinjector stage, which does not have an active mover mechanism; the other end is stretched by a tension weight of 33.5 kg. Each position sensor consists of a pair of induction coils electrically connected in series, and mounted on a vertically movable offset stage fixed at a support stage. The sensors are installed at four corners of the support table for Q-magnets and beam monitors, and a short support table for an accelerating structure. As for the long support table for the two accelerating structures, six sensors are installed at four corners, and both sides of the center of the table. The wire position is detected by a synchronous detection of the signal from the differential coils using 60 kHz, 100 mA AC current on the wire. The resolution of position sensor is 2.5$\mu$m. The dynamic range of the sensors is ±2.5 mm, which is determined by the gap length between two induction coils. The linac support tables are machined with an accuracy of less than ±10$\mu$m. These sensors are aligned along the sag of the wire with a vertical offset. As a result, the support tables are vertically and horizontally aligned with an accuracy of less than 20$\mu$m r.m.s.
Table 1: Parameters of 1.54 GeV ATF injector linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>1.54 GeV</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2 \times 10^{10}$ electrons/bunch</td>
</tr>
<tr>
<td>Bunches/Train</td>
<td>20</td>
</tr>
<tr>
<td>Bunch Spacing</td>
<td>2.8 ns</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>25 pps</td>
</tr>
<tr>
<td>Energy Spread (Full Width)</td>
<td>$&lt;1.0%$</td>
</tr>
<tr>
<td>Beam Emittance</td>
<td>$&lt;3 \times 10^{-4}$ m-rad (1σ)</td>
</tr>
<tr>
<td>Total length</td>
<td>88 m</td>
</tr>
<tr>
<td>Pre-injector Linac</td>
<td>18 m</td>
</tr>
<tr>
<td>Linac</td>
<td>70 m (active length: 48 m)</td>
</tr>
<tr>
<td>80 MeV Pre-Injector</td>
<td></td>
</tr>
<tr>
<td>Gun Voltage</td>
<td>200 kV [240 kV achieved]</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>80 MeV [105 MeV achieved]</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>20</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$2 \times 10^{10}$ electrons</td>
</tr>
<tr>
<td>Bunch Separation</td>
<td>2.8 ns</td>
</tr>
<tr>
<td>Population tolerance</td>
<td>$\leq 1%$</td>
</tr>
<tr>
<td>Bunch length (FWHM)</td>
<td>$&lt;10$ ps</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>$&lt;3 \times 10^{-4}$ rad m (rms)</td>
</tr>
</tbody>
</table>

Regular Accelerating Sections

| Accelerating Structure             | 2π/3 mode constant gradient          |
| Total length                       | 3 m                                 |
| Total number                       | 16                                  |
| Accelerating Field                 | 43 MV/m [52 MV/m achieved]          |
| Maximum Field                      | 33 MV/m [40 MeV/m achieved]         |
| with Beam-loading                   |                                     |
| RF Frequency                       | 2.86 GHz                             |
| Feed Peak Power                    | 200 MW/Structure                     |
| Klystron                           |                                     |
| Klystron Peak Power                | 80 MW [85 MW achieved]              |
| Klystron Pulse Length              | 4.5 μs                               |
| Number of Klystrons                | 8                                    |
| RF Pulse Compression               | Daul-iris SLED                       |
| Power Gain                         | 5.0 at peak                          |
| Klystron Modulator                 |                                      |
| Total Number                       | 8                                    |

Energy Compensation System

| Accelerating Structures            |                                     |
| RF Frequency                       | 2856 ± 4.32727 MHz                  |
| RF Frequency                       | 2856 ± 4.32727 MHz                  |
| Klystron                           |                                     |
| Total Number                       | 2                                   |
| Klystron Peak Power                | 50 MW                               |
| Klystron Pulse Length              | 1.0 μs                              |
| Klystron Modulator                 |                                     |
| Total Number                       | 2                                   |

4.c Energy compensation System

In the damping ring the variation of bunch spacing is not acceptable, the energy compensation system by using four dipole magnets is not applicable. The proposed ΔI energy-compensation system (ECS) is a new idea to compensate for the multi-bunch energy by keeping the bunch separation synchronized with the rf frequency. By passing the multi-bunch through an accelerating structure driven at an rf frequency which is slightly larger or smaller than the fundamental frequency, the multi-bunch would be obtained by the energy gain caused by the phase shift. As a result, the energy spread of the multi-bunch is compressed to a small value, which is required from the damping ring. The compensation energy depends on the Z-position of the electrons in a bunch, since the bunch has a bunch length and the compensated field has a slope of the part of sinusoidal wave. If the bunch is compensated by both a negative slope and a positive slope, the effect of the slope is canceled and the bunch would be accelerated or decelerated by a flat-top field. The system has high flexibility for bunch populations from zero to $4 \times 10^{10}$ electrons/bunch by adjusting the rf power of the klystrons. The system consists of two klystrons and two 3 m-long accelerating structures designed at two rf frequencies; 2,856±4.32727 MHz [15]. The energy spread of the multi-bunch compressed by the ECS would be smaller than that of a single bunch.

4.d Lattice

The lattice of the 1.54 GeV linac has been designed by using SAD simulation code. The beam acceptance of the linac is set to $7 \times 10^{-2}$ m, which is ±8σ of the incoming beam from 80 MeV preinjector. The result of a simulation of emittance blow-up due to the wakes of cavities under misalignment of accelerator components with an orbit correction using the beam position monitors. The procedure is performed by assuming the injection error $\Delta z = \Delta σ = 1$ mm, and skew rotation error of quadrupole $\epsilon = 0.2$ rad. The single bunch energy spread at the exit is $σ_z = 0.3\%$, and $|\Delta p/p| < 0.75\%$. These results show that a misalignment of less than 500 μm rms is not serious after a simple orbit correction.

Acknowledgement

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REFERENCES

Present Status of the KEKB Project
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ABSTRACT

KEKB (KEK B-Factory) is an 8 x 3.5 GeV, two-ring, electron-positron collider aiming at producing copious B-mesons for detecting CP-violation effect at bottom quarks. To achieve a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ required by experiments, the rings should store 1.1-A electrons and 2.6-A positrons. These large currents are distributed into 5000 bunches. The large currents and the large number of bunches excite strong coupled-bunch instabilities, which should be avoided by adopting special accelerating cavities and strong bunch-by-bunch feedback systems. Electrons and positrons collide at a finite angle of ± 11 mrad at an interaction point, which BELLE detector surrounds. The construction of KEKB started in 1994 and it will be commissioned in JFY1998.

I. INTRODUCTION

Two rings of the KEKB (3.5 GeV low-energy ring, LER, for positrons, and 8 GeV high-energy ring, HER, for electrons) will be installed in the existing TRISTAN tunnel of 3 km circumference and the infrastructure of TRISTAN will be maximally utilized. Taking advantage of the large tunnel size of TRISTAN, two rings will be set side by side; unnecessary vertical bending of trajectories that may increase the vertical emittance of the beams is minimized.

Figure 1 illustrates the arrangement of two rings. KEKB has only one interaction point, IP, at Tsukuba experimental hall, where electron and positron beams collide at a finite angle of ± 11 mrad. BELLE detector will be installed at IP. The straight section at Fuji is used for injection from the linac and also for installing RF cavities of LER. Cavities of HER will be installed in straight sections at Nikko and Oho. These straight sections are also reserved for wigglers for LER, which reduce the longitudinal damping time of LER from 43 msec to the value of HER, 23 msec. In order to make the circumference of the two rings equal, a cross-over should be made at Fuji experimental hall where two rings pass each other.

To facilitate full-energy injection into the KEKB rings, the present 2.5-GeV electron linac will be upgraded to 8 GeV[1]. The upgrade is done by combining the main linac with the positron production linac, increasing the number of accelerating structures, replacing klystrons with high-power ones, and compressing RF pulses by SLEDs. We can also increase the energy of electrons impinging on the positron production target from 250 MeV to 4 GeV, thus multiplying positron intensity by 16. The injection time of positrons to LER is estimated to be 900 sec. A new bypass tunnel of 130 m for transport lines between the linac and KEKB rings will be constructed in JFY1996 and 1997.

II. BASIC DESIGN

The main parameters of the KEKB accelerators are given in Table 1. HER and LER have the same circumferences, emittances, and the $\beta$ functions at IP. The large current, the large number of bunches, small bunch spacing, the small value of $\beta$ function at IP and finite-angle crossing of beams are the salient features of KEKB.

We adopt a noninterleaved sextupole chromaticity correction scheme to increase transverse dynamic apertures necessary for injection and longitudinal dynamic aperture necessary for making Touschek lifetime sufficiently long[2].

Fig. 1 . Configuration of KEKB accelerator system.
In this scheme sextupoles are arranged in pairs: two sextupoles in a pair are \( \pi \) phase-advance apart in both horizontal and vertical planes. Sextupole pairs are not interleaved. This scheme cancels out the geometric aberrations caused by the sextupoles effectively since the transfer matrix between sextupoles is -1.

One unit cell of the adopted lattice has a phase advance of \( 2.5\pi \) and includes two pairs of sextupoles, SF and SD. The addition of extra \( \pi/2 \) phase advance over 2\( \pi \) cell enables effective correction of chromatic kicks and significantly improves the dynamic apertures. In the adopted lattice the momentum compaction factor can be changed from \( -1 \times 10^{-4} \) to \( 4 \times 10^{-4} \) and the emittance from 50% to 200% of the nominal value. This flexibility makes a strong tool to tune the machine.

In the IP straight section of LER, a local chromaticity correction scheme is adopted to correct the large vertical chromaticity produced by the final focus quadrupole magnets close to IP.

We adopt a finite-angle crossing scheme of \( \pm 11 \) mrad. In this scheme, parasitic collision is not a concern even though every bucket is filled with beam; separation dipole magnets that would be necessary for a head-on collision are no longer necessary. The horizontal width of the beam pipe at IP is minimized in the finite-angle crossing where no synchrotron-light fans are produced by separation dipole magnets; smaller beam pipe improves the vertex point resolution and permits efficient use of the luminosity. We use superconducting final-focus quadrupole magnets in order to have a flexibility of tuning.

By computer simulation we found that although the finite-angle crossing somewhat reduces usable areas in the \( v_x-v_y \) plane due to synchro-betatron resonances, a fair amount of areas in the \( v_x-v_y \) plane is still free from reduction of luminosity, if we make the \( v_{xy}(\text{synchrotron tune}) \) smaller than 0.02[3]. We have also started an R&D work on superconducting crab cavities in order to prepare unpredictable beam-beam effects due to this finite-angle crossing. Crab cavities tilt the bunches and make them collide head-on at the interaction point.

### Table 1 Main Parameters of KEKB

<table>
<thead>
<tr>
<th>Ring</th>
<th>LER</th>
<th>HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>( E )</td>
<td>3.5</td>
</tr>
<tr>
<td>Circumference</td>
<td>( C )</td>
<td>3016.26</td>
</tr>
<tr>
<td>Luminosity</td>
<td>( L )</td>
<td>( 1 \times 10^{34} )</td>
</tr>
<tr>
<td>Cessing angle</td>
<td>( \theta_{x}/\theta_{y} )</td>
<td>( 0 \pm 11 )</td>
</tr>
<tr>
<td>Tune shifts</td>
<td>( \beta_x^{<em>}/\beta_y^{</em>} )</td>
<td>0.039/0.052</td>
</tr>
<tr>
<td>Beta function at IP</td>
<td>( t )</td>
<td>2.6</td>
</tr>
<tr>
<td>Beam current</td>
<td>( \alpha_z )</td>
<td>0.4</td>
</tr>
<tr>
<td>Natural bunch length</td>
<td>( \sigma_B )</td>
<td>( 7.1 \times 10^{-4} )</td>
</tr>
<tr>
<td>Energy spread</td>
<td>( s_B )</td>
<td>0.59</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>Particle/bunch</td>
<td>( 3.3 \times 10^{10} )</td>
</tr>
<tr>
<td>Emittance</td>
<td>( \epsilon_x/\epsilon_y )</td>
<td>( 1.8 \times 10^{-8}/3.6 \times 10^{-10} )</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>( \nu_x )</td>
<td>0.01 (-0.02 )</td>
</tr>
<tr>
<td>Betatron tune</td>
<td>( \nu_x/\nu_y )</td>
<td>45.52/45.08</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>( \alpha_p )</td>
<td>( 1 \times 10^{-4} - 2 \times 10^{-4} )</td>
</tr>
<tr>
<td>Energy loss/turn</td>
<td>( U_o )</td>
<td>0.81(1.5^+)</td>
</tr>
<tr>
<td>RF voltage</td>
<td>( V_c )</td>
<td>( 5 \sim 10 )</td>
</tr>
<tr>
<td>RF frequency</td>
<td>( f_{RF} )</td>
<td>508.887</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>( h )</td>
<td>5120</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>( \tau_E )</td>
<td>43(23^+)</td>
</tr>
<tr>
<td>Total beam power</td>
<td>( P_B )</td>
<td>2.7(4.5^+)</td>
</tr>
<tr>
<td>Radiation power</td>
<td>( P_R )</td>
<td>2.1(4.0^+)</td>
</tr>
<tr>
<td>HOM power</td>
<td>( P_{HOM} )</td>
<td>0.57</td>
</tr>
<tr>
<td>Bending radius</td>
<td>( r )</td>
<td>16.3</td>
</tr>
<tr>
<td>Length of bending magnet</td>
<td>( l_B )</td>
<td>0.915</td>
</tr>
</tbody>
</table>

\( ^+ \) without wigglers  
\( ^+^+ \) with wigglers
III. HARDWARE SYSTEM

The RF cavity for the KEKB should have a structure by which higher-order modes (HOMs) in the cavity are damped to the level where the growth times of the coupled-bunch instabilities excited by HOMs become comparable to or longer than the damping time. The fundamental mode of cavity also excites coupled-bunch instabilities if the detuning frequency of the cavity due to beam loading becomes comparable to or larger than the revolution frequency of the ring. The cavity should have enough stored energy in order to make the detuning frequency much smaller than the revolution frequency.

We are now developing two types of cavities for the KEKB. One is a normal conducting cavity called ARES and the other is a superconducting, single-cell, single-mode cavity.

T. Shintake showed that the amount of the detuning frequency can be drastically decreased by attaching a large volume, low-loss, energy-storage cell to an accelerator cell[4]. On the basis of this proposal, a 3-cell structure, where an accelerating cell and an energy storage cell is connected via a coupling cell is proposed and called ARES[5]. In order to suppress HOMs, a choke-mode cavity [6] is used as the accelerating cell of ARES. The first prototype accelerating cell of ARES was delivered to KEK and successfully tested up to 110 kW of wall dissipation which corresponds to a gap voltage of 0.73 MV.

A superconducting cavity has a large stored energy due to its high field gradient and is immune to the beam-loading. The superconducting cavity for KEKB is a single-cell cavity with two large-aperture beam pipes attached to the cell[7]. HOMs propagate toward the beam pipes, since their frequencies are above the cut-off frequencies of the pipes. HOMs are absorbed by ferrite HOM absorbers.

A full-size Nb model was constructed and tested in a vertical cryostat. The maximum accelerating field obtained was 14.4 MV/m with a Q value of $10^9[8]$. The prototype cavity for the AR beam study is under construction. Prototype HOM dampers made by HIP(hot isostatic press) method were successfully high-power tested [9].

Feedback systems that can damp the coupled-bunch oscillations of the beam with a bunch spacing of 2 ns are being developed[10]. A 2-tap FIR digital filter system works as the kernel of the signal processing unit. This kind of filter can be composed of memory chips and simple CMOS logic ICs without relying on DSP chips. By using 500 MHz ADC and DAC, two custom-made 4-bit GaAs 1:16 500-MHz demultiplexers and two 4-bit GaAs 16:1 500-MHz multiplexers, and having 16 parallel 2-tap FIR logic circuits, we can construct a signal processing unit on a single board. Kickers and wideband amplifiers are now being developed.

We have decided to use Cu as material for vacuum ducts by taking into account its low photodesorption coefficient, high thermal conductivity, and self shielding capability of X-rays. Cu ducts for LER are now under construction.

IV. SCHEDULE

Three-month long beam test is planned to be held in 1996 by the use of TRISTAN AR. We plan to store more than 500 mA electron beam in AR with a multibunch mode at 2.5 GeV. To accumulate this high current, the existing APS type RF cavities will be removed temporarily from the ring and an ARES cavity and a single-cell superconducting cavity for KEKB will be installed. The transverse and longitudinal feedback systems will be also installed and tested.

Main components of LER such as magnets and vacuum equipment are procured in JFY1995 and 1996, whereas those for HER in JFY1996 and 1997. TRISTAN will be terminated by the end of 1995 and dismantling of TRISTAN main ring will start from January 1996. By the end of 1996 the TRISTAN tunnel will become ready for installation of magnets. We plan to commission the KEKB with Belle detector within JFY1998.

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The Operation of RIKEN Ring Cyclotron


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Wako-shi, Saitama 351-01, Japan

INTRODUCTION

Almost nine years has passed since the first beam was extracted from the RIKEN Ring Cyclotron (RRC) successfully, and five years since the RIKEN Accelerator Research Facility was fully completed. As shown in Fig. 1. Since then, the RRC has been supplying a variety of beams with a good stability for a variety of experiments. As many improvements have been made, a machine shut-down due to trouble-shooting decreased and a beam tuning time spent in order to get a high quality beam was shortened.

OPERATION STATUS

All beams, which were accelerated with the RIKEN Ring Cyclotron (RRC) during experiments, such as medical science, radio-chemistry, health physics, material science, biology, atomic physics. Although the portion of beam time is so small, a variety of kinds of experiments were behove two years, are listed in Table 1, together with their energy range and total time spent for experiments. In this period, totally 23 kinds of particles were accelerated by RRC and used for experiments. Their masses as well as their energies cover a very wide range from 1 to 170. Figure 2 shows the plots of particles accelerated so far in the region of energy-mass space. The plots are ranging almost everywhere in the available region of the space.

As listed in Table 2, the total operation time for the last one year (from Sept. 1994 to Aug. 1995) amounted to 259 days. Among them, a total of 70 days were spent for beam tuning. Since a beam was prepared 72 times in this period, it takes 0.97 days on the average to tune one beam. The beam tuning time depends on how much an user requires a high quality beam, for example, a strict single-turn extraction, an extremely small beam spot, a well-separated single-bunched beam and so on. To meet these requirements completely, it takes sometimes longer than 1.5 days.

The beam time, which is used for experiments, is 189 days. Most of the beam time (86.7%) was devoted to nuclear physics experiments and the rest (13.3%) to other field experiments made, since beam time demanded for one experiment in these fields are very short as compared to that of nuclear physics.
Table 1  A list of particles which were accelerated by the RRC from Oct. 1993 to Aug. 1995.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy range (MeV/u)</th>
<th>Total time of operation (days)</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+</td>
<td>85 ~ 210</td>
<td>26.6</td>
<td>6.9</td>
</tr>
<tr>
<td>d**</td>
<td>135</td>
<td>50.0</td>
<td>13.0</td>
</tr>
<tr>
<td>12C</td>
<td>92 ~ 135</td>
<td>32.5</td>
<td>8.4</td>
</tr>
<tr>
<td>13C</td>
<td>100</td>
<td>34.3</td>
<td>8.9</td>
</tr>
<tr>
<td>14N</td>
<td>35 ~ 135</td>
<td>12.1</td>
<td>3.1</td>
</tr>
<tr>
<td>15N</td>
<td>115</td>
<td>11.5</td>
<td>3.0</td>
</tr>
<tr>
<td>16O</td>
<td>135</td>
<td>8.7</td>
<td>2.3</td>
</tr>
<tr>
<td>18O</td>
<td>42 ~ 100</td>
<td>51.7</td>
<td>13.4</td>
</tr>
<tr>
<td>20Ne</td>
<td>135</td>
<td>8.2</td>
<td>2.1</td>
</tr>
<tr>
<td>22Ne</td>
<td>70 ~ 110</td>
<td>25.0</td>
<td>6.5</td>
</tr>
<tr>
<td>24Mg</td>
<td>100</td>
<td>5.0</td>
<td>1.3</td>
</tr>
<tr>
<td>28Si</td>
<td>135</td>
<td>2.3</td>
<td>0.6</td>
</tr>
<tr>
<td>36Ar</td>
<td>7.6</td>
<td>9.3</td>
<td>2.4</td>
</tr>
<tr>
<td>40Ar</td>
<td>7.5 ~ 95</td>
<td>46.3</td>
<td>12.0</td>
</tr>
<tr>
<td>48Ti</td>
<td>7.6</td>
<td>2.9</td>
<td>0.8</td>
</tr>
<tr>
<td>50Ti</td>
<td>50</td>
<td>11.9</td>
<td>3.1</td>
</tr>
<tr>
<td>59Co</td>
<td>80</td>
<td>1.9</td>
<td>0.5</td>
</tr>
<tr>
<td>58Ni</td>
<td>95</td>
<td>5.9</td>
<td>1.5</td>
</tr>
<tr>
<td>84Kr</td>
<td>10.5 ~ 36</td>
<td>4.5</td>
<td>1.2</td>
</tr>
<tr>
<td>130Te</td>
<td>7.5</td>
<td>16.2</td>
<td>4.2</td>
</tr>
<tr>
<td>129Xe</td>
<td>7.5</td>
<td>9.8</td>
<td>2.5</td>
</tr>
<tr>
<td>134Xe</td>
<td>26</td>
<td>2.2</td>
<td>0.6</td>
</tr>
<tr>
<td>170Er</td>
<td>7</td>
<td>6.5</td>
<td>1.7</td>
</tr>
<tr>
<td>total</td>
<td>-</td>
<td>385.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* H+ is used for energies lower than 135MeV/u.

** Mostly polarized deuterons.

Table 2  An operation statistics of the RRC from Sep. 1994 to Aug. 1995

<table>
<thead>
<tr>
<th></th>
<th>259 days</th>
<th>70 days</th>
<th>189 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Operation time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam tuning</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear Physics</td>
<td></td>
<td></td>
<td>(86.7%)</td>
</tr>
<tr>
<td>Other fields</td>
<td></td>
<td></td>
<td>(13.3%)</td>
</tr>
<tr>
<td>RILAC injection</td>
<td></td>
<td></td>
<td>(20.4%)</td>
</tr>
<tr>
<td>AVF injection</td>
<td></td>
<td></td>
<td>(79.6%)</td>
</tr>
<tr>
<td>Unscheduled shut-down</td>
<td>14 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highvoltage trouble</td>
<td>8 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVF magnetic channel</td>
<td>5 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other reasons</td>
<td>1 day</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance or holiday</td>
<td>92 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>365 days</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The AVF-RRC operation was performed for 150 days (79.6%) and the RILAC-RRC operation for 38.5 days (20.4%). Stand-alone uses of the two injector have routinely been made during a time when the other injector is coupled with RRC. (f, h in fig. 1)

TROUBLE SHOOTING

In this one year, a total of 14 days of the scheduled machine time had to be canceled. Main reasons for these unexpected shut-downs were relating to deflectors of both the AVF cyclotron and the RRC. They sometimes did not work sufficiently due to their unendurable leak currents. A periodic maintenance with an open of a vacuum chamber is necessary in both cases.
Recently, a casing of a magnetic channel in the AVF cyclotron had small holes due to beam hitting and a serious vacuum leak occurred twice. The beam has tendency to go lower side in the extraction region. Though the reason for it is not clear at present, the magnetic channel installed at a vertical position by 2mm lower than the prescribed one.

In the rf system of the AVF, a part of the slide contacts of the movable shorting plate was melted and burned. and the vacuum leak occurred from the magnetic channel due to beam hitting. In the RRC rf, the vacuum leak occurred between the aluminum gasket and the ceramics that are used in the coaxial rf power feeder.

NEW TOPICS

$^{50}$Ti Beam

Recently a beam of $^{50}$Ti was accelerated and used for an experiment. To get an enough intensity, we had to use an enriched-material, which is extremely expensive. To save the quantity of it, when it is charged to the 10 GHz ECR source (a in Fig. 1), a thin alumina ($\text{Al}_2\text{O}_3$) pipe, a hole of which was filled with a small amount of powder of enriched (50%) Ti O, was used in stead of a normal ceramic rod. It could supply a $80\text{MeV}/\text{u}$ $^{50}$Ti beam with an intensity of 8pnA on a target for a week at least.

Parasite-mode operation

We have routinely begun to make use of parasite-mode operation. A sub experiment, such as a detector test, normally demands several times of short-term irradiation of a faint beam. On the other hand, a main experiment needs a long-term irradiation of a very intense beam, like a RIPS's experiment in E6 room. The beam is sent to the sub user as long as they need, normally for several ten minutes. Switching the beam delivery could be made in a second each time.

Monitor of single turn extraction

A combination of beam chopper on the injection beam line of the AVF cyclotron and the two beam detectors (e, g in fig. 1) using a micro-channel plate (MCP) has routinely been used both as phase monitors for stabilizing the magnetic fields of the cyclotrons and as monitors for single-turn extraction.

Single bunch selector

A single-bunched beam is sometimes required by users as a time trigger for the measurement of time spectrum. A very compact single-bunch selector, which consists of a fast beam chopper (b, c in fig.1) and a sub-harmonic buncher (d in fig.1), has been successfully developed. Both the devices are installed in a low-energy injection line of the AVF cyclotron. As long as a single-turn extraction is strictly achieved in each cyclotron, a pure single bunched beam with a repetition rate of as high as 1 MHz is available.

NEAR-FUTURE PROGRAM

An acceleration test of a new injector system of the RILAC is now under way in a provisional site. It consists of a single-stage 18GHz ECR ion source and a variable frequency RFQ linac. It will be installed at the injection line of RILAC in next spring, being the first-step improvement of the accelerators in aim of the new project, RI beam factory.

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4) A. Goto et al. in this proceedings.
5) Y. Yano et al. in this proceedings.
ABSTRACT

Sumitomo Electric Industries established a synchrotron radiation (SR) facility named “Harima Research Laboratories” in 1993. The facility is located in Harima Science Garden City where the large SR facility “Spring-8” is being under construction. Main purpose of our laboratory is to develop the advanced technologies on SR application, particularly for micro-fabrication, photo-chemistry and x-ray tomograph. In the facility, a 600MeV superconducting compact SR ring “NIJI-III”, a 100MeV compact linac and five beamlines have been installed. Nowadays, NIJI-III usually provides SR light to users for 16 hours in a day.

1. Introduction

Recently, it has been discovered that SR has potential for the industrial applications, thus a compact, easy-to-use SR machine has been awaited in this area. We have continued our R&D efforts to develop compact SR machine. It mainly consists of a linac and an SR ring. Both of them require compact design. We first launched the development of a compact SR ring under the direction of the Electrotechnical Laboratory of the Agency of Industrial Science and Technology. Incorporating many advanced technologies, such as a superconducting bending magnet, the compact SR ring named “NIJI-III” was completed1,2,3. NIJI-III was achieved its design goal of 200mA stored current at 600MeV and the demonstration of large area exposure, 50mm×50mm, using the electron-beam wobbling method4,5. Based on these results, at the end of July 1993, NIJI-III was transferred from Tsukuba to our newly opened Harima Research Laboratories in order to accelerate the development of advanced SR application technologies.

For the linac, we had accumulated the basic engineering technologies needed for system design through joint research with ISIR Osaka University, and completed the development of a compact linac by ourselves in 1993. The linac has an accelerating gradient of 22MeV/m, which is the world’s highest class for commercial machines5,6. We have thus succeeded in downsizing the linac, as well as the SR ring.

2. Facility overview7,8

Figure 1 is a bird's eye view of our facility. Both the linac and SR ring are installed in an accelerator room which is surrounded with 1.4m-thick shielding wall. Of the 3,500 square meter total floor space, 1,500 square meters is occupied by an accelerator room and an experimental hall.

The linac’s output beam, typically macro-pulse current of 100mA at 100MeV, is introduced into the SR ring through the beam transport system approximately 25m long. It injects an electron beam with small beam radius, less than 5mm, and minimum achromatism into the SR ring.

FIG. 1. Bird's eye view of the first floor of Harima Research Laboratories.

3. SR ring “NIJI-III”

A schematic configuration and main parameters of NIJI-III are summarized in Fig.2 and Table 1, respectively. NIJI-III is a rectangular-shaped ring with approximate dimensions of 3.5×6.4m. Since its lattice structure is likely Chasmann-Green lattice, a dispersion-free condition can be obtained in the long straight section and dispersion functions are kept small in the bending section. The latter characteristic is the key issue for realizing a small beam size at the light source point. Both horizontal and vertical beam sizes are smaller than 0.5mm in the bending section.

The superconducting bending magnets can generate a maximum magnetic field of 4.0T, which enables us to obtain a peak wavelength of 5Å at beam energy of 600MeV as shown in Fig.3. The most notable feature of NIJI-III is the power leads of the superconducting bending magnets. These are made of high temperature (HTc) practical superconductors fabricated by ourselves. These power leads offers advantages of reductions in Joule loss, suppression of ambient heat transfer and hence improving the economy of the cryogenics.

At the injection energy of 100MeV, a maximum stored...
current of above 150mA was achieved with an accumulation rate of 30mA/s. No transverse instability is observed at the injection energy. Although sextupole and octopole magnets are installed in NJII-III, those are no need to excite for electron storage.

Accelerating the stored beam to the final energy of 600MeV is accomplished by ramping all magnets simultaneously. Beam acceleration has been carried out in which currents of more than 100mA can be accumulated at the final energy. A ramping ratio between the exciting currents of superconducting bending magnets and of normalconducting quadrupole magnets is not a constant value through the acceleration, from 100MeV to 600MeV. This is attributed to magnetic saturation on the quadrupole magnets at high energy region and eddy current generated in the vacuum ducts in the bending section.

The beam lifetime was approximately 6 hours for the stored current of 100mA at 600MeV. The lifetime is thought to be limited by the vacuum pressure of $2 \times 10^{-9}$Torr. It will be lengthened by a decrease in pressure rise. NJII-III usually operates day and night when NJII-III provides SR light to users. Electrons are usually refilled into NJII-III 4 times per day.

![Fig. 2. Schematic configuration of NJII-III](image)

**TABLE I. Main parameters of NJII-III**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>600 MeV</td>
</tr>
<tr>
<td>Stored beam current</td>
<td>200 mA</td>
</tr>
<tr>
<td>Circumference</td>
<td>18.89 m</td>
</tr>
<tr>
<td>Bending magnetic field</td>
<td>4.0 T</td>
</tr>
<tr>
<td>rf frequency</td>
<td>158.7 MHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>10</td>
</tr>
<tr>
<td>Critical wavelength</td>
<td>13 Å</td>
</tr>
<tr>
<td>Horizontal betatron tune</td>
<td>2.37</td>
</tr>
<tr>
<td>Vertical betatron tune</td>
<td>1.35</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>0.087</td>
</tr>
<tr>
<td>Emittance</td>
<td>0.38 mm/mrad</td>
</tr>
</tbody>
</table>

**TABLE II. Main parameters of the linac**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>EIMAC Y646B</td>
</tr>
<tr>
<td>rf frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Beam energy</td>
<td>100 MeV (short pulse)</td>
</tr>
<tr>
<td></td>
<td>76 MeV (long pulse)</td>
</tr>
<tr>
<td>Macropulse current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>60 x mm/mrad</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>2 pps</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>22 MeV/m</td>
</tr>
<tr>
<td>Klystron</td>
<td>TII146</td>
</tr>
</tbody>
</table>

Electron gun is a thermionic triode gun based on a dispenser cathode assembly (EIMAC model Y646B). A high d.c. voltage of 200kV is applied to anode cathode gap in order to obtain high beam brightness. A brightness of more than $10^{11}$/m²/μrad² has been achieved in experiments carried out before installation into the linac system.

The bunching system consists of three tubes: subharmonic prebuncher (SHPB), prebuncher (PB), and buncher (B). The phase bunching characteristic of this system is evaluated by a ballistic-model simulation. As a result, for the electrons emitted from the gun, more than 40% are bunched into a 50 degree phase spread at the entrance of the buncher. The SHPB is a standing-wave cavity with a resonance frequency of 476MHz. It was made of stainless-steel. A portion of the inner surface of the cavity was coated by OFHC in order to optimize both a shunt impedance and Q-value of the cavity.
The accelerating tube is a disk-loaded waveguide with a constant gradient structure. There are no rf windows or bellows in the waveguide system between the accelerating tubes and the klystrons, in order to withstand the rf power even if the klystron generates its maximum rf power of 45MW. To stabilize the energy of the output electrons, two approaches are principally effective. Output power of the klystron is designed for stable, since its modulator generates a voltage pulse stabilized within 0.3% owing to parallel pulse forming network (PFN). Also, the resonance frequency of the accelerating tube is stable, since its temperature is controlled within ±0.02 degree by a water-cooling system.

5. Beamlines and SR applications

We have installed five beamlines in NIJI-III. Outline of the beamlines are summarized in Table III. In part of them, the distance from the SR light source point to the irradiation chamber is less than 3m, which enables us to obtain high photon density by no means inferior to GeV-class medium scale SR ring.

In this section, we briefly describe our representative activity on SR applications. Recently, micro-fabrications using a deep-etch x-ray lithography are demanded in communication technology, medical engineering and so on. We have studied on LIGA process, German acronym for Lithographic, Galvanoformung, Abformung, which allows microstructures of any lateral shape to be fabricated with structural heights of several hundred micrometers. We have succeeded in the development of PZT microstructures for micro-ultrasonic transducers\(^{(10)}\).

<table>
<thead>
<tr>
<th>TABLE III: Beamlines</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam</strong></td>
</tr>
<tr>
<td><strong>Photon energy (keV)</strong></td>
</tr>
<tr>
<td><strong>Mirror</strong></td>
</tr>
<tr>
<td><strong>Monochromator</strong></td>
</tr>
<tr>
<td><strong>Experiments</strong></td>
</tr>
</tbody>
</table>

6. Free electron laser (FEL)

Recently, we proceeded with studies on FEL in an infra-red region using our compact linac. Experimental conditions at present are summarized in Table IV. We have succeeded in observing a spontaneous emission ranging from 2 to 10 μm. Main components of the FEL system are briefly described in following section.

The linac’s output beam is introduced into an undulator section through the beam transport system (BTS). The BTS for FEL requires very severe spec: double achromatic and quasi-isochronous should be realized in the undulator section. Simulations concerning the beam optics were carried out for lattice design. The BTS consists of two bending magnets and five quadrupole magnets. The bending angle of the two bending magnets is very small, 25.0 degree without edge-focusing, to realize the quasi-isochronism.

<table>
<thead>
<tr>
<th>TABLE IV: Experimental conditions of FEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>beam energy</strong></td>
</tr>
<tr>
<td><strong>peak current</strong></td>
</tr>
<tr>
<td><strong>K parameter</strong></td>
</tr>
<tr>
<td><strong>magnetic field</strong></td>
</tr>
<tr>
<td><strong>FEL wavelength</strong></td>
</tr>
<tr>
<td><strong>gain</strong></td>
</tr>
</tbody>
</table>

Our undulator is the Halbach type using Nd-Fe-B permanent magnets. Total length of the undulator is 2m with periods number of 50. A roundtrip time in the optical resonator is set to be 24th harmonics of the micropulse interval time of 2.1ns. The optical resonator consists of two concaved Au-coated OFHC mirrors.

Gain calculation were carried out in accordance with the reference No.11. Small signal gain on our experimental system are estimated to be 10%. In this calculation, five modified coefficients are necessary to calculate. In our condition, the modified coefficient caused in the energy spread of the electron beam is by far smallest in them. Therefore, we have tried to find out the optimum conditions which enable to obtain the energy spread of less than 0.9%.

7. Conclusion

NIJI-III superconducting compact light source facility was operated at our newly opened Harima Research Laboratories in Harima Science Garden City. Nowadays, NIJI-III routinely operates in 600MeV-100mA and provides SR light to users for 16 hours in a day. We are just accelerating the development of advanced technologies on SR applications. Also, we intend to upgrade quantum radiation equipment such as FEL.

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Helium Beam Acceleration in The KEK Proton Synchrotron

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A helium beam has been successfully accelerated in the KEK 12 GeV Proton Synchrotron up to 23 GeV of the limiting energy of the main ring. Although a charge exchange injection of negative hydrogen ions has been used in the booster synchrotron, it cannot be applied to the injection of positive ions, such as helium ions and other heavy ions. A new type of septum magnet for a beam injection system which can realize both negative and positive ion injections, has been developed. The septum magnet has three conductor plates which combine the bump magnet and the septum magnet in a body. A newly developed injection system realized alternative use of both negative and positive ion injection schemes.

I. INTRODUCTION

The charge exchange injection system has been widely used for the injection system of proton synchrotrons, because of its excellent efficiency of multi-turn injection of proton beams. This system is also used to inject proton and deuteron beams into the KEK booster synchrotron [1]. This system, however, cannot be applied to the injection of positive ions, such as helium ions and other heavy ions. Therefore, a conventional multi-turn injection scheme must take the place of the charge exchange scheme. There is no space for another injection system because of the booster designed well-compact. To replace the injection devices every operation cycle is not practical.

To avoid this, a certain technical break-through is indispensable. A new injection system has been developed to realize both negative and positive ion injection. With this system, in April, 1994, a helium beam was successfully accelerated, and a physics experiment has been carried out [2]. Also, a high intensity proton beam has been accelerated by using this system.

Until now negative ion charge-exchange injection system and positive ion multi-turn injection system regarded to be a distinct system. But this new injection system has opened the multi-purpose uses of the proton synchrotron, i.e. from high intensity proton beam acceleration to high energy heavy ion beam acceleration. The principle of the newly developed positive/negative ion injection system and the first helium acceleration is summarized in this paper.

II. NEW INJECTION SYSTEM

A. Charge -Exchange Injection

A schematic layout of the combined injection system which is presently being used for proton and helium-ion acceleration is shown in Figure 1. Four bump magnets having single-turn conductor plates are arranged asymmetrically so as to enlarge the angle between the injection orbit and the circulating orbit under a limited magnetic field. Bump 2 is a newly developed magnet, which is combined with the septum magnet for positive ion injection.

During a charge-exchange injection, only the bump magnet is excited. This situation is quite equivalent to that in the conventional charge-exchange injection system. These bump magnets are connected in series, and are excited up to 0.39 T in order to change the closed orbit so that the beam impinges on a carbon stripping foil. In Figure 1 the dotted line indicates the charge-exchange injection. Negative hydrogen ions are fully stripped at the foil, and start to circulate in the ring. In order to prevent an emittance blow-up due to multiple scattering at the foil, the bump magnets must be turned off just after the completion of injection.

B. Multi-Turn Injection by a Septum Magnet

The solid line indicates positive-ion multi-turn injection which overlaps the charge-exchange by bump 2. A cross-sectional view of bump 2 is shown in Figure 2. This has been newly developed and plays the role to combine the bump magnet and the septum magnet. This combined magnet bump 2 has three single-turn conductor plates in the pole faces [3]. The electrical currents flowing through these conductors produce two dipole magnetic fields having opposite signs, which are separated by a middle thin conductor plate (1 mm thick), which forms a septum.

During positive-beam injection, the closed orbit must be shifted by 60 mm toward the septum magnet in parallel which is achieved by exciting two additional bump magnets (not shown in Figure 1). Their positions are one quarter of the betatron wavelength upstream and downstream from the injection point. Beams are gradually injected from the center of the phase space to the outside by changing the field excitation of the additional bump magnets.

![Fig. 1. New injection system for the KEK-PS booster](image-url)
III. POWER SUPPLY SYSTEM

A block diagram of the power supply for the bump and septum magnets is presented schematically in Figure 3. The wave form of the bump field (excitation current of the bump magnet) for charge-exchange injection is shown in Figure 4 (a). The bump magnets must be turned off just after completion of injection, in order to prevent any emittance blow-up due to multiple scattering at the stripping foil. This can be realized by using a PFN-type pulsed power supply. As for the septum magnet, the pulse width, since it depends on the number of possible turns at beam injection, would be enough for 30 μs. Although it may be possible to use DC current, in order to eliminate any cooling problems, pulsed-mode operation is necessary. The wave form of the septum field (excitation current of the septum magnet) is shown in Figure 4 (b). This can also be realized with a PFN-type pulsed power supply insulated from ground, whose electric power is provided by an insulating transformer. The PFN and its power supply, floated on a high-voltage insulation, are controlled through optical fibers [4].

As shown in Figure 4(c), in the middle thin conductor which forms a septum, a current that is twice as large flows instantaneously during positive ion-beam injection by overlapping the bump current and the septum current. However, since the pulse width of the current is less than 40% of the bump current, it is not necessary to add another cooling system to the ordinary magnet system.

IV. ACCELERATION OF HELIUM IONS

Most of the problems in RF acceleration of light ions of Q/A = 0.5 at the KEK-PS had been cleared at the time when deuteron acceleration succeeded in 1992. However, in the acceleration of helium ions, there remains difficulties with respect to multi-turn injection of the positive ions.

A. Booster Injection

The 750kV He$^{2+}$ ion beam is injected into the linac. The helium beam is accelerated under the 4xmode operation scheme[3]. Its velocity is half that in the case of proton acceleration. As a result, at the end of the linac it has 3% less momentum than that of proton beam. The beam transport parameters and booster injection parameters must be optimized according to the beam momentum.

During multi-turn injection the beam is painted on the horizontal phase space. As shown in Figure 5, trace (c), by changing the decay current of additional bump magnets, the circulating beam orbit during an injection period was moderately shifted for efficiently stacking the linac beam. This is also a new attempt in accelerator technology. Four turns of the linac beam were accumulated with this technique.
We observed a very fast beam loss; only half of the accumulated beam was extracted from the booster. This beam loss was caused at the time that the main bump magnet field fell sharply to zero. Field measurements of the main bump magnets showed that the eddy currents induced in the magnets caused a total error field, so as to cause closed orbit distortions, the maximum value of which was about 4 mm. The total error field due to the septum magnet eddy current, as well as the main bump magnet, was also measured. However, both of the error fields induced by eddy currents are of opposite sign and can cancel each other by adjusting falling time of both magnets.

After the schedule of helium beam experiments, the problem of beam loss at the fall period of main bump magnet field has been solved by this cancellation, which is confirmed by machine study using positive proton beams. The acceleration of higher intensity helium ion beams is expected in the next experiment.

B. Acceleration in the Booster and Main Ring Synchrotrons

For heavy ion accelerations in both the booster and main ring synchrotrons, the radio-frequencies of the accelerating systems are lower during injection, and sweep more widely than in proton acceleration. The tuning systems in both synchrotrons have been modified. The injection frequencies can be changed by attaching additional capacitors in both systems. Especially, in the main ring synchrotron, the bias current power supplies for the ferrite loaded tuning cavities were upgraded.

The intensity of a helium beam was expected to be at most on the order of $10^{16}$ particles per bunch. To stable accelerate such a low intensity beam the pre-amplifiers of both the position and beam phase monitors for the RF feedback systems have been improved.

During a commissioning run lasting one month, the helium beam was very stable, it was also expected at various energies of 8 GeV (2 GeV/u) to 20 GeV (5 GeV/u), based on the requirements of the physics experiments.

VI. ACKNOWLEDGMENT

I would like to express sincere appreciation to the Director General of KEK, H. Sugawara, as well as Profs. M. Kihara, Y. Kimura, Y. Yamane and T. Kawakubo for their continuous encouragement. I am also indebted to Prof. Mori, University of Tokyo, T. Kurosawa, Y. Arakida, and the staff of heavy ion acceleration group in the KEK PS for their valuable discussions and technical supports.

VII. REFERENCES


Figure 6. Helium acceleration in the main ring: (a) a helium beam intensity during a cycle, (b) a slowly extracted intensity and (c) a main magnet field pattern.
STATUS REPORT ON JAERI-AVF CYCLOTRON
Kazuo ARAKAWA, Yoshitomo NAKAMURA, Wataru YOKOTA, Takayuki NARA,
Takashi AGEMATSU, Susumu OKUMURA, Ikuo ISHIHORI and Mitsuhiro FUKUDA.
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1233, Watanuki-machi, Takasaki, Gunma 370-12, Japan.

Abstract
The JAERI AVF cyclotron has been used for experiments since January 1992. The routine operation of the cyclotron began in September 1992. The total operation times amounted to 10,000 hours in February 1995. So far, twenty-five ion species for ranging from hydrogen through xenon with energies of 10 - 520 MeV were used for experiments. This paper report status on the performance and operation of the JAERI AVF cyclotron.

1. Introduction
The TIARA (Takasaki Ion accelerators for Advanced Radiation Application) facilities have been constructed at the Takasaki Radiation Chemistry Research Establishment of Japan Atomic Energy Research Institute (JAERI) since 1987 for a materials science project using various ion beams in a wide range of acceleration energy. The facilities consist of an AVF cyclotron and three different types of electrostatic accelerators: a 3MV tandem accelerator, a 3MV single-ended accelerator and 0.4 MV ion implanter.

Large AVF cyclotron, so far, have been used mostly for fundamental nuclear physics and medical application to radiation therapy and radioisotope production. Our cyclotron1,2) is mainly used for R&D in materials science and other irradiation purposes. These applications of the cyclotron require that many kinds of light and heavy ions can be accelerated in a wide range of energies. To meet the requirement, continuing efforts have been made on new beam development, improvement of beam extraction and transmission, etc.

The operation of the AVF cyclotron for experiment was started from 1992 in daily operation mode on a trial base. The weekly continuous operation was started from September 1992. The total operation times amounted to 10,000 hours in February 1995.

2. Present Status
2.1 Operation
The JAERI AVF cyclotron is usually operated weekly. The yearly operation time is divided into three beam-time periods, each of which consists of 11 weeks of beam-times and allocated to experiments by Program Advisory Committee. Three weeks for maintenance and additional beam-times and about two weeks of operation intervene between the programmed beam-times. The experiment plan and beam-times are allotted for each period. The weekly operation is usually carried out continuously from Monday morning till Friday evening. Regular over-haul was carried out for 4 weeks in the summer.

Operation statistics of the cyclotron during past 4 years are shown in Fig. 1. The percentage of time in last two years used for experiments, beam developments and tuning were about 82%, 8% and 10%, respectively. The accelerated particles and their beam time are also shown in Fig. 2. The beam time for light ions exceed 50% of all as seen in Fig. 2. In order to meet the requests from many groups of researchers, the accelerated particles, their energies and the beam courses were changed as shown in Table 1.

2.2 Maintenance and Status
The beam extraction system consists of an electrostatic deflector and a magnetic channel and also of a gradient
corrector to focus the beam horizontally. The positions of the deflector and the magnetic channel can be controlled remotely. However, the position of the gradient corrector of a passive type could not be moved remotely. Recently, the gradient corrector was replaced by remote driving type from cyclotron. A RF amplifiers (EIMAC 4CW800B and 4CW50000E) were also replaced by new ones in the yearly overhaul.

Recently, just after the gradient corrector. The deflector and the magnetic channel can be controlled remotely. However, the position of the gradient corrector was replaced by remote driving type for easily optimizing a focus the beam horizontally. And we added the plate to this system in order to measure the total acceleration chamber in the cyclotron was replaced by remote driving type for easily controlling the slit width. A RF amplifiers (EIMAC 4CW800B and 4CW50000E) were also replaced by new ones in the yearly overhaul.

<table>
<thead>
<tr>
<th>Frequency of particle, energy and beam course change in FY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY</td>
</tr>
<tr>
<td>----</td>
</tr>
<tr>
<td>1992</td>
</tr>
<tr>
<td>1993</td>
</tr>
<tr>
<td>1994</td>
</tr>
</tbody>
</table>

A baffle slit system at the extraction hole of the acceleration chamber in the cyclotron was replaced by remote driving one for easily control the slit width. And we added the plate to this system in order to measure the total beam currents. To measure the beam profile from the cyclotron, a single-wire profile monitor was installed to just after the gradient corrector.

The accumulation of induced radioactivity in the acceleration chamber is making it more difficult to conduct maintenance work inside the cyclotron (maximum dose rate is 25 mSv/h). The strongest source of radiation is the electrostatic deflector. The septum electrodes of the deflector were replaced by new ones. Furthermore, we prepared a set of new deflector for rapid replacement in case of trouble. For the protection against radiation hazards, however, it will be necessary to replace some of the strongly activated parts, such as probe-head, magnetic channel, and magnetic channel probe-head.

3. Beam Development

3.1 Extraction Current and Transmission

Particles accelerated and extracted so far are listed in Table 2. The extraction efficiency is defined by the ratio of the beam current measured with the main probe at r=900 mm to that with the Faraday cup (FC) just after cyclotron. The average extraction efficiencies for harmonic 1, 2 and 3 are 56.0%, 65.5% and 56.3%, respectively.

The overall transmission efficiency is defined by the ratio of the beam current with the FC just after analyzing magnet to that with FC just after cyclotron. The single-wire profile monitor was installed to just after the gradient corrector.

The accumulation of induced radioactivity in the acceleration chamber is making it more difficult to conduct maintenance work inside the cyclotron (maximum dose rate is 25 mSv/h). The strongest source of radiation is the electrostatic deflector. The septum electrodes of the deflector were replaced by new ones. Furthermore, we prepared a set of new deflector for rapid replacement in case of trouble. For the protection against radiation hazards, however, it will be necessary to replace some of the strongly activated parts, such as probe-head, magnetic channel, and magnetic channel probe-head.

3.2 Single pulse Extraction

The beam chopping system consists of a pulse voltage chopper (P-chopper) and a sinusoidal voltage chopper (S-chopper). The P-chopper was made to chop DC beams from the ion sources into pulse beam in the injection line. The S-chopper was made to extract a single beam pulse after the exit of the cyclotron. The single pulses were successfully extracted for 70 MeV H\(^+\) and 175 MeV 40\(^{Ar}X\)\(^+\) ions using a chopping system as shown in Table 3.

3.3 Measurements of Absolute Beam Energy

The energy of the ion particle has been measured absolutely by using the crossover technique\(^4\). This technique is based on scattering kinematics, in particular the variation with the angle of the energy of the particles scattered by elastic and inelastic processes from different target nuclei. It requires a target consisting of a homogeneous mixture of reference nuclei having well-known excited states and projectile nuclei. The absolute energy of the incident particle is obtained from an angle, "crossover angle", at which the recoil projectile particles are scattered by around the crossover angle, a semiconductor detector was mounted on a movable arm.

Figure 3 shows a typical pulse height spectrum obtained when a 10 MeV proton was chosen since the crossover angle is relatively large and it is easy to detect the particles at backward angles. A 2.78mg/cm\(^2\) polyethylene film was used as the target including hydrogen and carbon nuclei to use the 4.439 MeV excited state in carbon. To detect the scattered particles at around the crossover angle, a semiconductor detector was mounted on a movable arm.

Figure 3 shows a typical pulse height spectrum obtained when a 10 MeV proton was chosen since the crossover angle is relatively large and it is easy to detect the particles at backward angles. A 2.78mg/cm\(^2\) polyethylene film was used as the target including hydrogen and carbon nuclei to use the 4.439 MeV excited state in carbon. To detect the scattered particles at around the crossover angle, a semiconductor detector was mounted on a movable arm.

<table>
<thead>
<tr>
<th>Results of extracted intensity and overall transmission.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>H(^+)</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>D(^+)</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>12(^{C}X)(^{+})</td>
</tr>
<tr>
<td>16(^{C}X)(^{+})</td>
</tr>
<tr>
<td>16(^{O}X)(^{+})</td>
</tr>
<tr>
<td>16(^{O}X)(^{+})</td>
</tr>
<tr>
<td>20(^{N}X)(^{+})</td>
</tr>
<tr>
<td>20(^{N}X)(^{+})</td>
</tr>
<tr>
<td>36(^{A}X)(^{+})</td>
</tr>
<tr>
<td>36(^{A}X)(^{+})</td>
</tr>
<tr>
<td>40(^{A}X)(^{+})</td>
</tr>
<tr>
<td>84(^{K}X)(^{20+})</td>
</tr>
<tr>
<td>128(^{X}X)(^{23+})</td>
</tr>
</tbody>
</table>
scattering on carbon nuclei and the right one is elastic scattering on hydrogen nuclei.

The relationship between the scattered angles and the pulse heights in the both interactions is shown in Fig. 4. The crossover angle was evaluated from the crossing point of the interpolating lines for the energies of the elastic and the inelastic scattering. To compensate an asymmetric factor of the scattering geometry, left and right angle measurements were carried out.

The average value of the crossover angle obtained from both angles was 44.3°. The absolute beam energy was evaluated at 9.9 MeV in this case. The uncertainty of the measurement is now under estimation.

![Pulse height spectrum at a scattering angle of 40 deg. for a nominal 10 MeV proton.](image)

![Relationship between the scattering angle and the pulse height for the elastic scattering and the inelastic scattering.](image)

### 3.4 Test of Metallic Ion Generation

The ECR ion beams are presently used for two purposes; (1) injection of highly charged ion beam into the AVF cyclotron, (2) study and development of ECR for high charged ion beams of gaseous and solid elements. A new gas feed was added for isotope gases which are usually very expensive. Tubes from gas cylinders are connected to the common line will be less than 3 cm³. Now it is used for ³⁶Ar and ¹²⁹Xe. Test generation of metallic ions are carried out by using insertion of ceramic rods into ECR plasma. Ions of Ni are generated from NiO and Cr are CrSi₂ and Cr₂O₃. Though the insertion depth was not optimized, maximum charge states are 17 for Ni and 15 for Cr, and ion beam currents are enough for acceleration by the cyclotron as shown in Table 4(3). These materials were chosen according to the result obtained previously by generation of Al, Mo, B and La ions, and beam stability were good.

<table>
<thead>
<tr>
<th>Material</th>
<th>NiO (μA)</th>
<th>CrSi₂ (μA)</th>
<th>Cr₂O₃ (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 17+</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>16+</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>15+</td>
<td>1.8</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>14+</td>
<td>2.8</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>13+</td>
<td>3.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12+</td>
<td>4.0</td>
<td>4.0</td>
<td>1.9</td>
</tr>
<tr>
<td>11+</td>
<td>-</td>
<td>5.8</td>
<td>2.7</td>
</tr>
<tr>
<td>10+</td>
<td>4.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9+</td>
<td>2.1</td>
<td>5.2</td>
<td>1.5</td>
</tr>
<tr>
<td>8+</td>
<td>1.2</td>
<td>4.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### References

Pulse Response of Y-796 Electron Gun and Space Charge Effects

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Abstract

For the purpose of the estimation of the characteristics of low energy short pulse in an injector, the peak currents and the pulse duration were measured by co-axial beam catcher at the distance of 25mm, 225mm and 475mm from the anode plane of Y-796 electron gun. The 200 ps duration pulse with the peak current of 13A and the energy of 90 keV lengthened until 390 ps time duration at the 225 mm measurement point. The computer simulation almost agreed with experiment results.

1. Introduction

The X-band linear accelerator, which can generate a ultra short single pulse in the femtosecond domain, is under design at Nuclear Engineering Research Laboratory, the University of Tokyo[1]. We planned the construction of the X-band linac, which consists of thermionic gun, a subharmonic buncher (SHB), two accelerating tubes and achromatic magnetic pulse compression system[2]. In order to generate a single pulse in X-band linac whose electron source is a thermionic gun, a shorter emission is required, because an electron beam from the electron gun must be compressed within one period of the X-band RF (87.5 ps), which is 1/4 period of S-band RF (350 ps). In order to determine a frequency of SHB, it is important to evaluate pulse response of a thermionic electron gun and space charge effects of high current short pulse in low energy region. In this paper, the pulse response of a thermionic electron gun and lengthening of its emission in the drift space are discussed.

2. Experimental

A test bench for measurement of waveform of an emission from a thermionic electron gun was constructed as shown in Fig. 1. It consists of a thermionic electron gun and a d-c biased grid-cathode pulse generator placed on a -90 kV high potential deck, focusing system and so on. Y-796 electron gun (EIMAC) was used as a thermionic electron gun. The accelerating potential of the electron gun is provided by 90 kV pulses of 8 μs duration. The duration of flat top...
is 4 \mu s. The beam sizes in the transverse direction was controlled by solenoid coils. We used two kinds of grid pulser (Pulser I and Pulser II). Pulser I has presently been used for normal operation of the UTNL linac. Pulser II was purchased from Kentech Corporation. Peak output voltages of each pulser are 300 V (Pulser I) and 1.7 kV (Pulser II), respectively. Their rise times are 1.2 ns and 100 ps, respectively. Their pulse width (FWHM) are 1.6 ns and 130 ps, respectively.

The waveform and total charge of emission from the electron gun were measured by using co-axial beam catcher. The diameter of the beam catcher is 14 mm. The signals passing through semirigid cable were measured by sampling oscilloscope (S-4, Tectronix) and DC microvolt ammeter (PM-18R, TOA Electronics Ltd.). The time resolution of the co-axial beam catcher is less than 50 ps. Measurement of the emission was carried out at the distance of 25 mm, 225 mm and 475 mm from the anode.

3. Results and Discussion

3-1. Pulse response of Y-796 electron gun
Typical output waveforms of Pulser I and of the emission measured at the distance of 25 mm are shown in Fig. 2. Figure 3 shows the relation between grid bias and emission current. The peak current was 800 mA. On the other hand, typical output waveforms of Pulser II and of the emission at the distance of 25 mm are shown in Fig. 4. Figure 5 shows the relation between grid bias and emission current. The peak current was 8 A. If enough voltage is applied, Y-796 respond to the trigger with the pulse length less than 1 ns.
3-2. Space charge effects
Lengthening process of the emission from the electron gun were measured in the drift space as shown in Fig. 6. It is found that the pulse was lengthened by the space charge effects. Lengthening by the space charge effects are calculated based on the disk model[3]. The results are shown in Fig. 7. The pulse widths almost agree with the experimental results. However, peak current does not. This is because beam loss is ignored in this simulation. Figure. 8 shows dependence of bunch lengthening on accelerating voltage. It is found that the bunch lengthening of 200 keV beam by the space charge effects is little at the distance of 225 mm from the anode. This distance is enough long to locate subharmonic buncher.

4. Conclusion
From the experimental results, it is found that Y-796 have pulse response was less than 1 ns. The longitudinal lengthening of low energy short pulse was evaluated.

Reference

Fig. 7. Bunch lengthening calculated based on the disk model.

Fig. 6. Pulse shapes of 90 keV electron beam measured at the distance of 25 mm, 225 mm and 475 mm form the anode.

Fig. 8. Dependence of bunch lengthening on accelerating voltage.
Abstract
Plasma emitter, which has been developed in Novosibirsk for diagnostics in Tokamak type plasma, is investigated conceptually in order to apply the source to a high intensity particle generation with long range focusing. The effect of thermodynamic cooling in the expansion of charged particles is examined as well as the effect of the restriction of radius in phase diagram of expanded collisionless plasma. The magnetic field is calculated for designing the geometric parameter of the plasma jet emitter.

1. Introduction
A charged particle emitter has been developed for high brightness ion and atomic beam formation by Davydenko et al. The emitter can supply beams with high brightness because of significant reduction of the transverse ion temperature in the plasma. The normalized brightness of 1keV proton beam arrived in 3x10^8 A/cm²rad² by using a sophisticated extraction lens system. The source should be useful for applications which need a dense and focused beam. As a mechanism of the ion beam formation, the effect of thermodynamic cooling is expected to make the beam emittance lower. The cooling should be investigated to realize a new performance for low emittance beam, as well as optimization of the plasma electrodes and nozzle.

2. Ion beam formation for low emittance
The schematic drawing of the electrodes of the plasma emitter is shown in Fig. 1 for a half part divided by the section.

Fig. 1 Schematic drawing of electrodes of the plasma emitter.

Fig. 2 Ion beam formation by the plasma emitter.
By considering quasi-continuum flow region at the nearest point to the aperture of the nozzle, thermodynamic cooling should come into effect. The ideal thermodynamic analysis of a neutral gas expansion gives changing of the temperature and the particle density as shown in Fig. 3. This effect appears only for a dense region of the plasma. Experiments using small PIG source plasma, show the optimum gas pressure of less than 10 mTorr for intense beam extraction from the plasma. On this condition, the mean free pass of the ion is over 1 cm. Therefore, the discharge should be examined at about 50 mTorr gas pressure in order to realize the quasi-continuum flow. The study of the plasma formation for high pressure is needed by experimental and computational works for the effective cooling.

3. Calculation of the magnetic field
The magnetic field components $H_z$ and $H_r$ are calculated by using integral expressions for the field of the plasma emitter. The expressions are included complete elliptic integral. The values are evaluated by numerical integration. Iron pieces are taken into account by assuming infinite permeability and by representing the magnetization by Ampere's currents on the surface of these pieces. The boundary problems are solved directly by Gauss Jordanian elimination. The ratio of the values of magnetic field should be 8.0 for cathode region and anode region, according to the information from Novosibirsk. By some modification of the shape of the iron yoke, the ratio can be achieved in the final shape of the yoke shown in Fig. 4. The calculated fields are shown in Fig.5 for the axial strength $H_z$ and the radial strength $H_r$.

4. Conclusion
In order to achieve the adiabatic cooling in the expanding plasma, dense discharge should be generated initially in the plasma emitter. A discharge in high magnetic field is one of the solutions for the requirement. The mechanism of ion beam formation of plasma jet emitter should be confirmed by experimental method and simulations.

Acknowledgement
We would like to thank V.I. Davydenko, C.D.P. Levy and A.N. Zelenski for suggestive discussions at TRIUMF.

Reference
Study of ECRIS for highly charged ion production
- HiECR MK3 -

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Meguro-ku, Tokyo, Japan

1. Introduction

The former HiECR had good performances in 6 and 10 [GHz] operations, while in the case of 14 [GHz] operation, the intensity of highly-charged heavy ions was very low [1,2,3]. It seemed that the result was due to the narrow gap (3 [mm] or less) between the surface of ECR zone and that of the chamber wall.

HiECR MK3 has been designed to produce strong axial mirror field and radial hexapolar field enough to 14 [GHz] operation.

The HiECR MK3 was constructed and operated for the first time.

2. HiECR MK-3

The former HiECR had been operated with the microwave frequency 6 or 10 [GHz]. Therefore some improvements were required so that the MK3 can be operated at 14 [GHz]. The number of mirror coils has added up to 9 (MK2: 7), the plasma chamber has been modified and the hexapole has been made newly. Schematic view of HiECR MK3 is drawn in Fig.1 and main parameters are shown in Table.1.

Table 1
Main parameters of HiECR (MK-3) Ion Sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave frequency</td>
<td>14 [GHz]</td>
</tr>
<tr>
<td>Diameter of chamber</td>
<td>70 [mm]</td>
</tr>
<tr>
<td>Hexapole magnet</td>
<td></td>
</tr>
<tr>
<td>- hexapole field on surf.</td>
<td>13.1 [kG]</td>
</tr>
<tr>
<td>- material</td>
<td>Nd-Fe-B</td>
</tr>
<tr>
<td>- inner diameter</td>
<td>76 [mm]</td>
</tr>
<tr>
<td>- length</td>
<td>145 [mm]</td>
</tr>
<tr>
<td>Mirror coils</td>
<td></td>
</tr>
<tr>
<td>- no. of coils</td>
<td>9</td>
</tr>
<tr>
<td>- max. current</td>
<td>600 [A]</td>
</tr>
<tr>
<td>- max. power</td>
<td>57 [kW]</td>
</tr>
</tbody>
</table>

Fig.1. Schema of HiECR MK-3

3. Magnetic Field

radial hexapolar field

Radial hexapolar fields were measured along the axis and radius(Fig.2). The value is 13.1 [kG] at the chamber surface.

axial mirror field

We measured the axial mirror field through the axis(r=0) with mirror coils current 600[A]. The result is shown in Fig.3.

ECR zone

The magnetic field components \( (B_r, B_\theta, B_z) \) at a position \( (r, \theta, z) \) in the cylindrical coordinates is the following.
\[
B_r = B_r^{\text{sol}} + B_r^{\text{hex}} \\
B_\theta = B_\theta^{\text{hex}} \\
B_z = B_z^{\text{sol}} + B_z^{\text{hex}} \\
|B| = \sqrt{B_r^2 + B_\theta^2 + B_z^2}
\]

The closed surface \( |B| = m_e \omega_f / e \) is called ECR zone and electrons are accelerated in this surface.

From the radial and axial field measurements, the axial size of the ECR zone is 78[mm] long and the diameter is 36[mm](the gap between the surface of ECR zone and that of the chamber wall; 17[mm]).

3. First operation

Fig. 4 shows a Ne ions spectrum obtained at the first 14 [GHz] operation. Wide peaks exists on right sides of every charge-state peaks. These seemed to be produced by the ions which had captured an electron in acceleration gap (Fig. 5). The vacuum must be improved after this.

\[
\begin{align*}
\mu\text{-wave} & \quad 270\text{W} \\
5.7 \times 10^{-6}\text{Torr} & \quad \text{N}_{2}; 0.2 \times 10^{-6}\text{Torr}
\end{align*}
\]

Fig. 4. Ne ions spectrum

Fig. 5. one electron capture in acceleration gap
4. Plasma volume and shape effect

In general, $+q$ charged ions current extracted from a plasma with volume $V$ is following [4].

$$I = \frac{n_q q e V}{\tau_q}$$

As concerns ECRIS, this relation is more complex because of influences of the anode position and the anode hole size and so on.

The new hexapole does not have return-yokes and it is covered with SUS and the surroundings of SUS are insulated by ethylene chloride.

Solenoid coils for adjustment of plasma volume are been possible to set around the new hexapole because of nothing of return-yoke. By varying the diameter of ECR zone, we will investigate the best plasma shape to generate highly-charged ions.

References


ACCELERATION OF DEUTERON AND ALPHA BEAMS IN THE KEK-PS INJECTOR

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Abstract

Many experiments have been carried out for helium ion beam acceleration in the KEK 12GeV Proton Synchrotron throughout in 1994. A helium beam has been successfully accelerated. The 750 keV Preinjector has a He⁺ ion source of multicusp type and a gas stripper cell installed in the low energy beam transport(LEBT). Maximum value of 4He²⁺ ion current at the exit of the Proton Linac was 1.6 mA. A deuteron beam was also produced by carbon stripping foil installed in the LEBT just after high current D⁺ ion source for machine tuning.

In addition helium-3 beam acceleration has been tried in the 40 MeV Proton Linac in 4n-mode acceleration. 3 He²⁺ ion beam current of 1.8 mA was observed.

1. Introduction

Acceleration of heavy ion beams in the KEK PS was discussed about more than 10 years ago. However, the project was stopped by several reasons and heavy ion acceleration in the KEK PS has not been realized so far. Very recently, as one of the possible candidates among the future plans of the KEK PS, the PS-Collider, which aims to accelerate and collide heavy ion beams with the beam energy of up to 7GeV/u for a gold beam, has been proposed.[1]
The PS-Collider is designed to use the present KEK PS as its injector, therefore a much more simple scheme compared with the previous one for accelerating heavy ions in the PS has been examined carefully for ease of operation. Simultaneously, possibility of a polarized deuteron beam acceleration in the PS has been also studied.[2]

In the KEK 12 GeV proton synchrotron, the experimental study of helium beam acceleration have been carried out and helium beam was supplied for the physics experiment.[4] There were several modifications: A helium ion source of multi-cusp type was installed in the second preinjector for the production and preacceleration of positive ions.[3]

2. Acceleration of He⁺ ion beam in the preinjector

The injector comprises a 750 keV Cockroft-Walton preinjector and a 40 MeV Alvarez linac. There are two sets of Cockroft-Walton preinjectors, the first preinjector is used to accelerate a high intensity beam of H⁻ and D⁻, whereas the second preinjector is for a He Ion Source

Fig. 1 Shematic drawing of a helium ion source.

Fig. 2 Multi-hole anode electrode for the helium ion source.
Low Energy Beam Transport

Ho'ito Linac

Gas Cell (Argon)

Preinjector Complex

Fig. 3 KEK preinjector complex for the acceleration of positive ions (deuteron and alpha).

polarized beam.

Some modifications of the second preinjector have been made in order to accelerate positive ions. The electric polarity of the Cockcroft-Walton high voltage generator and the power supply for bending magnets of low energy beam transport (LEBT) have been inverted. A multi-cusp ion source is utilized to produce singly charged helium ions.[6] Fig. 1 shows a schematic drawing of a helium ion source. This ion source has special anode hole electrode as shown in Fig. 2. An extraction voltage of 50 kV is supplied to the ion source, and a 50 keV-He+ beam is injected into the 700 kV accelerating column of the preinjector. In order to convert a He+ beam to a He2+ beam, a gas stripper cell has been installed in the LEBT as shown in Fig. 3. The 750 keV He2+ ion beam is injected into the linac. During linac acceleration, the helium beam is accelerated under the 4K mode operation scheme. Its velocity is half that in the case of proton acceleration. As a result, at the end of the linac it has 3% less momentum than that of proton beam. The beam transport parameters and booster injection parameters must be optimized according to the beam momentum.

3. Production of He2+ ion beam by a charge stripper

Production of He2+ ions by the charge stripper. Two methods of charge stripping: an argon gas cell and a carbon foil were tested to convert from He+ ions to He2+ ions. A gas charge stripper device was installed in just after first bending magnet in 750 keV beam transport line. The canal size of a stripper gas cell are inner dia. of 30 mm and full length of 600 mm and the maximum efficiency of charge transfer from 1+ to 2+ was 46% in particle number. Whereas a carbon foil stripper device which was installed in a straight section of beam line, a carbon foil stripper device showed the efficiency of charge transfer was about 50%. It was obtained the maximum capture efficiency at the accelerated voltage of 759 kV with a gas cell stripper. Whereas, in the case of a carbon stripper foil, additional higher acceleration voltage was required: 16 kV for 10 µg/cm², 24 kV for 20 µg/cm².

4. Acceleration of He2+ ion beam

Most of the problems in accelerating heavy ions of Q/A=0.5 at the KEK-PS had been solved at the time when deuteron acceleration succeeded in 1992. However, in the acceleration of helium ions, there remains difficulties with respect to multi-turn injection of the positive ions.

In 4K mode acceleration of deuteron in the linac, the possible injection energy is not only 375 keV, which is a just half of that for proton. A relatively high energy of 540 keV is also possible. It is found
Table 1. Typical Operating Parameters during Helium Acceleration

| Ion source | Type of ion source: | multi-cusp ion source with 19 multi-anode hole |
| Beam width: | 20 msec |
| Beam repetition rate: | 20 Hz |
| Extraction gap/voltage: | 14 mm / 50 kV |

**After pre-acceleration**

- He\(^+\) beam current: 7.6 mA (750 keV)
- He\(^{2+}\) beam current: 6.6 mA

**Linac beam**

- Beam current: 1.5 mA (20 MeV)
- 0.8 mA (40 MeV)

Emittance: \(\epsilon_v/\epsilon_H\) 0.94 / 0.75 mm.mrad

that not only the beam energy of 375 keV but the higher energy such as 540 keV can be acceptable for the linac. [7][8] In normal operation, 540 keV injection was chosen and the optimized beam capture efficiency in the linac was reached to about 30%.

Figure 4 shows a typical waveform of helium ion beam. Typical operating parameters during \(^3\)He\(^+\) acceleration is shown table 1.

5. Acceleration of \(^3\)He\(^{2+}\) ion beam

\(^3\)He\(^{2+}\) ions was also accelerated by 4\(\pi\)-mode in the Linac. A wave form of the \(^3\)He\(^+\) ion beam is shown in Fig. 5. In this operation, the voltage of Cockcroft is 567 kV, a beam intensity of 10 mA was obtained just after the accelerating column. It was obtained that he capture efficiency of the Linac was 26%, 7.0 mA at the Linac entrance and 1.8 mA at the exit of the Linac as shown in Fig. 5.

6. Conclusion

Helium beam acceleration is one of the setp to next step. It is proposed to develope the KEK Proton Synchrotron for acceleration of light ion beams. Figure 6 shows the proposed scheme of the

Fig. 6 Proposed scheme of the preinjector complex for the light ion beams with a Tandem accelerator.

preinjector complex for the light ion beams with a Tandem accelerator.[1]

At present, a heavy ion beam acceleration program has been scheduled for one month every April. Polarized deuteron acceleration is also planned.

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References

Development of a High Brightness Negative Hydrogen Ion Source

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ABSTRACT

Development of a high brightness negative hydrogen ion source has been performed for a high intensity proton linear accelerator. Negative ions are generated in a magnetically filtered multi-cusp plasma generator. The negative ion production is enhanced by seeding a small amount of cesium in the plasma generator. As the result of the ion source beam test, negative hydrogen ion beam of 36 mA (23 nA/cm²) was extracted from a single aperture at an acceleration voltage of 50 kV. To obtain higher ion beam current, the focusing of beamlets extracted from multi-aperture grid has been demonstrated with aperture displacement technique.

1. INTRODUCTION

At JAERI, construction of a 1.5 GeV/10 mA proton linear accelerator has been proposed for engineering tests of accelerator-based nuclear waste transmutation and for various basic science researches [1]. A high brightness positive hydrogen ion source was fabricated for the accelerator. The ion source has been successfully operated at the full design value of 100 kV and 140 mA peak [2]. At the next stage of the ion source development, a negative hydrogen ion source has been newly designed and fabricated. Negative ion beam is required mainly for basic researches to inject the beam into the storage ring which produces certain specific pulse duration and repetition rate at the high energy portion of the accelerator.

The basic performance of single aperture beam extraction system was investigated with the volume negative ion source which has been originally developed for the neutral beam injector for fusion application [3]. The multi-aperture beam extraction with aperture displacement technique was also tested with the modification of the positive ion source which was used for previous beam performance experiments [2].

2. SINGLE APERTURE EXTRACTION

Ion Source

Figure 1 shows a cross-sectional view of the volume production type ion source. The plasma generator, whose dimensions are 340 mm in diameter and 340 mm in length, has a large semi-cylindrical volume and strong magnetic cusp field. The source plasma is produced by arc discharge using eight tungsten filaments. The filaments are supported by molybdenum chips on coaxial feedthroughs. The plasma is confined by strong multicusp magnetic field. A magnetic filter, which is formed by Sm-Co permanent magnets, divides the generator into two regions and modifies electron energy distribution so as to produce negative ion. Negative ion production rate is enhanced by seeding a small amount of cesium in the plasma generator.

![Cross sectional view of the negative ion source](image-url)
diameter. The gap length are adjusted to 5.1 mm between the PE and EXE, 2.5 mm between EXE and ESE, and 30 mm between ESE and GE. The plasma electrode is made of molybdenum plate. There was a strong dependence of the negative ion production rate on the plasma electrode temperature. This is because the cesium coverage is optimized by the temperature rise to give a minimum work function of the plasma generator surface. The plasma electrode was heated up at 200 - 300 °C by pulsed arc discharge power and its temperature was controlled by the duty cycle of the power. The temperature was monitored by a thermocouple. The extraction electrode is made of a 11 mm thick copper plate with a water cooling channel and magnet grooves. In the extraction electrode, Sm-Co permanent magnets are inserted so as to produce a dipole magnetic field. This field deflects the extracted electron and prevents the leakage of the electron to the acceleration gap. The electron-suppression electrode is installed for trapping the leakage electron escaping from the extraction electrode. By applying deceleration voltage of a few kV, electron leakage is suppressed efficiently.

**Extracted Ion Current**

For measurements of the beam current and profile, a multichannel calorimeter was installed at 1.4 m downstream from the ion source in the beam diagnostics chamber, where no electrons reached to the calorimeter. Figure 2 shows the negative ion current as a function of the arc power at filling hydrogen gas pressure of 10 mTorr. The beam current increased with the arc power and reached to 36 mA at 45 kW. The arc efficiency which is defined by the ratio of the beam current to the arc discharge power is calculated to be 0.9 mA/kW.

**Beam Optics**

The emittance of the negative ion beam was measured by using a double slits with a Faraday cup system. To prevent the beam from spreading by space charge force, the vacuum pressure in the beam diagnostics chamber was kept at 8 x 10^{-5} Torr where beam neutralization effect is expected for negative ion beam. Figure 3 shows a typical emittance diagram at an acceleration voltage of 50 kV and a beam current of 20 mA. As shown with solid and dotted lines in the figure, there are two beam components corresponding to those which are extracted from central and peripheral region of the electrode, respectively. These two components have different intensity distributions as a function of the beam divergence. The normalized emittance of the beam from the central region was calculated to be 1.1 mm.mrad. Such a large amount of the beam from the peripheral region is due to aberration of beam optics and may be decreased by optimizing the beam extractor.
3. MULTI APERTURE EXTRACTION

The multi-aperture beam extraction with aperture displacement technique was tested. The basic design of the ion source is the same as the positive hydrogen ion source [2] except for the existence of the transverse magnetic field, which is created by changing the polarity of the cusp magnets near the plasma grid. A conceptual illustration of the aperture displacement technique is shown in Fig. 4. The peripheral apertures on electron-suppression grid and grounded grid are slightly displaced, and the negative ion beams extracted from peripheral apertures are steered by electrostatic lens. Each beamlet is merged into a single beam at the entrance of the accelerator.

In the preliminary beam test, the beam trajectories were measured by observing the Balmer-alpha light emission from the negative hydrogen ion with CCD camera. It has demonstrated that the beamlets from seven apertures were successfully merged into single beam at the focusing point of about 1 m downstream of the ion source.

Fig.4 A conceptual illustration of the multi-aperture displacement technique

4. SUMMARY

The beam test of the negative hydrogen ion source has been performed. The extracted ion beam current (density) from a single aperture of 14 mm in diameter was 36 mA (23 mA/cm²) at the arc discharge power of 45 kW. The test of the aperture displacement technique has also been performed. The preliminary test proved that the technique has a possibility to produce the high brightness beam. The R&D work of the technique is continued.

REFERENCES


DEVELOPMENT OF JAERI 18-GHz ECR ION SOURCE

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Abstract

An 18-GHz ECR ion source for multiply charged ions was constructed and is now in operation for development. A new distribution of the mirror field was adopted, of which minimum strength is varied by a solenoid coil installed between the mirror coils. Measured mirror field distribution is close to designed one and its maximum strength exceeds 1.4 T. The source is now being tuned by use of Ar ion generation. Relatively high base pressure in the plasma chamber has been improved by installing an additional vacuum pump. The source performance has been growing up gradually with the vacuum and Ar ions with charge states up to 13+ has been observed so far.

1. Introduction

The JAERI research programs on materials science and biotechnology using cyclotron beams require various heavy ion species including metallic ions in a wide energy range. According to the requirement, a new ECR ion source was constructed to generate ions with M/Q (ratio of mass to charge numbers) of less than 6.5, highest limit of the JAERI AVF cyclotron acceptance, for all the stable atomic elements.

The basic design of the source design was reported at last symposium. The detailed designs of the source, electric current supplies, a microwave power supply and a beam analyzing system were completed in October in 1993. After being manufactured, they were installed in the ion source room cited on the basement of the cyclotron building in February, 1994, and the first plasma was fired at the end of June. The source was named ECR-18 after the microwave frequency.

2. Source Description

We adopted a solenoid coil between a pair of the mirror magnets to vary the shape and the size of the ECR shell as shown in Fig. 1. The relative position of the ECR shell to the extraction hole is adjustable by moving the magnet assembly in the axial direction. This structure also allows easy replacement of the plasma chamber. The specification of the source is summarized in Table 1. Magnets were designed to obtain sufficiently strong fields so that a closed shell with the strength equal to twice the ECR field was produced (2coce shell). The maximum mirror field strength over 1.4 T was obtained in the calculation. Two mirror magnets have the same structure with soft ion yoke of 8 cm in thickness. They are magnetically separated and the mirror ratio reaches 14. Figure 2 shows the calculated and the measured mirror fields and they are in good agreement.

In order to obtain a strong sextupole field, we examined various configurations and combinations of the
The outer surface of the sextupole is cooled by air to avoid conduction of heat from the coils of which temperature rise up to 45°C, because the temperature leads to 1.5% reduction of the permanent magnet field and the heat cycle may deteriorate the magnet. The air is fed from an opening between a mirror coil and the solenoid, passes through narrow gaps about 3 mm between the coils and the sextupole, and goes outside from an opening between the mirror coil and the plasma chamber. Air flow rate of 10 L/min keeps the sextupole temperature lower than 30°C.

Ion beams extracted from the source are focused by a einzel lens in the extraction chamber and analyzed by a 90° bending magnet with the trajectory radius of 40 cm.

The microwave is fed through wave guides from the rear end of the plasma chamber in the axial direction. It is generally considered from many experiences that a microwave power of a few hundreds watts is enough for a small ECR plasma. In our design, the plasma size is relatively large and the higher frequency is apt to result in larger power loss in the waveguides. Therefore the maximum power was fixed at 2.5 kW.

Fig. 3 Configuration of the sextupole magnet. Arrows show magnetization direction.
Fig. 4 Charge state distribution of Ar ions.

Ar$^{12+}$ is about 4%. The mirror ratio at the optimum current is estimated at 2.4, which is close to that of the Caprice-type sources.

4. Conclusion

The 18-GHz ECR ion source was constructed at JAERI and is now in test operation by generating Ar ions since June, 1994. The source performance has been improving with vacuum in the plasma chamber, and the charge states up to Ar$^{13+}$ have been observed so far. The optimum currents of the solenoid coil, mounted between the mirror coils to vary the mirror ratio, show a tendency to increase with charge states. Further investigation is necessary for an appropriate explanation on a rule of the solenoid. The source performance will still grow by further optimization of the magnetic field, the position of the extraction hole and the improvement of the vacuum in the plasma chamber. After goal performance is attained by using Ar ions, the metallic ions will be generated in the next stage.

Acknowledgment

The authors are grateful to Mr. S. Kimura and Mr. T. Ushiku of IDX Co. for their helpful advice in detailed design and manufacture of the source.

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PLASMA JET_EMITTER: SIMULATION MODEL FOR THE PLASMA IN A SMALL ION SOURCE

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Abstract

A program that simulates a small ion source plasma in the cylindrical coordinate system is developed. In this computation, technique of Particle-in-Cell is used. The program includes the electromagnetic field of three dimensions, the process of the ionization by electron's collision, a discharge electric current and so on. Comparing the results of the calculation for ion source plasma using this program with experimental results for PIG ion source, we get good agreement for the electronic temperature, tin and the ion density. As a result of this calculation, we will be able to analyze the plasma jet emitter that has cylindrical discharge tube with axial magnetic field by considering the collision mechanism and the examination of the initial condition.

1 Introduction

In an accelerator, an ion source plays an important role to decide efficiency of acceleration, brightness and/or intensity of the extracted ion beam. To optimize a quality and a utilization rate of the extracted beam, the characteristics of the source should be investigated by using simulation technique as well as experimental work.

In this work, we pay attention to small ion sources which have a cylindrical discharge tube with axial magnetic field. This type of ion source includes the plasma jet emitter and PIG type ion source. For the first step, we have calculated the PIG ion source plasma, because of its simplicity. Our purpose is to establish the method of simulation and suggest a model for explaining physical phenomena in the small plasma space.

2 Plasma in the cylindrical discharge tube with axial magnetic field

Figure 1 shows scheme of our ion source. Discharge processes in the cylindrical discharge tube with axial magnetic field are as follows. Electrons extracted from the cathode surface are accelerated by the electric field between anode and cathode. Then electrons interact with neutral particles and ionize them. The electrons have excessive energy, so electrons go forward after interacting with the neutral particles. Then electrons drift toward to another side of cathode, they are accelerated by the reverse electric field and return to the discharge space. In this way, ionization chain is continued. This process is continued until the electron energy is less than ionization energy of neutral particle. These electrons drift to the anode. Ions produced by this ionization are attracted to cathode and knock the cathode. Then the cathode releases secondary electrons. They repeat above processes. As a result of this effect of amplification, the discharge reaches to the anode and discharge current becomes the value that is decided by the internal resistant of circuit. Characteristic of this ion source is that it has a small discharge space, because of spiral motion of electron by the axial electromagnetic field.

3 Modeling of the cylindrical discharge tube with axial magnetic field

This system has a symmetrical geometry about the \( r = 6 \) plane. The electromagnetic field in the discharge space is uniform in the direction of \( \theta \). Therefore we use the \( r - z \) coordinate in order to minimize the simulation space (see Fig.2). Actual geometry between the cathode and anode is more complex, but in the calculation we simplify this geometry as shown Fig.2.

We make assumptions about the interactions between charged particles and the walls as follows. Electrons are absorbed at the anode. When ions collide with the anode, they are elastically scattered. Ions are absorbed at the cathode. There is no interaction between the cathode and electrons.

4 Method of simulation

Basic equations and some conditions used for simulation are as follows.

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Accumulation of electric field data by successive method

Calculation of particles' velocities at t—Δt/2

Calculation of field's data

Generation of Particles

Not achieve to equilibrium state

END

Fig. 3 Flow-chart of the simulation.

\[ \frac{\partial \mathbf{v}}{\partial t} = q(E + \mathbf{v} \times \mathbf{B}), \quad (1) \]

\[ \nabla^2 \Phi = \frac{\rho}{\varepsilon}, \quad (2) \]

\[ \nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t}, \quad (3) \]

\[ \nabla \cdot \mathbf{B} = 0, \]

where \( m \) is the mass, \( \mathbf{v} \) the velocity, \( q \) the electric charge, \( \mathbf{E} \) the electric field, \( \mathbf{B} \) the magnetic field, \( c \) the light velocity, \( J \) the current density, \( \varepsilon \) the dielectric coefficient, \( t \) the time, \( \rho \) the charge density, \( \Phi \) electric potential. These equations are translated to the finite-difference equations and numerically solved.

To develop the simulation code, we use a PIC (Particle-in-Cell) method. This code uses Leap-Frog method \((2)\) to calculate Eq.\((1)\). Though this simulation is done in \( r - z \) plane, \((r, z, \theta, v_r, v_{\theta})\) are used as the parameters of particles. Because this calculation is carried out in the three-dimensional electromagnetic field.

The potential distribution is divided into two cases.

(a) The potential distribution by impressing voltage on the cathode without electric charge density.

(b) The potential distribution with electric charge density (not impressing voltage on the cathode).

In the computation, the case (a) data is used as the basic potential distribution data by electrode and the case (b) data is used as the potential distribution data for expressing the spatial electric charge effect. Finally, the whole potential distribution is computed by piling up these data.

The discharge current is estimated by only considering the number of ionization events; ionization phenomena play significant roles in the present simulation. The number of ions and electron which are generated per unit time is assumed so as to be equivalent to be experimentally obtained result\([1]\).

In this work, to simplify this model we use only the hydrogen ions and electrons. This calculation is carried out by using spur particles which represent huge number of these particles, because many particles exist in the discharge space. Cathode potential is -1.8 kV, axial magnetic field is 0.09 T. Figure 3 shows the flow chart of the simulation. This computation is continued until the number of particles reach to equilibrium value.

5 Results and discussion

The Figure 4 shows the potential distribution along the \( z \) axis \((r = 0 \text{ mm})\). Fluctuations of the potential are seen all over the discharge space. The steep potential gradient which is located in the ion sheath is seen near the cathode \((z = 26 \sim 28 \text{ mm})\). This is characteristic phenomenon in the plasma.

Figures 5 and 6 show energy distribution of electron and hydrogen ion, respectively. Both distributions have maximum value near 0 eV and exponentially decrease toward high energy. The average energy of the electrons is 5.67 eV. That of the hydrogen ions is 3.74 eV. These results are slightly higher than the values of experimental report\([1]\) because the electrons are caught and accelerated by the fluctuation of the potential.

Both number densities of electron and hydrogen ion are around \(10^{12} \text{cm}^{-3}\) and these values are approximately equal to the experimental values\([1]\).

6 Conclusion

In this work, a simple model for the simulation of the plasma in the cylindrical discharge tube with axial magnetic field was established. The results of this calculation agreed well with the experimental result\([1]\). From these results, this model could be useful for studying the plasma in the cylindrical discharge tube with axial magnetic field.

The simulation of the plasma could be done more accurately by examining the width of \( \Delta \), the number of the super particle and the boundary condition of the Maxwell equation. Furthermore, we will be able to analyze the plasma jet emitter by considering the collision mechanisms and the initial condition of particles.
Fig. 6 The distribution of the hydrogen ion energy.

References


Abstract

Conceptual designs of the RF systems for both 3 GeV and 50 GeV proton synchrotrons are described. The RF systems provide an accelerating voltage per station of 40 kV because of a high accelerating rate, and also the systems are required to be stable for the heavy beam loading to accommodate high intensity proton beam acceleration. In order to reduce enormous beam loading, a low plate-resistance tetrode and a fast feedback technique are considered to use.

I. Introduction

Accelerator complex for the JHP is located in the KEK site and consists of four accelerators: pre-injector, 200 MeV linac, 3 GeV booster and 50 GeV main ring synchrotrons.1)

The booster is a rapid-cycling proton synchrotron and will be constructed in the present KEK-PS tunnel. The booster magnet is excited by using a resonant network 2). The repetition rate of the booster is 25 Hz, in future 50 Hz operation is scheduled. A circulating average beam current in the booster is designed to 200 μA. The beam is supplied to the adjacent 3 experimental facilities as well as injected into the 50 GeV main ring. Because of a high repetitive operation, a sweep-rate of rf-frequency and an accelerating voltage needs to be high. The RF harmonic numbers of both rings are 4 and 34, respectively. Thirty-two bunches from the booster are injected into the main ring.

The main ring synchrotron is located on the northern part of the KEK site. The size of ring is about four times larger than that of the booster ring. The main ring synchrotron operates in a cycle of 6 seconds; the accelerating period is 2.5 seconds. The main ring synchrotron is also a high current beam accelerator. Proton beams of $4 \times 10^{14}$ ppp (particles per pulse) is designed to be accelerated. The circulation beam current in the main ring is about twice larger than that in the booster, the beam loading effects in the main ring acceleration become more serious than in the booster.

In both the synchrotrons, for stable accelerations of high current beams, the reductions of heavy beam loading effects must be dispensable. The main parameters of both the rings summarized in Table 1.

II. RF System for The Booster

A. Cavity and RF-station

The requirements for the high intensity and rapid cycling synchrotron determine many parameters on the RF system. In the case of the booster, a fast time-response for tuning a cavity and to minimize a heat power loss in the cavity should be required.

The rf-frequency range is from 2. to 3.4 MHz, at the request of experimental users. For this frequency range, a ferrite-loaded re-entrant cavity is practical. The number of the rf-stations is 10 and the length of the station is 3 m. One rf-station consists of four quarter-wave coaxial lines, there is two accelerating gaps to obtain the required acceleration voltage.

Under the conditions of maximum acceleration rate of 220 GeV/sec and an intensity of $5 \times 10^{13}$ ppp, the beam consumes a maximum peak power of 180 kW per rf-station. An accelerating voltage of 40 kV per station must be required at a synchronous phase angle of 45 degrees.

The design of cavity strongly depends on the choice of ferrite materials. A μQf-product ($\mu$: relative permeability of a ferrite, Q: quality factor of a ferrite and f: operation frequency) is one of the key parameters when the cavity impedance is
A shunt impedance \( R_{sh} \) in an equivalent circuit of the resonant cavity is given by:
\[
R_{sh} = \frac{\omega L Q}{\mu Q f}.
\]  
(1)

On the other hand, the beam current flows in the opposite direction of the generator current. The beam induced voltage acts on decelerating the beam. The maximum peak current of circulating beam is 7 amperes. Though its fundamental Fourier component \( I_b \) depends on the bunching factor and the longitudinal distribution, its maximum value is twice of the peak current and 14 amperes. This enormous beam current affects on all the RF system through the accelerating gaps and feedback systems. The stability for the beam loading is estimated by a relative beam loading \( Y \),
\[
Y = \frac{I_b}{I_0},
\]
where \( I_0 \) is an RF generator current to give the same gap voltage without beam load and with cavity tuned to resonance and equals to shunt-resistor current \( \mu Q f \). For stability \( Y \) must be less than 2. In order to reduce the relative beam loading, a low plate-resistance tetrode is considered to use because the resonant cavity resistance can be reduced.

In our design, for instance, the required RF generator current is \( \sim 10 \) amperes; \( Y = 1.4 \). Peak power loss in ferrites is set to be \( -200 \) kW per cavity. In this case, the shunt impedance of 4000 \( \Omega \) and ferrite materials of which minimum \( \mu Q f \)-value is greater than \( 4 \times 10^9 \), would be necessary.

B. Feedback System

The rf-generator current \( I_0 \) is smaller than the circulating beam current. Specially, during the beam capture process in the booster, because the accelerating voltage should be low to avoid a longitudinal emittance growth. The relative loading \( Y \) becomes larger and the beam loading effects grows big. To reduce such loading effects, several rf-feedback systems must be considered to control the accelerating rf-system in stable.

For the resonant cavity, beam induced voltage \( V_{\text{beam}} \) is:
\[
V_{\text{beam}} = -R_{\text{eff,sh}} \cdot I_b,
\]
where \( R_{\text{eff,sh}} \) is an effective shunt impedance which is an impedance seen from a beam. The effective shunt impedance must be reduced to minimize the beam induced voltage.

III. RF System for The Main Ring

In the 50 GeV main ring, the rf-frequency is swept 3\% during the acceleration, and the average acceleration rate is \( \sim 20 \) GeV/second, which is ten times less than the booster acceleration rate. However, the beam loading current in the main ring is more than twice larger than in the booster. The choice of ferrite materials and the design, which take into consideration such a heavy beam loading, are very important.

A. Cavity and RF-station

The number of the rf-stations is 5 in the main ring. As the accelerating rate is \( \sim 20 \) GeV/second, the required accelerating voltage is 40 kV per rf-station at the synchronous phase angle of 30 degrees. The rf-frequency is swept from 6.86 to 7.07 MHz. The beam intensity is \( 4 \times 10^{14} \) pps. The corresponding peak current is \( -13 \) amperes. Considering twice of the peak current as the beam loading current, even if the relative loading \( Y \) allows 2, the generator current becomes larger than that in the booster. The RF feedback system is definitely required to compensate such a heavy beam loading.

Table 2 summarizes RF parameters for both the booster and main rings.

IV. Summary

In the recent high intense proton synchrotrons, the beam current inclines to be larger than the generator current. Nevertheless, the ferrite-loaded resonant cavity is the most practical as a tunable cavity in the frequency regime of several mega-hertz. In those ferrites, the heat loss limits to increase the generator current and RF voltage, because the quality factor and the curie point of ferrite materials are relatively low.

In FY1995, we have started to examine the ferrite materials. In these examinations, the basic parameters of loaded ferrites will be cleared.

The preliminary design for the RF systems for both 3 GeV booster and 50 GeV main ring synchrotrons are described. As the performances of ferrite materials are not clear, the design is limited at this moment.

The author thanks all members of the KEK-PS groups for useful discussions and their encouragement.

V. References

Table 1
Specifications of the booster and main ring synchrotrons

<table>
<thead>
<tr>
<th></th>
<th>3 GeV Booster</th>
<th>50 GeV Main Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>339.4 m</td>
<td>1442 m</td>
</tr>
<tr>
<td>Transition gamma</td>
<td>6.25</td>
<td>27 i (imaginary)</td>
</tr>
<tr>
<td>Beam energy</td>
<td>inj. / ext.</td>
<td>200 MeV / 3 GeV</td>
</tr>
<tr>
<td>$B_p$</td>
<td>inj. / ext.</td>
<td>2.15 / 12.8 Tm</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>inj. / ext.</td>
<td>0.687 / 4.08</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>inj. / ext.</td>
<td>0.50 / 0.86 MHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>25 Hz (50 Hz)</td>
<td>6 sec</td>
</tr>
<tr>
<td>Accelerating period</td>
<td>20 msec</td>
<td>2.5 sec</td>
</tr>
<tr>
<td>Accelerating rate</td>
<td>220 GeV/sec</td>
<td>20 GeV/sec</td>
</tr>
<tr>
<td>Number of particles</td>
<td>$5 \times 10^{13}$ pps*</td>
<td>$4 \times 10^{14}$ pps</td>
</tr>
<tr>
<td>Beam current</td>
<td>200 $\mu$A</td>
<td>10 $\mu$A</td>
</tr>
<tr>
<td>Circulating current (peak)</td>
<td>4 $\sim$ 7 A</td>
<td>13 A</td>
</tr>
<tr>
<td>Beam power</td>
<td>0.6 MW</td>
<td></td>
</tr>
</tbody>
</table>

* protons per pulse

Table 2
RF parameters of the booster and main ring synchrotrons

<table>
<thead>
<tr>
<th></th>
<th>3 GeV Booster</th>
<th>50 GeV Main Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of acceleration gap per station</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Max. rf-voltage per gap</td>
<td>20 kV</td>
<td>20 kV</td>
</tr>
<tr>
<td>Max. phase angle</td>
<td>45 degree</td>
<td>30 degree</td>
</tr>
<tr>
<td>Accelerating voltage</td>
<td>400 kV</td>
<td>200 kV</td>
</tr>
<tr>
<td>Number of RF stations</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>RF harmonic number</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>RF frequency sweep range</td>
<td>2.00 $\sim$ 3.43 MHz</td>
<td>6.86 $\sim$ 7.07 MHz</td>
</tr>
<tr>
<td>Length of rf-station</td>
<td>3 m</td>
<td>3 m</td>
</tr>
<tr>
<td>Diameter of beam pipe</td>
<td>20 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>50 %</td>
<td>42 % (2.5 sec/6 sec.)</td>
</tr>
</tbody>
</table>
DEVELOPMENT OF A COMPACT LINAC FOR FEL OSCILLATION

Tsuyoshi HAGA, Kunihiko Tsumori, Tsuyoshi Shinzato, Katsuji EMURA and Hioshi TAKADA

Abstract

We developed a compact linac as both an injector for synchrotron radiation (SR) and an electron source for free electron laser (FEL). The linac has a high accelerating gradient of 22 MeV/m and is very compact. Recently, we proceeded with studies on FEL using this linac. The beam acceleration of 10 μs macropulse duration at 50 MeV was achieved and energy spread and peak current were 0.6% and 28 A, respectively.

1. Introduction

Recently, it gets much attention that synchrotron radiation (SR) light has potential for the industrial applications, thus a compact SR machine has been awaited. We have continued our R&D efforts to develop compact SR machines. The SR machine consists of a linac and an SR ring. Both of them require compact design. We first launched the development of a compact SR ring (NIJI-III) using superconducting magnets. It has already completed in 1991.

For the linac, we completed the development of a compact linac by ourselves in 1993 (Fig. 1) and achieved the electron beam acceleration at 100 MeV-100 mA in July 1994. The compact linac has two special features. One is a high accelerating gradient (22 MeV/m) and another one is the two mode accelerating (SR and FEL mode).

Recently, we proceeded with studies on FEL using this linac. On this paper, the beam characteristics of our linac and the experimental results of FEL are described.

2. Compact linac for FEL oscillation

Since very severe qualities of electron beam, described as follows, are needed for FEL oscillation, we make some efforts in our linac.

1) long macropulse duration
2) narrow energy spread
3) low emittance
4) high peak current

We aim for FEL oscillation in an infra-red region. In order to achieve the energy spread of 0.6%, we proceeded with studies on FEL using this linac. The beam acceleration of 10 μs macropulse duration at 50 MeV was achieved and energy spread and peak current were 0.6% and 28 A, respectively.

The output voltage stability of less than 0.3% was achieved for the klystron modulator. A klystron modulator was developed with cooperation from Nissin Electric Co., Ltd. The klystron has a high-power driving pulse with a voltage of 305 kV and current of 340 A (short pulse mode). The klystron modulator has several features as follows:

1) PFN (Pulse Forming Network) consisting of parallel networks of 21 capacitors and 21 reactors
2) stepping motors to simplify a reactance adjustment of the PFN circuit

The beam characteristics of our linac and the experimental results of FEL are described.

2.1. Long macropulse duration

When we discussed the macropulse duration of the electron beam for FEL experiments, the results of FELIX [4] was referred. As the intensity of FEL saturates after 3 μs or so from the pulse rising of the beam, the macropulse duration of more than 10 μs is necessary for the infra-red FEL oscillation.

A klystron used in our linac is the TH 2146 by Thomson Tubes Electroniques. It is capable of producing the two different microwaves of 1 μs duration (45 MW) to inject the SR-ring and of 10 μs (22.5 MW) for FEL. The mode of SR/FEL can be changed automatically.

2.2. Narrow energy spread

In order to achieve the energy spread of 0.6%, we attempted to stabilize the temperature of an accelerating tube and the output voltage of a klystron modulator.

Temperature variation of the accelerating tube causes thermal expansion/compression of the oxygen-free copper, the major structural material for the accelerating tube, and causes the resonance frequency to shift by approximately 50 kHz/°C. Since the accelerating tube has a quite high Q of 12,500, even a slight shift of resonance frequency can cause impedance mismatching, and the microwave power that can be injected into the accelerating tube is consequently reduced. As a result, beam energy varies. To further narrow the energy spread, the temperature stability of the cooling water must be improved.

Some time ago we developed a high-precision cooling water system for optical fiber testing. For the present study we developed, with assistance from Sumitomo Densetsu Co., Ltd., a cooling water system with a very high temperature stability of less than ±0.02°C.

With conventional cooling water systems, the beam energy spread caused by temperature variation of the accelerating tube is 0.7%, whereas it is below 0.1% with the our cooling water system.

Suppressing beam energy fluctuation requires stable output pulse voltage for the klystron modulator. A high-stability klystron modulator was developed with cooperation from Nissin Electric Co., Ltd. The klystron demands a high-power driving pulse with a voltage of 305 kV and current of 340 A (short pulse mode). The klystron modulator has several features as follows:

1) PFN (Pulse Forming Network) consisting of parallel networks of 21 capacitors and 21 reactors
2) stepping motors to simplify a reactance adjustment of the PFN circuit

The output voltage stability of less than 0.3% was achieved as shown in Fig. 2.
The electron gun is a thermionic triode gun based on a dispenser cathode assembly (EIMAC model Y646B). A high D.C. voltage of 200KV is applied to anode-cathode gap to obtain low emittance. The shapes of the electrodes were optimized through simulations. A normalized emittance of 7 n-Hm mm-rad and beam current of 1.5A were obtained in the electron gun testing.

2-4. High peak current

To achieve high peak current (25A), an SHPB system (an SHPB cavity and a 476MHz rf amplifier) was installed in the compact linac. The SHPB is a standing-wave cavity with a resonance frequency of 476MHz. Short filling time and high shunt impedance are necessary to reduce the rf amplifier load. In order to optimize both Q-value and shunt impedance of the cavity, a portion of the inner surface of the cavity was coated by OFHC.

To supply rf signals to the SR ring (158.6MHz) and the grid pulsar of the burst-mode electron gun (79.3MHz), we chose a frequency multiplier system which can generate the microwaves of 79.3, 158.6, 476, 2856MHz. In general the lowest frequency is chosen as a fundamental one. On the other hand, the frequency stability for acceleration (2856MHz) is most important. In consideration of the frequency limitation of IC-counter, the harmonic relation of four microwaves, the results of RIK and so on, we chose 467MHz as the fundamental frequency. The rf power amplifier for the SHPB is all-solid-state one and its maximum rf output power is 4.6kW.

The electron beam emitted from a cathode is focused by the focusing electric field of the Wien-anode gap. Also the beam is defocused by the space charge effects in the bunching section. Thus, according to the increase of electron density, the beam focusing of the solenoid is changed.

An ideal magnetic field of nine helmholtz coils arranged along the bunching section is given by Kapchinsky-Vladiminsky equation. If electron beam energy is lower than 5MeV, using the V-K equation, the magnetic field Bs to fix a radius of an electron beam can be calculated from:

$$ B_s(T) = 3.69 \times 10^{-3} \frac{I[A]}{\rho / [m]} $$

where I is peak current of electron beam, r is beam radius, $\beta = v/c$, and $\gamma$ is Lorentz factor.

The longitudinal magnetic field distribution along the bunching system at present is shown in Fig.3. The field optimized at the experiment is identical with the calculation.
3-2. Energy spread measurement

Small signal gain depends on the energy spread of the beam. The energy spectrum at 50MeV is shown in Fig.8. The energy spread (FWHM) of 0.6% was achieved.

4. Conclusions

We have developed the compact linac as both the injector for NIJI-III and the electron source for FEL oscillation. The accelerator tube cooling system with high temperature stability and the klystron modulator with an output pulse voltage stability of less than 0.3% help the achievement of narrow energy spread and the stable micropulse cycle. As a result, the acceleration of 50MeV with energy spread of 0.6% was achieved. The SHPB system was installed and we tested its performance. As a result, the SHPB system was successfully operated and the peak current increased from 6A to 28A. We achieved the experimental condition of FEL. Also we intend to accomplish FEL oscillation.

Acknowledgements

The authors wish to thank T. Hori of JAERI SPRING-8 project team for his advice.

References

COLD TEST OF A 25.5 MHz DOUBLE-COAXIAL λ/4 RESONATOR

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Abstract

A 25.5 MHz λ/4 coaxial line resonator has been constructed. The resonator has a double-coaxial structure and the total length is as short as 1.3 m. Drift tubes mounted at the open end of the central conductor compose six acceleration gaps. This resonator is to be used as a rebuncher in a linac complex for the acceleration of unstable nuclei. The cold test on the completed resonator has been made and the result is consistent with the half-scale model tests.

1. Introduction

A linac complex for the acceleration of the unstable nuclei produced by cyclotron beam bombardment is under construction at Institute for Nuclear Study, University of Tokyo [1]. The ions from ISOL with charge-to-mass ratio 1/30 at minimum will be accelerated first by 25.5 MHz RFQ linac of split-coaxial type [2] up to 170 keV/u and, after charge stripping, will be further accelerated by 51 MHz interdigital-H linac [3] up to 800 keV/u. The reason of the doubled operation frequency for the interdigital-H linac is to make the tank size small and to obtain higher shunt impedance. This configuration, however, requires a rebuncher between two linacs to adjust the longitudinal beam-emittance to be efficiently accelerated by the rear linac [4]. The rebuncher with these specifications may be prepared based upon the λ/4 transmission line resonator with a few acceleration gaps. The natural length of the λ/4 resonator for the frequency of 25.5 MHz, however, is very long, 2.94 m. To make the tank size compact, we have developed a double-coaxial resonator, which is a folded coaxial line, and in which the outer conductor of the inner coaxial line is concurrently the inner conductor of the outer coaxial line. Thus the length is, in principle, about half of the natural line length.

The resonator with these specifications may be prepared based upon the λ/4 transmission line resonator with a few acceleration gaps. The natural length of the λ/4 resonator for the frequency of 25.5 MHz, however, is very long, 2.94 m. To make the tank size compact, we can employ the so-called spiral resonator, even in which the length of the inner conductor stays to be the same, and we can not expect the mechanical stability of the drift tube to be installed at the open end of the conductor. Thus we have developed a double-coaxial resonator, which is a folded coaxial line, and in which the outer conductor of the inner coaxial line is concurrently the inner conductor of the outer coaxial line. Thus the length is, in principle, almost half of the natural line length. Furthermore it is known that the resonant line length of the transmission line which is composed of two parts having different characteristic impedances becomes shorter than the one for uniform transmission line [5-6]. The capacitance accompanying the drift tubes also contributes to shorten the resonant line length.

By using a half-scale model, we have determined the detailed design dimensions of the resonator [5], and have constructed a real resonator. The length from the bottom of the resonator to the center of the drift tube is about 1.04 m which is short enough to install the resonator between the floor and the beam level.

The outline of the completed rebuncher is described in section 2 and the result of the cold tests is given in section 3.

2. Construction of the λ/4 Resonator

In Fig. 1 is shown the cross section of the 25.5 MHz double-coaxial λ/4 resonator constructed as a rebuncher. The dimensions of the resonator and the drift tube parameters are given in Tables 1 and 2, respectively. Due to the floating capacitance around the drift tubes, about 37 pF, the resonant transmission line length is shortened by 30%. Further reduction of the length is realized by increasing the difference in the impedances between the inner and the outer coaxial lines. Since the diameter of the outer coaxial line is limited to the extent of the six-cell drift tube length, we have to shorten the distance between the intermediate and the central conductor. To lighten possible multipactoring, the central conductor is a square pillar while the intermediate conductor is a cylinder. Thus the impedance of the outer coaxial line is 1.8 times as large as that of the inner conductor, which brings 19% reduction of the resonant transmission line length. These effects in addition to the folding of the transmission line enabled us to construct a rebuncher with a limited length.

The tank is composed of an upper lid, an outer conductor cylinder and a bottom flange. The intermediate conductor is supported between the cylinder and the lid. They are assembled by use of sealing gaskets and rf contactors. Drift tubes of earth potential are mounted inside the upper lid, on which are also furnished an evacuating port, a capacitive tuner, a vacuum gauge port and a viewing port in addition to entrance and exit beam...
The resonant frequency drastically decreases when the drift tube and will decrease the resonant frequency. When possible resonant frequency deviation of the completed resonator does not exceed the capability of the adjustable reactive-tuner, we need no other tuners. After the cold test on the completed resonator, the insertion length for any of the fixed-type tuner will be specified if necessary.

3. Cold Tests of the Resonator

A. Resonant Frequency

We expected for the completed resonator to have the resonant frequency lower than 25.5 MHz by some tens kHz, which may be brought to proper frequency only by use of adjustable reactive-tuner. The resonant frequency without any tuner, however, resulted in rather high frequency, 25.52 MHz. This may be partly due to the installation of the cooling water channel inside the tank, which reduces the tank volume and increases the resonant frequency. Thus we have to use the capacitive tuner to bring the resonant frequency into the range covered by the adjustable reactive-tuner, which is shown in Fig. 2. As is seen in the figure, the tunable range is about 100 kHz. The characteristics of the capacitive tuner is shown in Fig. 3. The resonant frequency drastically decreases when the drift tube approaches the drift tube closer than 100 mm. We

<table>
<thead>
<tr>
<th>Number of Cells</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Cell Length</td>
<td>12.3 mm</td>
</tr>
<tr>
<td>Gap Distance</td>
<td>20 mm</td>
</tr>
<tr>
<td>Inner Diameter</td>
<td>60 mm</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>100 mm</td>
</tr>
<tr>
<td>Drift Tube Edge</td>
<td>10 R</td>
</tr>
<tr>
<td>Fabrication and Setting Accuracy</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Transit Time Factor</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The dimensions of the 25.5 MHz rebuncher

<table>
<thead>
<tr>
<th>Central Conductor</th>
<th>60x60x90 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Diameter of the Intermediate Conductor</td>
<td>150 mm</td>
</tr>
<tr>
<td>Thickness of the Intermediate Conductor</td>
<td>5 mm</td>
</tr>
<tr>
<td>Inner Diameter of the Outer Conductor</td>
<td>690 mm</td>
</tr>
<tr>
<td>Characteristic Impedance of the Inner Coaxial Line</td>
<td>48 Ohm</td>
</tr>
<tr>
<td>Characteristic Impedance of the Outer Coaxial Line</td>
<td>88 Ohm</td>
</tr>
<tr>
<td>Length of the Double-coaxial Structure</td>
<td>850 mm</td>
</tr>
<tr>
<td>Total Inside Length of the tank</td>
<td>1170 mm</td>
</tr>
<tr>
<td>Height of the Basemen</td>
<td>108 mm</td>
</tr>
<tr>
<td>Distance from the Floor the Drift Tube Center</td>
<td>1175 mm</td>
</tr>
</tbody>
</table>

The drift tube parameters of the rebuncher
decided the distance between the tuner edge and the drift tube to be 50 mm, the resonant frequency corresponding to which comes into the middle of the tunable range by the adjustable reactive-tuner.

B. Q-values

The unloaded Q-value is about 6,000, which is consistent with the value expected from the measurement on the half-scale model made of brass [5]. We have measured Q-values under the various conditions both for the capacitive and reactive tuners. The result shows there is no significant change in Q-value.

C. Longitudinal Electric-field Distribution

The longitudinal electric-field distribution along the drift tube axis as measured by bead perturbation method is shown in Fig. 4. The bead is made of aluminum, the diameter of which is 10 mm. One can see that the field strength in each gap is almost constant, as expected from the measurement on the model.

Shunt impedances on and off the axis are shown in Fig. 5 to show horizontal and vertical position dependence. The shunt impedance on the axis is 20.3 Ω/m which is close to the value expected from the model measurement. The reason why the shunt impedances become higher at the positions far from the center is that the electric field including its radial component is higher there than on the axis. Our purpose of this series of measurements is to examine possible asymmetry of the field distribution in the drift tube bore. One-sided capacitive tuner may affect the field symmetry along the horizontal direction and the vertically asymmetric structure of the drift tube support may introduce asymmetry in vertical direction. As can be seen in the figure, there is no asymmetry in the horizontal direction, and we can say that the capacitive tuner gives no effect on the field distribution in the drift tube bore. On the other hand, obvious asymmetry in the vertical direction is seen. The origins of this asymmetry may include the effect of the dip of the bead trajectory due to the gravitation. Further examination will be made by using computer code MAFIA.

4. Conclusion

In constructing 25.5 MHz λ/4 resonator, we have employed a double-coaxial structure, which enabled us to make the total resonator length as short as 1.3 m. The results of the cold tests on the resonator are almost consistent with the measurements on the half-scale model made of brass. Preparation of both capacitive and reactive tuners is quite efficient to adjust the unexpected resonant-frequency shift. Next step will be to excite the resonator with high rf power. Since multipactoring is more or less expected, a pulsive aging system is prepared. Beam acceleration test is scheduled at the end of 1995 fiscal year.

REFERENCES

DEVELOPMENT OF AN RF ELECTRON BEAM IRRADIATION SYSTEM

T. Fujisawa, T. Hirasima, T. Katori, S. Wada, S. Kohmoto, and M. Odera

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Abstract

A prototype electron beam irradiation system using a re-entrant type RF accelerator (630mm in length, 500mm in diameter) has been studied to make a compact device for electron beam processing. The maximum beam energy is planned to be 900 keV. The resonator is powered by a self-excited oscillator. This report gives brief explanations and the present status.

Table 1. Specifications of ELECTRON SHOWER.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>300 - 900 keV</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>±5%</td>
</tr>
<tr>
<td>Maximum beam intensity</td>
<td>10 mA</td>
</tr>
<tr>
<td>Scanning width</td>
<td>30 cm</td>
</tr>
<tr>
<td>Beam spot size</td>
<td>&lt;20mm in diameter</td>
</tr>
<tr>
<td>Line power</td>
<td>3 phase, 200V, 35 kVA max.</td>
</tr>
<tr>
<td>Space for accelerator</td>
<td>Floor: 1600*900 mm, Height: 1850mm</td>
</tr>
</tbody>
</table>

1. Introduction

Recently many electron accelerators are used in industries for electron beam (EB) processing. Most of accelerators whose beam energy is lower than 5 MeV are DC type. The main reason why DC machines are used, is because the electric power efficiency of DC machines is much better than that of RF machines, and principle and technology of DC machine are well established comparing to the RF machine. An RF accelerator, however, is much smaller and less expensive than a DC machine in the energy higher than 300 keV. Furthermore, RF accelerator is more reliable than DC machine because any insulator is not used in the area where strong electric field arises and no accessory is required such as a reservoir of SF6 gas for DC machine. Then we studied a prototype RF electron accelerator to develop an electron beam irradiation system named 'ELECTRON SHOWER' for industrial use.

As shown in our previous report 1), the principle of the accelerator is established, that is, the self-excited tetrode oscillator2) functions well and overcomes multipactoring in the resonator without use of the conventional DC bias scheme. The new bunching system3) gives a sufficiently good energy resolution for EB processing. The maximum acceleration voltage, however, was 300 kV and the averaged intensity 0.1 mA. Then we have improved machine and increased the acceleration voltage up to 800 kV and the averaged beam intensity up to 10 mA. Now, a unit for industrial application based on the study is under construction.

2. Specifications and Outline of ELECTRON SHOWER

Table 1 shows the specifications of 'ELECTRON SHOWER' (ES) that were already described in our previous report 1). These, however, are typical values and should be changed according to requests by a small modification of the prototype without change of fundamental construction.

3. Radio-frequency system

The principle of radio-frequency system and structures of ES were already described 1). Here, the brief explanation for RF system and for its modifications is given. The inner conductors (stem: 270mm in length, 80 mm in diameter) made of copper are...
mounted on the flat end of the outer cylindrical conductor and faced to each other at the center of the resonator. As shown in Fig. 2 the, stem in which the electron gun is mounted, has slots to generate the electric field for the velocity modulation of the extracted electron beam.

The resonant frequency of the fundamental mode is 182 MHz, and the measured Q-value is 15000. The shunt impedance is estimated to be about 3 M ohm from the Q-value of the resonator coupled to the oscillator. The resonator is powered by self-oscillator system and the oscillation is switched by the control grid bias. Table 2 shows the specifications of the oscillator.

<table>
<thead>
<tr>
<th>Specifications of the oscillator.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Maximum RF power</td>
</tr>
<tr>
<td>Duty</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Tube</td>
</tr>
</tbody>
</table>

5. Present status

5-1. Beam loading

The insufficient maximum acceleration voltage of 300 kV in our previous report, was caused by poor adjustments of coupling between oscillator and resonator, and also of feedback elements. It is, however, difficult to optimize the coupling and feedback ratio, because these depend strongly on the acceleration voltage, biases of the tetrode and beam loading. Particularly, it is difficult to adjust the parameters when the beam is accelerated, because the shunt impedance of the resonator including beam loading is, for example, one thirds of the impedance without beam loading in a case of 300 keV 100 mA(pulse peak) acceleration. Figure 3 shows a time structure of the acceleration voltage when the beam is accelerated. Even if the self-excited oscillator were adjusted to operate under beam loading, the acceleration voltage decreased considerably when the beam was injected. Now, intensity of 100 mA(pulse peak) has been stably accelerated at 300kV.

4-2. Focusing system

The duty factor for normal operation of ES is 1/10. Then the peak current of 100 mA is required to accelerate the averaged current of 10 mA. Furthermore, the intensity more than 1A is concentrated in the narrow phase of RF acceleration field by velocity modulation. In such a case, very high tension as a few tens kV is usually applied to an extraction electrode to suppress the space charge effect. The low extraction voltage of 5.5 kV is, however, supplied in ES because a machine for industrial application should be as compact and inexpensive as possible. For effective transportation of the low energy beam to the main acceleration gap, a beam focusing system consisting of cylindrical permanent magnets is mounted in the stem(see figure 2). The beam focusing system consisting of cylindrical magnets is also mounted in the other stem to transport the electron beam to the bending magnet.

4-3. Buncher coupled inductively to the main resonator

We developed a new type buncher system whose RF voltage is generated by an inductor in the middle of the stem Appendix 4. Figure 2 shows a schematic view of the stem having the buncher. An electron gun and also a beam focusing system are installed in the stem. The RF electric field of the buncher is anti-phase with the main accelerating field.

4-1. Electro gun

A triode type electron gun is operated in pulse mode by switching the grid bias in synchronous to the pulse mode of the main RF field. The cathode of electron gun made of LaB₆(4 mm in diameter) is heated by pyrolytic-graphites set on both sides of the cathode. The grid made of molybdenum or tungsten mesh is set in front of the cathode with gap of 1 mm. The extraction electrode is one similar to a Pierce type as shown in Fig. 2.

5-2. Acceleration test

Figure 4 shows the typical energy spectrum of the electron beam analyzed by a bending magnet. The RF modulation voltage proportional to the main acceleration voltage is adjusted to obtain the best energy resolution at the beam energy of 250 keV. The typical result of acceleration test is summarised in Table 3. The energy resolution of 5% at 300keV is sufficient for EB processing.
Fig. 4 Typical energy spectrum.

Table 3 Typical result of acceleration test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum acceleration voltage</td>
<td>820 kV</td>
</tr>
<tr>
<td>Beam intensity (330 keV, duty=1/10)</td>
<td>100 mA</td>
</tr>
<tr>
<td>Energy resolution (300 keV)</td>
<td>5%</td>
</tr>
</tbody>
</table>

5-3. Irradiation test

It is required to irradiate sample uniformly in wide area. In the present case, as the machine operates in pulse mode (width: 100 micro sec, period: 1 ms), the beam was scanned by so low frequency (50 Hz) that a beam spot of a pulse overlaps with that of the successive pulse. The uniformity of ±10% is obtained.

The depth dose curve measured by use of CTA films is shown together with one obtained with DC machine in Fig. 5. The disagreement between the data is little problem for EB processing.

Fig. 5 Depth dose curve obtained by ES

We usually estimate the effect of irradiation by dose (Gy). Most of data of electron beam irradiation, however, are obtained by DC machine. Then we carried out preliminary experiments such as sterilization, cross linking of rubber, polymerization, coloration of glass, and etc. In most of the tests, we could not find out difference between effects of RF and DC machines, but found that one thirds of dose required for DC machine gave same effects on one of polymerization experiments. This result shows the typical example that irradiation effect depends on dose rate.

6. EB system for industrial use

Figure 6 shows the cross sectional view of electron beam irradiation system designed based on study for prototype machine. The reasons why the accelerator are set vertically are as follow:

1) The energy resolution obtained is sufficient for usual EB processing. Then the beam energy has not to be analyzed with a magnet.
2) Most of materials are irradiated in horizontal plane.
3) The transmission efficiency of beam is naturally better for a system without a bending magnet.

Fig. 6 Cross sectional view of ES for industrial use.

7. Conclusion

The prototype electron irradiation system was successfully studied and also preliminary experiments have been carried out. Now the machine is installed in a university and used for several experiments. The system for industrial application based on the prototype is under construction.

We thanks Dr. Batygin for his help in calculation of electron trajectories and Mr. Chiba for providing convenience for calculation of RF electric fields.

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4) Patent pending, TOKU GAN HEI 7-85826.
COLD MODEL MEASUREMENT OF BIPERIODIC L-SUPPORT DAW

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Abstract

Cold model test of a biperiodic L-support Disk-and-Washer linac structure is performed. The structure is a variant of the biperiodic 4-T support DAW. Each washer is supported by two L-shaped supports 180° apart azimuthally. The results of the cold model tests are described.

1. Introduction

An electron linac has been installed at the Accelerator Laboratory, Institute for Chemical Research, Kyoto University. It is mainly intended to be used as the injector for the electron storage ring KSR, which is being assembled. The disc-loaded wave-guides are installed as the accelerator tubes, which are operated at 2857MHz. Because of the limited space in the building, only three accelerator tubes of three meter in length can be installed. The available RF power from a klystron is up to 20 MW for each tube, and then the output electron energy is expected to be about 100 MeV at the peak current of 100 mA.

In order to have a shorter damping time in the storage ring, the higher injection energy is desirable. A new accelerating tube with a higher shunt impedance is thus required to achieve the higher accelerating gradient with the same RF power.

A cold model made of Aluminum is fabricated to study the possibility of a DAW structure with biperiodic washer supports. The coupling-mode frequency shift by the supports, and biperiodic disturbance on the field distribution are measured and compensated in cold model tests. The mode spectra is also measured.

2. Biperiodic L-support DAW

The DAW structure has outstanding features in high stability, good vacuum properties, high shunt impedance, and ease of fabrication. It was found that the mode overlapping problem can be overcome by the biperiodic support configuration with the careful choice of the tank diameter (See Fig. 1). There is variety of options for DAW linac structure with such washer support. For example, in the configuration with a large tank-diameter, the operating frequency drops between two split TM111-like mode passbands, and the shunt impedance is higher. When the tank diameter is small, both passbands are above the operating frequency, and the mode density is smaller. The basic configuration described here is the extension of the PIGMi geometries, except for the thicker washers and the reduced tank diameter by 20%. This geometry has fewer undesirable modes and a shorter filling time compared with the large diameter 4-T support DAW. The washer thickness is increased for the cooling water channels inside the washers. Because the L-support configuration has only two supports on a washer, there are only one inlet and one outlet for the cooling water, and the fabrication of the coolant path is straightforward, although the design of the path is not straightforward. This may simplify the fabrication problem compared with the 4-T support geometry whose washer has two inlets and two outlets on. The multiple inlets and outlets may cause the fabrication problem when the paths have splits and merges. A typical design specification based on SUPERFISH calculation is listed in Table 1. The notations for the DAW dimensions are shown in Fig.2.

3. Tuning Process

The positions of the washer supports are determined so that their effect on the accelerating mode is minimized. Then, the coupling mode frequency fc is inevitably disturbed by the existence of the supports, and its frequency is pushed up from its calculated value. Because fc should coincide with the accelerating-mode frequency fa, fc should be compensated. Besides this effect, the biperiodicity of the supports breaks the uniformity of the electric field distribution on the axis. Because the supports reduce the electric field around them, the coupling coefficients between the

---

Fig.1 DAW with Biperiodic support
cells are not uniform, yielding the biperiodic modulation on the field distribution. In order to improve the coefficient unbalance, the disk radii Rdn and Rds (see Fig. 2) are changed biperiodically; namely, the disks with the washer supports have a larger radius than that without supports, which enlarges the disk-washer opening. Thus, the coupling coefficients are enhanced biperiodically, and the coupling frequency is corrected by adjusting the average of Rdn and Rds. Finally the accelerating frequency will be tuned by modifying the washer radius Rw.

The tunings are performed with a six-washer geometry. The coupling mode frequency is measured in the geometry with the half washer endplates, which has three disks with supports and three disks without support (See Fig. 3-a). Although the simple biperiodicity in the whole system is broken, this geometry will give the correct coupling frequency. There is another option of the support direction; namely, the quad-periodic geometry where the support direction changes alternatively (See Fig. 3-b). Photos 1 and 2 show the typical parts for the model cavity, and the close view of the disk-support-washer assembly.

| Rc/λ | 0.585 | - |
| θ | 1.0 | - |
| Frequency | 2.856 GHz | |
| L=6λ/4 | 26.24 mm | |
| Re (cavity radius) | 61.40 mm | |
| Rd (disk radius) | 49.6 mm | |
| Td (half disk thickness) | 12.53 mm | |
| Rw (washer radius) | 42. mm | |
| Tw (half washer thickness) | 2.5 mm | |
| θ (nose angle) | 30 degree | |
| Rn (nose radius) | 1.2 mm | |
| Rb (bore radius) | 5.13 mm | |
| G (gap) | 14.84 mm | |
| Rt (supporting point) | 32.3 mm | |
| Rr (support curvature) | 9. mm | |

Table 1 DAW cavity dimensions

![Fig. 2 Notations for DAW dimensions](image)

![Photo 1 The typical parts for the DAW cold model](image)

![Photo 2 Close view of the disk-support-washer assembly](image)

4. Measurements and results

Figure 4 shows the geometry for the mode spectra measurement. Although it is intended to be the "bi-periodic configuration", the bi-periodicity is broken by the terminations. It does not have a mirror symmetry even. Figure 5 shows the preliminary result of the mode spectra measurement for the "bi-periodic configuration". Because of the broken bi-periodicity and the fewer number of cells, the understanding of the mode spectra is somewhat complicated. Because the stem modes have very low Q-values, and could not be observed easily, they
are not shown in the figure. The TE_{11} mode passband is degenerated in this support configuration, and only one passband is shown. Because the symmetry of the support configuration breaks the degeneracy, TE_{21} mode has two passbands: namely TE_{21E//} (electric field parallel to the support) and TE_{21E⊥} (electric field perpendicular to the support). The TE_{21E//} couple strongly to the TM_{01} modes, and they are mixed together particularly around the π mode. It makes the mode identification process difficult.

The mode overlapping on the acceleration mode is avoided in this configuration. The TM_{11}(-like) passband splits into two narrow passbands and both passbands sit 86MHz above the operating frequency. The slope of the TM_{02} passband around the π mode shows the high coupling and is the same as the designed one, which indicates that the confuence condition comes close sufficiently. Because of the boundary condition of the termination, the coupling mode cannot be observed in the same configuration as the one that shows the accelerating mode. This situation makes the confirmation of the confuence difficult. The measurement with more cells is going on.

![Fig. 4 Geometry for the accelerating mode](image)

5. Acknowledgment

The authors thank Mr. Tonguu for his help in the measurement. The present work is supported by Grant-in Aid for Scientific Research from Ministry of Education Science and Culture of Japan.

6. References


RF CHARACTERISTICS OF THE BULLET-SHAPE SiC ABSORBER FOR KEKB

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Abstract

Sixteen bullet-shape sintered SiC (silicon carbide) ceramics were used as the HOM absorbers for a prototype of KEK B-factory (KEKB) normal conducting cavity[1]. RF simulations show that the reflection rate from the SiC absorber increases abruptly when the frequency decreases under 1GHz. This behavior can be explained as the attenuation property of a cylindrical dielectric waveguide. The RF characteristics of the SiC absorber are discussed by analyzing properties of the cylindrical dielectric waveguide.

1. Introduction

A prototype of normal conducting cavity for KEKB was designed and built [2]. This prototype cavity is loaded with a coaxial waveguide for damping higher order modes (HOM's). The waveguide is equipped with a notch filter. Figure 1 shows a schematic drawing of this cavity with the SiC absorber. For HOM absorption, sixteen bullet-shape sintered SiC ceramics are inserted from the end of the coaxial waveguide. The absorber dimensions are 40 mm in diameter, and 400 mm in total effective length including a 100-mm nosecone section. Each SiC absorber has a cooling water channel bored inside and is directly cooled. The HOM power (at frequencies above 0.7 GHz) to be handled will be on the order of ~10 kW per cavity, corresponding to ~1 kW per absorber. The permittivity of the SiC material is 22.2-6.10j at 0.75GHz and 20.7-4.58j at 1.5GHz. The design of the SiC absorber is based on the S-band waveguide load for the 2.5-GeV electron linac in KEK[3].

Closed circles (a=20mm) in figure 2 show the frequency response of the reflection ($S_{11}$) from the HOM absorbers in the test cavity, which is simulated with hfs5[4]. The TEM mode in the coaxial waveguide is assumed in this simulation. When the frequency decreases under 1GHz, the reflection increases rapidly. This poor absorption properties under 1GHz should be improved because some HOM's exist at 0.7-0.8GHz.

2. Frequency response of the HOM absorber

Several solutions, which improve the frequency response at 0.7-1.0GHz, were obtained through numerical simulations with hfs5. It was found that effective parameters are the radius of the absorber (a) and the real part of the permittivity (e'). Figures 2 and 3 show the effects of these parameters. Larger values of a and e' improve the absorption at lower frequencies. But the length of the absorber is not so effective as a and e'. Figure 4 shows the effect of the nosecone section at the tip of SiC. A SiC absorber without the nosecone section has a similar frequency response at 0.7-1.0GHz. The taper improves the absorbing properties above 1GHz.

The frequency responses shown Figures 2 and 3 resemble the cutoff response of a metal waveguide filled with a dielectric material. This suggests that the RF propagation properties in the SiC absorber, which is considered a kind of waveguide, are essential in its
1.2 1.4 1.6
Frequency (GHz)

Figure 3: $S_{11}$ frequency response of the SiC absorbers with different permittivities.

1.5 2 2.5
Frequency (GHz)

Figure 4: The effect of the nosecone on the $S_{11}$ frequency response.

3. Propagating mode in the SiC absorber

In order to identify the propagating mode clearly, a simplified 2-dimensional lossless model without a cooling water channel was simulated in a parallel plate transmission line. Figures 5-(a) and 5-(b) show the electric field of the propagating mode obtained by the HFSS simulation. The electromagnetic wave (HE_{11}-like mode) is mainly propagating inside the SiC at 1.5GHz. On the other hand, the electromagnetic wave tends to propagate outside the SiC at 0.7GHz.

4. Analysis using waveguide theory

Here we will analyze the attenuation properties of the cylindrical dielectric waveguide which is regarded as a simplified model of the bullet-shape SiC absorber. Attenuation in a dielectric circular rod was studied by Elsasser and Chandler in detail[5][6]. The analytical solutions of the propagating modes are described in many textbooks. We shall follow the notation in the textbook by Kawakami [7]. We will choose a cylindrical coordinate system $r, \theta, z$ with the $z$ axis lying along the guide axis. The radius of the rod will be $a$; dielectric constants inside and outside the rod will be $\epsilon_1$ and $\epsilon_2$ (which are assumed real numbers). The longitudinal components of the field vector are, inside the rod,

$E_z = A_n J_n(\beta_n r) \cos(n \theta + \delta_n) e^{j\omega t}$
$H_z = B_n J_n(\beta_n r) \sin(n \theta + \delta_n) e^{j\omega t}$

with $\beta_n = (\omega^2 \epsilon_0 - \beta_n^2)^{1/2}$ and outside the rod,

$E_z = C_n K_n(\alpha_n r) \cos(n \theta + \delta_n) e^{j\omega t}$
$H_z = D_n K_n(\alpha_n r) \sin(n \theta + \delta_n) e^{j\omega t}$

with $\alpha_n = (\beta_n^2 - \alpha_n^2 \epsilon_2 \mu_0)^{1/2}$

where $J_n$ is a Bessel function; $K_n$ is a modified Bessel function. $K_n$ decreases exponentially for large values of $r$.

The continuity of the tangential components of the field at the boundary $r=a$ gives the following relation.

$\frac{\eta_1}{\epsilon_1} + \frac{\eta_2}{\epsilon_2} = \frac{\eta_1}{\epsilon_1} \frac{\epsilon_0}{\omega} \frac{\mu_0}{\mu} \frac{\epsilon_2}{\epsilon_2}$

Or

$u + w = \frac{\eta_1}{\epsilon_1} \frac{\epsilon_0}{\omega} \frac{\mu_0}{\mu} \frac{\epsilon_2}{\epsilon_2}$

where $u = \beta_n a$, $w = \alpha_n a$, $\eta_1 = J_n(u)/(J_n(u))$, $\eta_2 = K_n(w)/(K_n(w))$.

In addition, $u$ and $w$ are related by the equation

$u^2 + w^2 = \frac{\eta_1}{\epsilon_1} \frac{\epsilon_0}{\omega} \frac{\mu_0}{\mu} \frac{\epsilon_2}{\epsilon_2}$

or

$\frac{\eta_1}{\epsilon_1} \frac{\epsilon_0}{\omega} \frac{\mu_0}{\mu} \frac{\epsilon_2}{\epsilon_2}$

From the equation (4-1) the values of $u$ and $w$ of the HE_{11} mode $(n=1)$ are obtained by numerical calculations. These are shown in figure 6. On the other hand, the equation (4-2) expresses a circle on the $u-w$ coordinate. The radius of the circle is $\omega k_0 (\epsilon_1 - \epsilon_2) \mu_0 \eta_1^{1/2} = \nu$. Numerical solutions are obtained by the intersections of the circle (expressed by (4-2)) with the curves in Fig. 6. No matter how small $\nu$ becomes, even at $\nu=0$, there is always an intersection. This means that this mode has no cutoff frequency.

In order to evaluate the field outside the rod, we will pay attention to the value of $w (\equiv \alpha_n a)$. When $w$ is large enough, $K_n(w)/(\eta_1 \epsilon_0 \mu_0)$ decreases rapidly as $r$ increases, then the outside field of the propagating mode is confined near the rod surface. Figure 6 shows that $w$ increases abruptly above the same value of $u$, especially when $\epsilon_1$ is large. Above this value of $u$ the solution of $w$ becomes large with extreme rapidity with small increase of the...
Figure 6: The values of $u$ and $w$ of the HE$_{11}$ mode ($n=1$) are obtained by numerical calculations. A quarter of the circle is given by equation (4-2).

circle radius ($=v$) of (4-2). Let us define this critical value of $v$ as $v_r$. When $v$ is smaller than $v_r$, the field is spread out and only small amount of the field exists inside the rod. On the other hand, when $v$ is larger than $v_r$, the field concentrates inside the rod and near the rod surface. If the dielectric waveguide is lossy, the attenuation change abruptly at $v=v_r$. Since $v$ is a function of $\omega$, $a$ and $\varepsilon_r$, indicated in (4-2), the attenuation properties strongly depend on these three parameters. It should be noted here again that the absorption properties of the SiC depend on the parameters. Figure 7 shows $w/a(=\alpha_f)$ as a function of frequency for three radii of the rod. The values of $w/a(=\alpha_f)$ are plotted in figure 8 as a function of frequency for three dielectric constants of the rod.

The critical frequencies indicated by arrows in figures 7 and 8, which correspond to $v_r$, show good agreement with those of the SiC absorber shown in figures 2 and 3.

5. Conclusion

The frequency response of the bullet-shape SiC absorber can be explained as the attenuation properties of the cylindrical dielectric waveguide in which the HE$_{11}$ mode propagates. The electric field pattern of the propagating mode dominates the frequency response of the SiC absorber mainly. This dielectric waveguide model gave us much information to design the bullet-shape and similar type absorber. The result of this analysis suggests that a thicker SiC absorber rather than the present design would be better. Furthermore, a shorter absorber design would be possible because the length of the absorber is not so effective to the frequency response. The design of a new SiC absorber is being under way.

6. Acknowledgment

The author would like to thank T. Kageyama for valuable discussions.

7. References

RF system of SPring-8 Linac

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Abstract
The construction of the SPring-8 linac (2856 MHz, 60 pps) was started in 1991 March. In 1993, we modified the design of Linac RF system. We choose new 80 MW klystrons, instead of 35 MW klystrons. With this situation, RF power from one klystron is led to two accelerating structures, instead of one accelerating structure. This linac is composed of 13 high power klystrons and 2 medium power klystrons with 26 accelerating structures.

I. INTRODUCTION
The 2856 MHz RF system of SPring-8 linac is shown in Fig. 1. This system is composed of three systems. One is the injector (buncher and pre-bunchers) line and the driver system of main klystrons by the booster klystron. The injector line is already completed and tested in Tokai establishment of JAERI [1]. This system ware transferred from Tokai to Harima in summer 1995. Next is the phase measurement system with the reference line. Last is the high power RF system with wave guide circuit. There are required the phase stability of 2 degrees on the beam line.

II. BOOSTER KLYSTRON AND DRIVE LINE
The 2856 MHz low-level CW output of a highly stable master oscillator is divided into two signal lines. One is provided for the booster klystron through a pulse modulator and a 300 W TWT amplifier. The other provides for the reference line through the 1 W CW amplifier to the phase measurement system.

The output of the booster klystron is fed into the injector line (two prebuncher and buncher). Drive line is divided by a 6-dB directional coupler from injector line. The injector line is filled with 2 kg/cm² SF6 gas. In the drive line, about 1 MW RF power that controlled by DRφA with SF6 gas is provided in pressured dry air at 2 kg/cm². Each fo these klystrons are driven by RF (about 1 kW), branched by directional coupler, from the drive line with IφA (Isolator, Phase shifter, Attenuator).

III. PHASE MEASUREMENT SYSTEM
For high stability beam control, the RF system needs phase measurement and feedback system. The drive line consists of an 120 m length copper wave guide. The phase of the drive line for last klystron drifts by 11.2 degree/°C. For correction of the phase drift, φCMP detects a phase drift by comparing with the standard phase of the reference line.

The reference line is the phase stabilized coaxial cable (Mitsubishi Cable). Electrical length of this cable is stabilized at 2 PPM/°C (0.5 degree/°C at 140 m). The standard phase of the reference line is picked up from the long pulse beam (or the monitor directional coupler of the buncher). The beam phase after II0 accelerating structure is detected by a waveguide type pickup cavity (only long pulse mode).

The output of the phase discriminator after sample hold is fed the VME analogue modules. The VME control the IφA of the klystron input of the drive line.

When the linac was driven in the long pulse (1 μs beam width) mode, the beam phase with the pickup cavity can duplicate to the reference line using the phase shifter after the CW AMP in Fig.1. On the shortpulse or single pulse mode, we will use the
buncher input phase instead of the pickup cavity.

**IV. HIGH POWER RF SYSTEM**

The first accelerating structure (H0 accelerating structure in Fig. 1) is powered by one 80 MW klystron (Toshiba E3712). After the second accelerating structure, the RF power from one 80 MW klystron is divided by a 3 dB directional coupler, and fed to two accelerating structures exclude the e⁺/e⁻ converter section. It is important to control optimized phase and power for the positron converter section. The accelerator structure of the converter section (M1 section in Fig. 1) is driven by the 35 MW klystron (MELCO PV3035) as 1:1 drive.

For a 1.15 GeV electron beam, the RF power of 26 MW is fed into all accelerating structures that produce an electric field gradient of about 16 MeV/m. As we have some margin when one or two klystrons faults, we should keep the linac energy for injection by the rest klystron.

Each klystron is driven by traditional a 190 MW pulse modulator [3] with a flat top of 2 μs within the voltage fluctuation of ±0.5 % at 60 pps. This modulator output will be lead to main klystron with the 1:16 pulse transformer. The voltage stability ofPFN charging is achieved of ±0.5 % using the De-Q'ing method.

Wave guide circuits is composed of RF windows, 3 dB directional couplers, vacuum pumps and phase shifters. As the wave guide is fevered by about 50 °C increment at 80 MW without cooling, it is cooled by water of the ordinary water cooling system. On one side route to behind the 3 dB directional coupler, a high power phase shifter is prepared. By this, each phase of accelerating structure can be controlled.

Recently, the high power test of the wave guide circuit was carried out by Toshiba Co'. The result and the photograph are shown in Fig 2 and Fig 3 [4]. A large RF power up to 80 MW-4 μs-60 pps shall pass through the wave guide system. Critical components
such as ceramic-RF-window and a phase shifter are adopted in this high power system. After 420 hours aging process a stable operation with the maximum RF power was realized. Especially, the high power phase shifter was operated in the full RF power without breakdown.

V. CONCLUSION

The installation of the linac is started in May, 1995 in Harima. RF system will be started to install in October, 1995. The aging of the waveguide circuits will be started in April, 1996. And the first beam commissioning of this linac will start at the first of August 1996.

References


MODULATORS FOR SPring-8 LINAC

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Abstract

Pulse modulators for 80MW klystrons (TOSHIBA E3712) had been designed. The modulator is a line-type pulser, consists of rectifier section (a rectifier circuit, IVR and step-up transformer), charging section (de'Qing circuit) and discharging section (PFN). In the charging section, re-chargeable de'Qing circuit are used, and the discharging section is composed of four parallel coupling type PFN (Pulse-Forming-Network). A first modulator was already constructed and tested in June 1995. The test data were good enough compared with design parameters. In this paper, modulator design are mentioned, and performance test are reported.

1. Introduction

As the SPring-8 is a commercial operating machine, it is to be desired that shutdown or maintenance time is shorter as possible. So even if one or two klystrons failed, beams of which energy is more than 1GeV has to be provided, to the Synchrotron. For this reason, we selected TOSHIBA E3712's, of which peak output power are 80MW, for main klystrons. The number of E3712's are 13, and each klystron feeds rf power to two accelerator structure except of first klystron for just after bunching section. Usual operating power from E3712 klystron will be about 52MW compared with design parameter of 80MW.°

So in this system, 13 sets of 190MW Modulators for E3712 are required. Design of the modulator had been accomplished and now, 7 units of modulators are delivered to the SPring-8 site, another 6 modulators are now under construction by TOSHIBA Corporation. All modulators will be delivered to SPring-8 site until this November.

2. Design of Modulator

The modulator is separated into two units, control unit and high voltage circuit unit. Size of the high voltage circuit unit is 3900Wx1900Dx2300H. The control unit are mounted in two 19 inch racks. The parameter of the modulator is shown in Table.1. Outline of circuit is also shown in Fig.1.

2.1 Rectifier Section

The rectifier section consists of IVR, step-up transformer, and rectifier circuit. Input voltage of the IVR is 3φ420V, and output voltage is 580V maximum. We selected the IVR that minimum output voltage is 260V, not 0V, so that it is smaller compared with the same class IVR. Output voltage of the step-up transformer is 25kV maximum. In order to keep phase balance, halves of the 13 modulators are delta-star connection, and others are delta-delta connection. Input power of the modulator is 95kVA.

2.2 Charging Section

For regulating charging voltage, we adopted a de'Qing circuit in a usual way. A de'Qing circuit is a re-chargeable type circuit21, and has a range of 7% regulation. Almost all energy stored in charging choke are fed back to the rectifier circuit. So This section can be made compact.

2.3 Thyatron

Originally, thyatron F-157 (ITT) is adopted as switch tube.31 Its maximum anode voltage and current arc 75kV and 15,000A respectively. These tubes are mounted in several modulator and tested for two months. But pre-fire trouble were appeared. The number of pre-fires are different in each tube case, they were averagely occurred twice or three times during 8 hours operation. So we decided to replace thyatrons. New thyatron is F-351 (ITT). It is remodeller of F-241, which has been used at SLAC for many years and had few pre-fire trouble. But F-351 is a new tube and does not have operation data. Maximum anode voltage is 55kV and current is 10,000A. Major difference between F-351 and F-157 is the number of gaps. F-157 is three gap type but F-351 has two gaps.

Table.1 Modulator parameters

<table>
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<td>Output Voltage</td>
<td>391kV</td>
</tr>
<tr>
<td>Output Current</td>
<td>474A</td>
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<td>Pulse Width (FWHM)</td>
<td>5 μsec</td>
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<td>Pulse Width (flat top)</td>
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<td>Voltage Regulation at flat top</td>
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<tr>
<td>Regulation Value of de'Q</td>
<td>±7%</td>
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<tr>
<td>Pulse Trans. Turn Ratio</td>
<td>1:16</td>
</tr>
</tbody>
</table>

- 76 -
So F-351 is more compact and volume of inner gas are smaller compared with F-157. Two F-351’s are tested in two different modulators individually. There were no knock out during 8 hours operation.

2.4 Discharging Circuit

Design value of pulse width of flat top is more than 2μsec with fluctuation of less than ±0.5%. In order to obtain this design, pill-box type oil condensers, of which leakage inductance are less than 250nH (This includes value of circuit between the condenser and an analyzer) are selected for pulse-forming-network (PFN) condensers. And moreover, pairs of adjoining coils in the PFN have mutual inductances which decrease leakage inductance of the condenser equivalently. In this case, value of mutual inductance is arranged equal to the leakage inductance. But it is difficult to form large mutual inductances. So in order to obtain small leakage inductance of the condensers, we selected small capacitor. Therefor, the PFN forms 4 parallel networks. Each network has 14 sections. Capacitance is 0.015μF, and maximum voltage is 50kV. Simulation data of this coupling type PFN cleared the fluctuation level.

Impedance of the PFN is about 3.3Ω. The PFN is designed not to be negative mismatch, but slightly positive mismatch during discharge. But if positive mismatch keeps after discharge, stored energy in primary side of pulse-transformer backs to the PFN and the condensers become to have initial storage charge. In order to avoid this, the PFN designed to be slightly negative mismatch after discharge and the storage charge of condensers are discharged by shunt circuit.

Assemblies of modulator output cable are triaxial, made by STANGENES, where two cables are connected parallel to a pulse-transformer tank. A pulse transformer and the tank are also made by STANGENES.
2.5 Control

The modulator itself is controlled by a sequencer unit, and communicates to the upper control system through VME boards, which are mounted near the modulator body. An analog signal between the sequencer and the modulator are range of less than 10V. So it is very important to reduce noise level of the modulator. Three kinds of filters, isolators, passive filters or bypass condensers, are inserted in cable lines.

3. Test Results

Now 7 modulators had finished performance test and all of them achieved output power level (see Table.1) which are needed to drive klystrons.

Fig. 2 shows the fluctuation of klystron beam voltage with connection to a dummy klystron. These waveforms are after 8 hours operation with keeping full power. Length of pulse top with fluctuation of less than ±0.5% are about 2.1usec in each case.

Noise level of the analog signal connected between the sequencer and the VME board are observed. Magnitude of signal is 10V maximum but there was spike noise of about 20V at the point of thyratron trigger. Earth level fluctuations or noise at another timing were not occurred. Something like LC filters for reducing the spike noise are needed.

Control test from the VME had been also done. We could confirm expected communications.

4. Conclusion

Halves of the modulators have been constructed and they were cleared the design value. Noise level were relatively smaller than predicted level.

All modulators are accomplished by this November and operation start will be next year April.

5. References


Abstract
A ferrite loaded untuned type RF cavity has been fabricated and tested for a compact proton synchrotron dedicated for medical use. Using a new power-feed method named as multi-feed coupling, a gap voltage of more than 1kV has been achieved with the generator power of 1.5kW in the frequency range from 1.5MHz to 10MHz. These values satisfy the requirement of a few hundred volts for the medical synchrotron. The multi-feed coupling has been confirmed to be effective by high power tests. The temperature rise caused by power loss in ferrite cores was less than 25 degrees up from the room temperature at 2 hours after the start of the power feeding when the generator power was 1kW. This cavity can therefore be operated only by the forced air cooling system.

1. Introduction
Nowadays a compact proton synchrotron has been hoped to be used efficiently for treatment of tumors. We proposed a medical compact proton synchrotron which consists of combined type magnets with the circumference of about 23m[1]. In the compact synchrotron, due to its short circumference, the cavity voltage required in an acceleration process is relatively lower than that of a large synchrotron, though a wider operating frequency range is needed. Based on this condition, an untuned type RF cavity in which the tuning procedure of resonant frequency is not necessary, has been adopted as an accelerating system for the synchrotron[2]-[3].

Untuned type RF cavities have already been constructed in several laboratories[4]-[7]. These cavities consist of a quarter or a half wavelength coaxial resonator and magnetic materials with large permeability. Power loss caused by the imaginary part of the complex permeability in the magnetic materials plays an important role in obtaining a wide operating frequency range. However, in general, this effect makes it difficult to get a high accelerating voltage in the untuned type RF cavities. We have developed a new power-feed method named as multiple power feeding(multi-feed coupling) so as to increase the accelerating voltage over a wide frequency range compared with the conventional direct or push-pull power feeding. In section 2, the principle of the multi-feed coupling is described in brief. The construction of the high-power model cavity and experimental results of the multi-feed coupling are mentioned in section 3.

2. Multiple Power Feeding
An untuned type RF cavity is characterized as a simple RLC resonant circuit, in which R, L and C correspond to the resistance of the cavity, the inductance of the magnetic materials (ferrite cores) to obtain a wide operating frequency range, and the capacitance of the accelerating gap, respectively. In the direct coupling which is the usual method of power feeding, RF power generated by the power source is fed into the inner conductor directly and returned to the source through the outer conductor. The cavity voltage \( V_d \) is given as

\[
V_d = \sqrt{2P \left| Z_d \right| / (1 + S)}
\]

where \( P \), \( P_g \), \( Z_d \) and \( S \) are the net power, the generator power, the shunt impedance of the cavity and the value of voltage standing wave ratio(VSWR), respectively. The \( Z_d \) depends only on the inductance L of the ferrite cores because their permeabilities are large enough to get the wide operating frequency range. As \( Z_d \) increases, a large impedance mismatching between the cavity and the power source occurs and almost all of the generator power is reflected back to the source. The \( V_d \) cannot be in-

Fig. 1. Equivalent Circuit in Multi-feed Coupling.
creased because of the decrease in the net power fed into the cavity. The reflector power becomes too large to operate the power source under this condition. This effect is the main cause of lower accelerating voltage in the untuned type RF cavity.

In order to reduce the reflection power and increase the cavity voltage, the impedance mismatching must be improved keeping the cavity impedance higher. A new power-feed method, hereafter we call multiple power feeding (multi-feed coupling), was developed to solve this problem. Figure 1 shows the equivalent circuit in multi-feed coupling. The cavity and the generator are divided into the same number of sub-circuits as the loaded ferrite cores. Assuming \( n \) the loaded number of the ferrite cores, the cavity is represented by the series connection of \( n \) sub-circuits whose impedance is one-nth of that of the direct coupling. The coupling impedance between the cavity and the power source can therefore be decreased to one-nth while the total impedance is equal to that of the direct coupling. In this scheme, the reflection power is much reduced and the cavity voltage is increased by the series connection of the sub-circuits. The cavity voltage in the multi-feed coupling \( V_m \) is given by

\[
V_m = \sqrt[2]{\frac{2P}{Z_n}}
\]

\[
= n\sqrt{\frac{2}{\frac{4S/n}{(1+S/n)^2}} \frac{P_d}{n^n} Z_d}
\]  

where \( Z_n \) is equal to the impedance of the sub-circuit given by \( Z_d/n \). If the VSWR is large enough, \( S>>n>1 \), \( V_m \) can be \( n\) times larger than \( V_d \). However, if the VSWR \( S \) is nearly equal to \( n \), \( S=n>1 \), \( V_m \) can be \( \sqrt{n}/2 \) times larger than \( V_d \). Hence, in the real cavity, \( V_m \) is expected to be between \( \sqrt{n} \) and \( \sqrt{n}/2 \) times of \( V_d \). In this analysis, mutual inductances between the ferrite cores are ignored.

3. High Power Experiments

3.1 High-Power Model Cavity

In low power level, the effects of multi-feed coupling have already been verified[2]-[3]. To confirm RF and thermal characteristics in the multi-feed coupling, the high-power model cavity has been fabricated and tested. The cavity has been constructed with a double re-entrant coaxial resonator and Ni-Zn ferrite cores manufactured by Hitachi Metals Ltd. The outer and inner diameters are 550mm and 160mm, respectively. The lengths of the cavity and the accelerating gap, vacuum-sealed by ceramic duct, are 400mm and 20mm, respectively. Photo 1 shows the high-power model cavity. The dimensions of the ferrite cores installed in the cavity are 500mm and 280mm in outer and inner diameters, respectively and 25.4mm in thickness with the complex permeability of about \((1000,100)\) at 5MHz. The number of ferrite cores is 8 to increase the cavity voltage. In the multi-feed coupling, the same number of independent RF-power amplifiers are employed. The RF power is fed into the cavity through the one-turn coil wound on each ferrite core in such a way that the magnetic flux is generated in the same direction. At first, low power tests were performed to measure VSWR using a network analyzer. The experimental results show that the cavity can be operated from 1MHz to 10MHz which satisfies the proposed specification of the operating frequency range from 1.57MHz to 8MHz[1].

3.2 Measurement of Cavity Voltage

Figure 2 shows the block diagram of measurements. The cavity voltage induced at the accelerating gap was measured with a voltage divider connected to the direct coupling loop. The voltage divider consists of capacitors of 1pF and 100pF, giving the dividing ratio of 1/100. Figure 3 shows the dependence of the cavity voltage on the generator power and the operating frequency. The generator power \( P_d \) means the total power toward the cavity. Up to 2kW, RF power can be fed into the cavity stably in the multi-feed coupling. The cavity voltages at the frequency of 2MHz, 4MHz and 8MHz are indicated with blackened circles, squares and open circles, respectively. It is obvious that the cavity voltage of more than 1kV was achieved with almost flat property in the required operating frequency range from 1.5 to 8MHz. The experimental result satisfies the voltage of 500V required for a medical compact proton synchrotron. Figure 4 shows the frequency dependence of the cavity voltage normalized by the value in the case of the direct coupling. Measurements with the
feed power of more than 200W were not carried out in the
direct coupling, because the waveform of the cavity volt-
age was deformed. The figure presents the measured val-
ues at \( P = 200W \). Blackened circles and solid line indicate
the experimental results and the calculated values, respec-
tively. The latter is obtained from equation (2) by using the
VSWR measured by the low power experiments. Mea-
sured and calculated values are in good agreement. Mean
value of the voltage ratio is 1.8 which can be explained by
equation (2) substituting \( n=8 \) and \( S=13 \). It also confirmed

the effects of the multi-feed coupling.

The cooling system consists of only two forced air-
cooling fans which are attached to the lower part of the
outer conductor. The temperature rise of the cavity wall
and ferrite cores was measured under \( P = 1kW \), and the
highest values are plotted in figure 5. The temperature
reached the equilibrium value, namely, 25 degrees up from
the room temperature, at 2 hours after the start of the
power feeding. The result shows the cavity can be driven
only by the forced air-cooling.

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Construction of 100 MeV Electron Linac in Kyoto University

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Abstract

An electron linear accelerator and a compact storage ring have been constructed at Kyoto University. The beam energy of the storage ring is 300 MeV and will be utilized as a synchrotron radiation source. The output beam energy of the linac is 100 MeV and the designed beam current is 100 mA at the pulse width of 1 μsec. The construction of the linac had been finished and the test is under going. The electron beam of 300 mA is extracted from the electron gun and the peak RF power of 20 MW is successfully fed to the accelerating structures at the pulse width of 2 μsec.

1. INTRODUCTION

A compact electron storage ring (Kaken Storage Ring, KSR) and the linear accelerator are now under construction at the Institute for Chemical Research, Kyoto University [1]. The layout of the accelerators is shown in Fig. 1. The KSR has a race track shape and the maximum beam energy is 300 MeV. It will be used as the synchrotron radiation source from the dipole magnet and the insertion device. The critical wave length of the synchrotron radiation is 17 nm. It will be also used for the research of the free electron laser.

The beam energy of the electron linear accelerator is 100 MeV. Table 1 shows the main beam parameters. For the linac construction, some components of the JAERI linac were transported from the Japan Atomic Energy Research Institute (JAERI) to the Kyoto University [2]. The linac is used for the beam injection to the KSR and some beam experiments. The beam parameters are determined by the condition of the beam injection to the KSR and the restriction of the size of the building. Photo 1 shows the view of the front part of the accelerator. The electron gun, the buncher, and the first accelerating structure from the right to left.

Table 1 Beam parameters of the linear accelerator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>1 μsec</td>
</tr>
<tr>
<td>Maximum Repetition</td>
<td>20 Hz</td>
</tr>
</tbody>
</table>

Photo 1 View of the front part of the accelerator. The electron gun, the buncher, and the first accelerating structure from the right to left.

Figure 1. Layout of the electron linac and the KSR.
of the front part of the accelerator.

2. ACCELERATOR

The electron gun has the Pierce electrode and the cathode assembly is the Y-796 (Eimac). The maximum extraction voltage is -100 kV. The pulse width of the grid pulser is variable from 10 nsec to 1 μsec. The beam current of 300 mA has been achieved at the pulse width of 1 μsec.

The pre-buncher is a single reentrant cavity. It is designed to bunch the beam within the phase spread of 60 degree. The buncher is a disc-loaded and 3 step constant gradient structure. It has 21 cells and the total length is 777 mm. The designed phase spread is within 3 degree at the beam current of 100 mA when the input power is 12 MW.

There are three main accelerating structures. The main characteristics of the accelerating structure are listed in table 2. The maximum electric field is 45 MV per an accelerating structure without beam loading at the input power of 20 MW.

The doublet of the quadrupole magnets is used as a focusing element between the accelerating structures. The calculated beam radius along the beam axis is shown in Fig. 2. It is assumed that the normalized emittance is 100 π-mm-mrad. The calculated beam radius is kept within 6.5 mm along the beam axis. The steering coils are placed at the entrance of the first and the third accelerating structures.

3. RF SYSTEM

The block diagram of the RF system is shown in Fig. 3. The master RF oscillator is a synthesized signal generator (HP-8664A). The booster klystron (TH-2436, Thomson) has a gain of 40 dB and the output power is 10 kW. The pulse width is 3.5 μsec. The output power is divided by the 4-way RF divider and supplied to the four main klystrons. RF attenuators and phase shifters are inserted between them.

The main klystron is ITT-8568. The maximum output power is 21 MW. Figure 4 shows the input RF power of the buncher and the three accelerating structures. The peak RF power is 12 MW at the buncher and 20 MW at the accelerating structure. The RF frequency is 2857 MHz and the repetition is 7 Hz. The RF pulses are picked up by the directional couplers and detected by the RF diodes.

The modulator is composed of the high voltage power supply, the pulse forming network (PFN) and the pulse transformer. The stabilized power supply for the modulator is

<table>
<thead>
<tr>
<th>Table 2 Main specification of the injector.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron Gun (Pierce type)</strong></td>
</tr>
<tr>
<td>Cathode Assembly</td>
</tr>
<tr>
<td>Extraction Voltage</td>
</tr>
<tr>
<td><strong>Accelerating Structure</strong></td>
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<tr>
<td>Mode</td>
</tr>
<tr>
<td>Number of Cell</td>
</tr>
<tr>
<td>Bore Radius</td>
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<tr>
<td>Length</td>
</tr>
<tr>
<td>Operating Frequency</td>
</tr>
<tr>
<td>Maximum Electric Field</td>
</tr>
<tr>
<td><strong>Klystron (ITT-8568)</strong></td>
</tr>
<tr>
<td>Cathode Voltage</td>
</tr>
<tr>
<td>Output RF Power</td>
</tr>
<tr>
<td>Gain</td>
</tr>
</tbody>
</table>

Figure 4 Input RF pulse to the buncher and the three accelerating structures. The peak power is 12 MW and 20 MW, respectively. The repetition is 7 Hz.

Figure 2 Calculated beam radius along the beam axis. The normalized emittance is assumed to be 100 π-mm-mrad.
adopted to keep the electron beam energy constant. The maximum voltage is 25 kV and the current is 500 mA. The voltage stability is less than 10⁻³. It feeds the electric power to the three PFNs for the accelerators at the repetition of 20 Hz.

4. BEAM MONITOR

The current monitor is installed between the accelerating structures. The monitor is the ferrite core with the coil. The current sensitivity is 1 mV/mA.

The beam profile monitors will be installed at the close to the current monitors. The material of the beam screen is an alumina ceramic in which a little chromium oxide is homogeneously doped (Desmarquest, AP995R). The beam profile monitor is also used for the emittance measurements combined with the upstream quadrupole magnets.

5. CONTROL SYSTEM

The block diagram of the device control system is shown in Fig. 5. The controller units have the GP-IB interface and connected by the optical fiber each other. The fiber cable isolates each devices and reduces the noise. The master controller is a personal computer IBM-PC/AT with ISA GP-IB card (AT-GPIB, National Instrument). The control software works on the Microsoft Windows system. A user can operate by the mouse or a touch panel.

6. SUMMARY

The construction of the 100 MeV electron linac had been finished and the tests of the main components such as the klystrons and the electron gun were carried out. We succeeded to feed the 20 MW into the accelerating structure at the repetition of 7 Hz. The conditioning work is now in progress. The beam acceleration test of 100 MeV is scheduled in autumn 1995.

7. ACKNOWLEDGMENTS

The authors have grateful thanks to the Dr. Kobayashi and Dr. Shoji at JAERI for their advises about the electron linac. We also thank to Mr. Shoda and the staffs of the Nihon Kensetsu Kogyo Co Ltd. for their work. Mr. Kazama at ICR helped us for the construction and we would like to present our thanks to him.

REFERENCES

§1. INTRODUCTION
The purpose of this study is to propose an aluminum chamber with superior performance and high reliability at low cost for the recycler ring in Fermilab. Key performance advantages of aluminum chamber and components in comparison to stainless steel are provided with the requirements needed for developing the recycler ring. Analysis and actual case experience indicates that when stainless steel components are irradiated by antiproton beams, melt-down can occur, but not aluminum as it has a very high tolerance.

It is understood that the antiproton storage ring has basically no effect of dynamic outgassing. However, for high current proton storage ring such as CERN-ISR had dynamic gas desorption effect. Antiproton ring has negative potential, then ionized ion is trapped within antiproton beam.

§2. BENEFITS OF ALUMINUM
Extrusion is possible to make elliptical chamber with heater groove as shown in Fig.1.

Clean extruded pipe has very low specific outgassing rate, $Q_0$ at 150°C, 24 hours baking with following performance: Torr s cm$^{-2}$

- 99.99% high purity aluminum: $2 \times 10^{-14}$
- guaranteed high purity aluminum: $10^{-13}$
- without bakeout of aluminum: part in $10^{-10}$
- originally proposed stainless steel: $10^{-12}$

Based on the aluminum vacuum system performance characteristics, the major advantages are:

1. Reduce pumping speed of ion pumps.
2. Extend distance between ion pumps.
3. Before baking residual gas is mainly water after baking residual gas is mainly hydrogen. If bakeout by chemical process of COF$_2$ is employed, a vacuum of $10^{-10}$ Torr region can be achieved with a mild bakeout 80°C instead of the normal temperature of 150°C.

4. Energy loss $dE/dx$ is proportional to material density, $\rho$ and atomic number squared of the material, $z^2$. The localized high heat flux for aluminum was more than several ten of times higher than stainless steel material against melt-down and the fine leak from the flanges.

Temperature distribution of localized heat flux irradiated flange is shown in Fig.2 due to low energy loss and high thermal conductivity.

Fig.2 Temperature distribution irradiated from localized high heat flux against stainless steel and aluminum.

§3. VACUUM BEAM CHAMBER
A. Beam chamber
Circumference of the ring is about 3,300 m long. Since the bending angle for half cell is less than 1°, it is not necessary to provide a bending process for bend beam chamber. Extruded aluminum tube with elliptical aperture and heater groove are used for bending magnet and quadrupole magnet chambers. Length of the unit beam chamber is about 17 m long. Thickness of the elliptical chamber is 4 mm. Total number of 17 m long beam chamber is about 200 pieces along the entire ring. Using automatic welding beam chamber, beam position monitor and bellows can be joined without flanges as shown in Fig.3.

End of the chamber against gate valve has flange. The design and construction of bellows for 17 m long vacuum beam chamber require thermal expansion and contraction of about 34 mm for 100°C temperature rise during baking procedure.

Fig.3 Half cell beam chamber of 17 m long consists of bellows, beam position monitor joined automatic welding without flanges.

Flanges for the pumping manifold ICF-114 and the gauges ICF-70 are adopted on the vacuum chamber. Gate valve will be used aluminum alloy products. The distance of the gate valve is about 150 m long.
D. Beam chamber material

The high purity 99.99% aluminum should be used to minimize adsorption and desorption from the chamber wall. The high purity aluminum are produced by gas bubbled flushing of argon and halogen mixture to reduce the internal hydrogen to less than 0.05 cm³/100g-Al. A special extrusion process using an oxygen and argon mixture with water content in the 10 ppm range is used in the chamber to keep the surface clean. Depth profiles of the oxide layer of the EX extruded surface were analyzed by Auger electron spectroscopy. It was found that the oxide layer for the EX extruded surface was about 30 Å thick. On contract, the oxide layer for an ordinary extruded aluminum surface is 120-180 Å thick.

C. Beam position monitor

Beam position monitors are required for every quadrupole magnets. Total number of the beam position monitors are about 200 pieces. Primary candidate for beam position monitor is electrostatic pickup type. The cut electrodes which as an elliptical aperture same as beam chamber are installed in aluminum housing. The electrodes are made from titanium plate. Assembled electrode is mounted on aluminum flange using ceramic insulators. Output signals are fed using non-magnetic SMA coaxial feedthroughs. The housing utilize extruded aluminum tube. After installation of electrode inside the housing and calibration using wire as beam position monitor, the flange and the housing assembly are welded by electron beam welder.

D. Clean machining and surface treatment

Beam chambers, flanges, beam position monitors are machined using clean machining system, namely EX plasma process. EX plasma process means machining in clean oxygen and argon mixture environment with Corona discharge, thus producing ozone. The Ozone is extremely active with strong oxidation and cleaning effect. After the surface has been cleaned, high density non-porous oxide layer is formed with extremely low outgassing rate.

To eliminate additional carbon contamination, ozone treatment was applied on metal surfaces. The surface of aluminum without any treatment were exposed to ozone using dry air including ozone. No carbon was detected in the sputter profiled layer using Auger electron spectroscopy.

E. Flange, bellows and feedthrough

The aluminum alloy flange is compatible system for stainless steel CF type flanges. A basic feature of the system is the use of A2219-T87 die forged aluminum alloy. The knife edge is a mirror-finished surface, processed by a diamond tool. A titanium carbide coating is applied to the surface of the knife edge by ion plating. TiC treatment on the knife edge provides nearly perfect protection from sticking between the knife edge and the gasket, and against surface scratches. The machined gasket is A1050-H24. The combination system of an aluminum alloy and an ordinary stainless steel CF flanges using aluminum gasket and aluminum alloy bolts are leak-tight during thermal cycles.

Aluminum alloy A3004 seamless bellows are produced by hydraulic forming of a seamless tube and provides the most uniform wall thickness with the longest fatigue life. The thickness of the corrugated part of the bellows is 0.3 mm while the thickness of the welding edge is 4 mm. This bellows has life time of more than 1,000 cycles for ±5 mm expansion and 35 mm contraction. RF shield is not necessary inside the bellows due to long beam bunches.

SMA type feedthrough has good RF characteristics over a frequency range of DC-4 GHz. These coaxial types made of aluminum and ceramic brazed are useful for beam position monitor. The outer shield can be welded using electron beam welder to aluminum housing.

F. Automatic welding assembly

Automatic welding equipment for an elliptical chambers were developed for small size, light in weight, easy to handle, and ensures uniform penetration. This equipment is designed to move the TIG welding torch along the elliptical cross section of the vacuum chamber by adopting orbits. The arc torch is supported by automatic arc voltage controller with servo mechanism. Guide orbit of the automatic welder can separate two, and can adopt fixed beam chambers installed in bending and quadrupole magnets. Moving area of automatic welder is inside of 500 mm in diameter circle.

§4. PUMPING SYSTEM

A. Pumping system

Given the criterion of an average vacuum \(10^{-12}\) Torr range, the distance of lumped ion pumps of 30 l/s is determined on the assumed value of the specific outgassing rate \(Q_o\). Fig. 4 shows pressure distribution along the beam chamber against three kinds of specific outgassing of chamber and pump distance.

a) Stainless steel chamber: \(Q_o = 10^{-12}\) Torr l/s cm² and pump distance: 8.5 m long. This value is acceptable given in reference 1 and not acceptable.
b) Aluminum chamber: \(Q_o = 10^{-11}\) Torr l/s cm² and pump distance: 17 m long. This value is acceptable against requirement.
c) Aluminum chamber: \(Q_o = 10^{-14}\) Torr l/s cm² and pump distance: 36 m long. This value is expected as a margin.

![Fig. 4 Pressure distribution along the beam chamber.](image-url)
compared to the standard is recommended. A D-shaped I-V characteristic (fold-back over current protection) ion pump power supply was used in the TRISTAN without any problems.

Roughing pump system are transportable cart station. After starting ion pumps, roughing pump station of turbomolecular pump and dry-pump combination will be separated from the inlet seal right angle valve with manual operation. Dry-pump consists of diaphragm type and drag pumps combination. This combination is oil-free pump system. Distance of the roughing pump is about 70 m long. Two roughing pump stations are adopted inside section with 150 m separation by gate valves.

5. Operations

Estimated pumping time will be about several hours from atmospheric pressure to operating pressure of turbomolecular pump. Upon reaching to $10^{-10}$ Torr range using chemical process at 150°C instead of ordinary 150°C baking, sputter ion pumps operation is activated by a single ON switch for many of the ion pumps along the storage ring.

§5. PROTOTYPE BEAM CHAMBER FOR EVALUATION

The prototype beam chamber is two 17 m long with elliptical shape joined aluminum alloy bellows without flanges. Total length is 34 m long. The unit chamber of 8.3 m long has dummy beam position monitor, pumping manifold of ICF-114 and gauge port of ICF-70 flanges as shown in Fig.5. Ends of beam chamber are flanges of ICF-152. These flanges are only use for connect and disconnect for transportation. Two 30 l/s ion pumps are installed. A 50 l/s turbomolecular pump and dry-pump combination as a roughing pump is installed. All-metal seal right angle valve installed between the beam chamber and turbomolecular pump. Distance of the ion pump is 17 m or 34 m long. The expected ultimate pressure on the ion pump is $10^{-10}$ Torr range during the 150°C, 24 hours baking period.

The chemical process using COF₂ and fast pump-down process using super-dry nitrogen will be applied for the test chamber.

§6. KEY RECOMMENDATIONS

1) Construct extruded aluminum beam chambers, each 17 m long. The unit chamber installed with bellows, beam position monitor, pumping manifold.

2) Using automatic welding, beam chamber, beam position monitor and bellows can be joined without flanges.

3) Install ion pumps at a distance 17 m or 34 m apart to achieve the predicted ultimate pressure of $10^{-10}$ Torr range.

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References


Fig.5 A prototype beam chamber consists of dummy beam position monitors, pumping ports, gauge ports and bellows.
Conditioning of Positive Inflector Voltage for The Injection of Negative Ions at TARN-II

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Abstract

An ultrahigh vacuum of the order of $10^{-8}$ Pa has been kept to obtain sufficient beam life times for the beam experiments at TARN-II. Recently, positive high voltage was applied to inflector electrodes to inject $\text{H}^+$ ion beam in the ring. In this case, vacuum pressure rose up to the order of $10^{-6}$ Pa and residual gas components of CO and CO$_2$ remarkably increased. We tried to get a required inflector voltage at normal vacuum pressure by conditioning the electrodes. As a result, vacuum pressure was improved to $1.2 \times 10^{-8}$ Pa at high voltage of +44 kV.

1. Introduction

An ion storage/cooler synchrotron with an electron cooling system TARN-II has been operated for the studies of atomic physics and accelerator technology[1]. Vacuum pressure of the order of $1 \times 10^{-8}$ Pa is required to get sufficient beam life times for the beam experiments. The ring has a hexagonal shape with six long straight sections and has a circumference of 78 m. Ion beams from an SF cyclotron are transported through a beam line and injected into the ring by an electrostatic inflector system which was originally used at the former storage ring TARN [2,3]. Recently, positive high voltage, as well as usual negative voltage, was applied to the inflector electrodes to inject $\text{H}^+$ ion beam. Initially vacuum pressure increased to the order of $10^{-6}$ Pa. We tried to get the inflector voltage required to inflect the beam at a normal vacuum pressure by conditioning the electrode.

2. Electrostatic inflector

The inflector system is composed of successive one pair of electrode with an arc length of 300 mm and a gap of 8 mm. A mean radius of curvature is 5005 mm and an inflection angle is 6.9’. The septum electrodes are made of tantalum foils of 0.1 mm thick and are earthed to ground potential. The high voltage electrodes are made of stainless steel and supported by ceramic insulators. Designed maximum electric field at the gap is 100 kV/cm. Three beam probes are inserted at upstream, middle and downstream of the electrodes. The inflector system is shown in Fig. 1.

3. Conditioning

Usually, vacuum pressure of the order of $10^{-8}$ Pa has

Fig. 1. The plan and side view of the electrostatic inflector.
been kept at the beam time in which negative high voltage of about 50 kV was applied to the electrodes (for example 10 MeV-HeD). However, when positive high voltages were applied to the electrodes, a huge amount of outgassing occurred and the vacuum pressure at the long straight section (SI) in which inflector electrodes are equipped increased to the order of $10^{-8}$ Pa. Main outgassing was observed at the downstream inflector (inflector 2) and any change of vacuum pressure was not observed while a high voltage of +50 kV was applied to the upstream electrode (inflector 1).

In order to improve the deterioration of vacuum, two aging processes were applied to the electrodes. 1) positive high voltage aging.

When a high voltage of +60 kV at the inflector 1 was applied, electric leakage current was lower than 0.1 mA and any change of vacuum pressure was not observed. On the other hand, at the inflector 2, a high voltage was applied gradually to +45 kV. At this voltage, electric leakage current was 1.3 mA and vacuum pressure increased to $10^{-7}$ Pa. After recovery of vacuum pressure to the order of $10^{-8}$ Pa, the high voltage was increased to 48 kV. Such a conditioning was performed at the interval of about 10 hours per day. An example of vacuum pressure during conditioning is shown in Fig. 2. Vacuum pressures when high voltage switched on and switched off are shown by (A,B,C) and (1,2,3), respectively.

Improvement of the vacuum pressure by conditioning is shown in Fig. 3 (A). Vacuum pressures of HV on and HV off shown in Fig. 3 correspond to the pressures at (1,2,3) and (A,B,C) in Fig. 2. The accumulation time while high voltage was applied to the electrodes was shown as aging time. The total conditioning time of 100 hours was achieved with positive high voltage. The vacuum pressure was then decreased from $10^{-8}$ Pa to $3.5x10^{-7}$ Pa at high voltage of +60 kV and from $1.4x10^{-8}$ Pa to $1.2x10^{-8}$ Pa at +44 kV.

2) Negative high voltage aging.

Total conditioning time of 200 hours was achieved while a high voltage of -60 kV were applied to the both electrodes, inflector 1 and 2. Results are shown in Fig. 3 (B). The vacuum pressure decreased from $3.5x10^{-7}$ Pa to $7.2x10^{-8}$ Pa at a high voltage of -60 kV and from $1.5x10^{-8}$ Pa to $1.0x10^{-8}$ Pa at -30 kV.

In the case of positive high voltage aging, residual gas spectra at the high voltage on (A) and
off (B) were measured. Results after aging times of 30 hours are shown in Fig. 4. Variations of the residual gas components by the aging are listed in Table 1. Ratios of ion current at HV on and HV off, I(on)/I(off), are remarkable for the outgas components of CO and CO₂ at the aging time of 30 hours. However, the ratios decreased by a factor of 4 after 85 hours.

### Table 1 Variations of the residual gas components by the aging

<table>
<thead>
<tr>
<th>Gas</th>
<th>Ion current(au)</th>
<th>I(on)/I(off)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Holds</td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td>30</td>
<td>3.0x10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>2.0x10⁻⁷</td>
</tr>
<tr>
<td>CH₄</td>
<td>30</td>
<td>3.4x10⁻⁸</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>1.5x10⁻⁸</td>
</tr>
<tr>
<td>H₂O</td>
<td>30</td>
<td>5.5x10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>1.2x10⁻⁹</td>
</tr>
<tr>
<td>CO</td>
<td>30</td>
<td>1.2x10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>1.5x10⁻⁹</td>
</tr>
<tr>
<td>CO₂</td>
<td>30</td>
<td>6.7x10⁻¹⁰</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>7.0x10⁻¹⁰</td>
</tr>
</tbody>
</table>

We deduce that some oil vapor condensed on the electrode and the insulator, because the temperature of the inflector was lower than other parts of the vacuum chamber during the baking time.

### 4. Conclusion

1) When positive high voltage was applied to the inflector electrode to inject H⁺ ion, remarkable outgassing occurred and vacuum pressure increased to the order of 10⁻⁸Pa.
2) Improvement of vacuum pressure was achieved by conditioning the electrodes with positive and negative voltages. For example, vacuum pressure was improved from 1.4x10⁻⁸Pa to 1.2x10⁻⁹Pa at operation voltage of +44 kV.
3) We deduce that high residual gas components of CO and CO₂ come from pump oil which stuck to low temperature place during baking time. Baking at a temperature as uniform as possible for the whole system is important.

### References

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3) F. Soga et al., "Beam Transport and Injection System from the SF Cyclotron to the TARN-II Synchrotron Cooler Ring" INS-T-494(1990)
Abstract

A bellows assembly with an RF-shield has been designed for the KEKB collider. The RF-shield suppresses the excitation of the higher order mode (HOM) at the bellows gap and reduces the impedance. Our new-designed RF shield is a usual finger type but has extra spring fingers to ensure the sufficient electrical contact between contact fingers and beam duct. The wearing test is performed using an experimental model over 5000 expansion-contraction cycles with a 20 mm stroke and any mechanical problem is not found except for the dust production due to the abrasion. Since the abrasion depends on the contact force, the heating of the model is measured transmitting 80 kW of 508 MHz microwave in atmosphere for several contact forces and the necessary contact force, 50 g/finger, is obtained experimentally.

1. Introduction

The collider of the KEK B-factory consists of two rings, High Energy Ring (HER, for 8.0 GeV electrons) and Low Energy Ring (LER, for 3.5 GeV positrons). The average beam currents for the HER and the LER are 1.1 A and 2.6 A, respectively. The designed bunch length (σz) is 4 mm for both rings, which gives the strict limitation on the impedance of vacuum components [1]. For easy installation and alignment, about 750 bellows assemblies are to be installed in each ring and, therefore, are likely to be one of large impedance sources in the ring. The RF-shield has a role to flow the wall current as smoothly as possible and reduce the impedance [2-4].

The main criteria in designing the RF-shield is to keep a good electrical contact while absorbing the expansion and contraction during the beam operations. Failure to meet this criteria will result in electrical discharge and possible melting on the contact point [5]. Large enough contact force without excess wearing is required, but there has been no practical data for the contact force so far.

A bellows assembly with an RF-shield for the KEKB collider has been specifically designed to meet these requirements. The RF-shield is a usual finger type but has a special spring fingers to press surely the contact fingers on to the beam tube. The wearing test was performed using an experimental model. To find the necessary contact force, furthermore, the heating of the RF-shield was checked transmitting 508 MHz microwave through the model. We report here the structure of the bellows assembly and these experimental results.

2. Structure

A schematic drawing of the bellows assembly for the LER is shown in Fig.1. The RF-shield is composed of three parts, a inner tube, a contact finger and a spring finger (slide finger). The contact finger is positioned between the spring finger and inner tube. Since the contact finger is outside of the inner tube, the impedance of the bellows assembly is kept very small. For 1 mm thick inner tube, for example, the calculated broad band impedance (Z/n) and the loss factor (k) of a bellows assembly are 4.23×10⁻⁶ Ω and 2.5×10⁻³ Ψ/Pc, respectively for the LER. The electrical contact between the contact finger and the inner tube is ensured by the spring finger. Each spring finger is in contact with one contact finger with an appropriate force. The structure can be applied for not only the circular beam tube but the non circular one, such as racetrack or rectangular shape. Cooling water channels in the drawing should be attached to absorb the heat flux due to the reflected synchrotron radiation power, the joule loss and the higher order mode (HOM) loss [3].

Figure 2 shows the outlook of an experimental model of the bellows assembly (without bellows). The model is for the LER and has a circular cross section. The inner diameter is 94 mm and overall length is 160 mm. The spring finger and the contact finger have thickness of 0.4 mm and 0.2 mm, and widths of 4.6 mm and 5.5 mm, respectively. The gap between each contact finger is 0.5 mm. In total 50 contact fingers surround the inner tube. RF-shield has a maximum expansion stroke of 20 mm and transverse offset of
1 mm. The inner tube has 1 mm thickness. Good elasticity is required for the spring finger to maintain sufficient contact force. Furthermore, high thermal conductivity is necessary for the thin fingers to avoid excess heating. Both the spring finger and contact finger are therefore made of Beryllium-Copper (Cu720). The contact point of spring finger is coated with about 1 μm TiN to reduce wearing. Both the contact finger and spring finger were heat treated at 315 °C. All other parts of the bellows assembly including the inner tube are made of Stainless Steel (SS304).

3. Experiments

3.1 Mechanical test

Testing was carried out using a model with the same parameters described above under a pressure of 1x10^-2 Torr. The contact force per finger was set in the range from 150 g to 170 g. The RF-shield was expanded and contracted 5000 times over a stroke of 20 mm, which corresponds to 100000 times with a stroke of 1 mm that will be experienced by the real bellows assembly during 10 years beam operation. One stroke took approximately 10 seconds.

We observed finally no kinking or sticking of contact fingers and found no mechanical problem. However, metal particles due to the wearing of contact parts were observed. The mean size of particles was approximately 50 μm. Such particles have been found to reduce the beam lifetime or broaden the beam size when passing through or trapped to the beam [6]. Since the wearing is inevitable for finger type RF shield, the particle generation is one of the important problems in the present design. An approach to reduce the particle is to choose appropriate combination of the materials or the coatings for the contact finger, the spring finger and the inner tube. The wearing test is now undergoing for several promising materials such as inconel, titanium or hastelloy. The second effective solution is to choose a sufficient but not excess contact force. We have tried to find the suitable contact force experimentally as described in the following section.

3.2 Heating test

Excess heating at the contact points was checked by transmitting 508 MHz microwave for several contact forces using the experimental model. The microwave was applied because it can simulate more realistic wall current excited by the bunched beam than the DC current. The CW 508 MHz microwave was supplied from a 10 MW klystron used for the RF cavity of the TRISTAN Main Ring. The average and the peak beam current of LER are 2.6 A and 156 A, which are induced by 14.3 kW and 600 kW of 508 MHz microwave power, respectively. In the experiment the microwave power up to 80 kW was transmitted and was sufficient to investigate the heating due to the average beam current.

Figure 3 shows a schematic diagram of the experimental apparatus. A 50 Ω coaxial transmission line was formed using the model bellows assembly and a brass rod as an inner conductor. The transmission mode is TEM mode. The wall current, therefore, has only axial component that is just the same as the real wall current in the beam tube. The bellows model is similar to that described in Sec.2 but has the length of 200 mm and the body of Aluminum alloy. Spring fingers under five different loads investigated, that is, load 1 (0 to 3g), load 2 (15g), load 3 (50g), load 4 (90g) and load 5 (160g). The bellows assembly is thermally isolated by a cover to simplify the experimental condition. The input power was increased in step of 10 or 20 kW and maintained at each power level for about 10 minutes. Temperatures were monitored using three thermocouples positioned at the inlet, at the middle and at the outlet of bellows assembly.

Figure 4 shows the increase rate of temperature (°C/sec) versus input microwave power. The temperature is the average of three thermocouples. The straight line is the result for the case of the minimum power loss, that is, without any contact resistance, calculated using the surface resistance and the specific heat of the model. From this figure it can
seen quite clearly that abnormal heating occurs for the load less than 50 g/finger. To see more definitely the effect of contact force, the power loss per 10 kW input power is plotted versus the average contact force in Fig.5. Observation of the fingers after the experiments revealed arcing spots on the contact fingers with a load less than 50 g/finger.

From the results it can be concluded that the contact force larger than 50 g/finger is necessary to provide the sufficient electrical contact. Considering manufacturing and setting errors, however, the spring finger should be designed to provide the contact force of 100 g/finger at least. This value is much less than that in the mechanical test (170 g/finger), and the problem associated with metal particles may be reduced. Be careful, however, that the experiments were done in atmosphere where the water vapor in the air will work as a lubricant. Furthermore, the frequency of wall current in the experiments is far low compared to those in the real beam tube. The more realistic investigation will be necessary.

Fig.4. The increase rate of temperature (°C/sec) versus input microwave power. The straight line is the calculated minimum increase rate of temperature.

Fig.5. The power loss per 10 kW input power versus the average contact force. The dotted line is the calculated minimum power loss.

4. Summary

A bellows assembly with an RF-shield has been developed for the KEKB. The RF shield is a usual finger type but has the special spring fingers to press the contact finger without fail. The minimum contact force was investigated experimentally by transmitting microwave up to 80 kW though the bellows assembly in atmosphere. A contact force above 50 g/finger was found to be necessary to avoid abnormal heating. Considering manufacturing and setting errors, however, the spring finger should be designed to provide the contact force of 100 g/finger at least. A test using 2856 MHz microwave to check the arcing in vacuum is now in preparation. Further tests to find the best combination of finger materials will be also carried out in high vacuum.

Acknowledgment

The authors would like to thank the members of TRISTAN Vacuum Group in KEK for their useful discussions. The authors also express their deep gratitude to H.Nakanishi of TRISTAN RF Group for his valuable suggestions instruction during the RF experiments.

References

A Design of the Injection Scheme and a Construction of Model Kicker Magnet for the High Brilliance Lattice of the Photon Factory

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Abstract

New injection schemes for the three kind of low emittance lattices of the photon factory was designed. A traveling wave type kicker magnet is applied to make a injection pulse bump. A model kicker magnet was also designed and constructed. The magnet is traveling wave kicker magnet and the impedance of the test magnet was designed to 6.25Ω. The experimental measurement of properties of the magnet will be mentioned.

1. Introduction

In recent few years, the third generation high brilliant synchrotron radiation facilities are constructed and to start the operation. At the photon Factory, we are studied to design new high brilliant lattices those gives a small emittances near to the third generation synchrotron radiation source. In this paper, it is described that a design of the injection system for the high brilliant lattices of the Photon Factory and a construction of a test model of the kicker magnet.

2. Design of injection system

The design of the injection system consists of the four kicker magnets and the two septum magnets. Hence the injection point is just same position as in the previous lattice, these pulse magnets are located almost same place as in the previous arrangement. In the present new design, a fast injection bump (faster than the revolution time 624 nsec) is applied to obtain an enough wide aperture for the first few turns of the injected beam. The present existing septum magnets are used again in the new system. Under these conditions, we optimized the design of the injection pulse bump for three set of high brilliant lattices. The phase advance of the lattices are 90 degree, 105 degree, and 135 degree. In table 1, the parameters of the injection bumps and the positions and angles of the injected beam at the injection point are listed.

Table 1

<table>
<thead>
<tr>
<th>Injection Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse bump (mm.mrad)</td>
</tr>
<tr>
<td>90° lattice</td>
</tr>
<tr>
<td>105° lattice</td>
</tr>
<tr>
<td>135° lattice</td>
</tr>
</tbody>
</table>

The design of the injection bumps are shown in Fig.1. The position and angle of the injected beam are set 27.5 mm and 1.5 mrad or 2 mrad. The magnitude and angle of the injection bump are set 17 mm and 0 mrad. The steering angles of the kicker magnets are listed in table 2.

Table 2

<table>
<thead>
<tr>
<th>Steering angles of the kicker magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
</tr>
<tr>
<td>3.20 mrad</td>
</tr>
<tr>
<td>K2</td>
</tr>
<tr>
<td>K3</td>
</tr>
<tr>
<td>K4</td>
</tr>
</tbody>
</table>
3. Construction of a model 6.25Ω-kicker magnet

As mentioned in previous section, a fast injection bump (faster than the revolution time 624nsec) is applied to obtain an enough wide aperture for the first few turns of the injected beam. To realize the fast injection bump, the traveling wave magnet is chosen as the kicker magnet. This magnet is divides the C-shaped ferrite core into discrete sections to form a uniform impedance transmission line[4-5]. The sections are capacitively coupled to the return conductor through a discrete capacitors. To obtain intense magnetic field with limited space of the kicker magnet, the smaller characteristic impedance of the magnet is better. Recently, a 6.25Ω traveling wave magnet was developed by J.Dinkel et al. at the Fermilab[6]. We also designed 6.25Ω traveling wave magnet, and to construct a test-model of the kicker magnet. The design parameters of the magnet are listed in Table 3.

Table 3
magnet design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic length</td>
<td>360mm</td>
</tr>
<tr>
<td>Gap height</td>
<td>60mm</td>
</tr>
<tr>
<td>Gap width</td>
<td>170mm</td>
</tr>
<tr>
<td>Peak field</td>
<td>9422 Gauss (at 500 A)</td>
</tr>
<tr>
<td>Characteristic impedance</td>
<td>6.25Ω</td>
</tr>
<tr>
<td>Field propagation time</td>
<td>187nsec</td>
</tr>
<tr>
<td>Number of cell</td>
<td>30cell</td>
</tr>
<tr>
<td>Inductance per 1 cell</td>
<td>38.9nH</td>
</tr>
<tr>
<td>Capacitance per 1 cell</td>
<td>996pF</td>
</tr>
</tbody>
</table>

A schematic drawing of the designed magnet is shown in Fig. 2. In this construction of the test-model, poly vinyliden fluoride (PVdF) was used as a dielectric of the capacitor to obtain the capacitance of 996pF.

---

Fig. 1 design of the injection bumps

Fig. 2 A schematic drawing of the magnet
A general view of the constructed test-model magnet is shown in Fig.3.

In the frequency region from 1kHz to 100kHz, the measured capacitance is almost constant value 37.5 nF and the measured inductance is 1.6μH. By these values of capacitance and inductance, the characteristic impedance of the magnet conclude to be 6.5 Ω. A discrepancy between the calculated value of the characteristic impedance of 6.25Ω and measured value of 6.5Ω is considered to error in the inductance measurement and fringing effect from the edges in the capacitance measurement. The return connection between the conductors produce additional inductance.

4. Capacitance and Inductance Measurements of the Test-model Magnet

The 29-cell magnet’s total capacitance and inductance were measured using an HP4284A Precision LCR Meter. Results of the capacitance and inductance measurements are shown in figures 4 and 5 respectively.

Fig.4 measured capacitance of the magnet

Fig.5 measured inductance of the magnet

references
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Magnet Alignment System of the SPring-8 Storage Ring using Laser

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Abstract
The SPring-8 storage ring is under construction. The girders on which several magnets are put are surveyed with a laser tracker by making network. After the smoothing the relative displacements are within ±0.04 mm. A laser and a CCD camera system is used for a precise alignment of quadrupole and sextupole magnets on a girder. The target shift from the 5m-straight line can be measured to be less than 10 μm. The misalignment of them are estimated to be less than the tolerance.

Introduction
The storage ring has a 1436m circumference which surrounds the hill called Mihara-Kuriyama, and has 48 cells. Each cell has 17 quadrupole and sextupole magnets put on three girders, and two bending magnets. Whole ring was surveyed before building construction two times. After tunnel construction, all monuments were surveyed again. According to these survey results, the 88 monuments positions were decided. After the girders are set up, both the end magnets on the girder are surveyed by the laser tracker SMART310, and then girders are smoothed.

Five or seven magnets on the girder are aligned precisely using a laser and CCD camera system and tiltmeters. The hole center on the magnet fiducial plane are shifted from the line right above the magnetic axis, and the shifted values have been acquired at the magnet measurement process. Spherical targets which diameter is 75 mm are used at several steps, that is survey, level measurement, pre-alignment and precise alignment.

Tolerances for magnet misalignment
The tolerances for the magnets of this storage ring are listed in Table 1. In order to reduce the sensitivity to the misalignment of quadrupoles adopted alignment method is to divide the alignment into two stages, that is in a girder (tolerance 50 μm) and between girders (0.2mm).

Table 1 Tolerances for magnet misalignment

<table>
<thead>
<tr>
<th>Magnet</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>0.05</td>
<td>0.05</td>
<td>0.2</td>
<td>0.2</td>
<td>0.21</td>
</tr>
<tr>
<td>Sextupole</td>
<td>0.05</td>
<td>0.05</td>
<td>0.2</td>
<td>0.2</td>
<td>0.21</td>
</tr>
</tbody>
</table>

*1)*Ax, Ay, and Az denote the horizontal, vertical, and longitudinal displacement errors, respectively.
*2)*θx, θy, and θz denote the rotation errors around the horizontal, vertical, and longitudinal axes, respectively.

Monuments Survey 1
Before building construction, 21 concrete blocks shaped like tombstones were made along the ring every 60 m, and monument plates were buried on the top. Monument is placed at the intersection point of the straight lines at both sides of the bending magnet. These monuments and geodetic points outside the ring were surveyed two times with a distance meter ME5000 and a theodolite T3000. The error ellipses of these results were smaller than the circle of radius 1 mm.

Monuments Survey 2
The laser tracker is for the first time employed in the measurement of storage ring networks. The SMART is a dynamic measurement system, that is laser can chase the target wherever we move. This system consists of a laser interferometer, a rotating mirror on two axes with two angle encoders and servo motors, a position diode etc. The tracker gives 3D spherical coordinates of a target in space with a distance resolution of 1 μm, an angular resolution of about 1 arc sec.

Experiments show the laser tracker has a distance accuracy of 0.001+0.2ppm×l(mm) and an angular accuracy of 10 μrad. This accuracy will result at least 7.3 mm traverse disclosure for the storage ring orbit if SMART is simply used for coordinate measurement. Alignment network for SPring-8 storage ring is designed as a distance-only trilateral network. Several aspects are optimized. The laser tracker has different accuracy for distance measurement when its position changes in respect to measuring targets. To reduce the influence of angular error, the laser tracker's positions within network are chosen by checking the distance accuracy it results:

\[ M = \sqrt{\frac{h_1^2 \cos^2 \alpha}{l^2} + \frac{h_2^2 \cos^2 \beta}{l^2} + \frac{h_1^2 \sin^2 \alpha}{l^2} + \frac{h_2^2 \sin^2 \beta}{l^2}} \]

where \( l \) is the length between two measuring points, \( \alpha, \beta, \gamma \) are angle and lengths from laser tracker to...
these points, \( m_a, m_b, m_c \) are their measurement accuracy respectively. To calibrate measuring distance, a 20m-long stand is being made to compare SMART with HP 5527A interferometer.

When putting the target on the monument, a tripod is used. The laser light when measuring the target is in the plane which height is 1700mm. The height of the stage on the wall is also 1700mm. The body of SMART sensor unit is modified so that we can adjust the height and shift horizontally. This is because the survey can be carried out without using the rotary encoder for vertical angle.

After tunnel construction, all 88 monuments including 21 points were surveyed with SMART. Since this survey network was narrow and the circumstances were not good, it was difficult to decide the monuments coordinates using only SMART. Thus the data of the angles between the 24 monuments were added. The difference between survey 1 and survey 2 was small.

**Magnets Setting**

The quadrupole and sextupole magnets are set.

Alignment of both end magnets on the girder

There is a fixed target stage on both end magnet. This stage is used for the alignment between girders and for a reference stage of the precise one in a girder. Both the end magnets are aligned using survey 2 results. This alignment is necessary before girder alignment. The magnets except both end are also aligned roughly to make shorter the time used for precise alignment in a girder.

**Alignment between girders**

1. Survey

The network precision depends on both the accuracy of laser tracker and the structure of network, and also the ratio of measurement length to the width of net. Measurement lengths are optimized by simulation study of error accumulation. The results show that the measurement length shorter than 15 m (1/2 cell) has least error accumulation rate along the ring.

The alignment network is composed of 288 quadrupole fiducial points and 96 auxiliary brackets on inner wall. Over 50 percent distances are measured directly by laser tracker interferometer. Precision for magnet positioning is estimated on the assumption that the distance measurement errors have a Gaussian distribution. Error ellipse analysis shows that maximum position displacement of magnets in respect to geodetic coordinate less than ±1 mm, relative displacement between adjacent girders of ±0.05 mm are expected. Simulations results are well coincide with precision estimation.

First survey and smoothing is 4 cells, second 8 cells, third 8 cells, and so on. Also the monuments are surveyed for references in these survey. The shift values from the smoothed fitting curve are calculated.

2. Smoothing

The girders are adjusted according to these values. The girder is monitored with eight digimatic indicators.

**Level survey**

The level reference on the wall is for pre-alignment of the magnet. It is important to smooth not the wall references but the magnet stage. This level survey is done after the girder position on the horizontal plane is fixed and is locked. Wild N3 is used. Now NA2 with a diode laser instead of N3 is tested. A PSD(Position Sensitive Devise) is used as the detector. However, this method is too sensitive to the NA2-PSD distance.

**Alignment of bending magnet**

Bending magnet is aligned with SMART after the...
alignment. Target for SMART is put on the tiltemeter as shown in Fig. 4. and its coordinates are displayed in real time on the CRT.

Alignment of quadrupole and sextupole magnets in a girder

Laser and CCD camera System

A laser source is put on the fiducial plane of the aligned bending magnet because the adjust of laser is easy. This He-Ne laser shown in Fig.5. has a special filter and a collimator to make parallel light beam of gaussian shape. The diameter of a pinhole is 25 μm. The diameter of the light beam is about 3mm and its change is within 2% from 1m to 5 m. A CCD camera is used for a detector shown in Fig.6. The CCD camera can always see the distribution of light beam which is sensitive to the mechanical stress because of small pinhole.

It is difficult to receive the laser light directly on the CCD device because of the interference striped pattern. Thus the coating to suppress the reflection is used. However the interference pattern remains a little. The CCD device on which an optical fiber plate was tested. This camera showed no interference pattern, but it was too sensitive to the incident angle of the light.

The signal of the image comes into a video frame grabber board in the Macintosh computer. The center coordinates are extracted from this two dimensional distribution. Though the size of a CCD cell is 11 μm x 11 μm, the accuracy of this system is about ±2 μm in the ±0.5 mm region at 60 cm distance. The total counts of summed up distribution is of the order of 10^8.

The straightness of this laser and CCD system was checked with 4m-long stage. The small deformation of the stage was observed by a tilt sensor. The straightness is estimated to be within 10 μm during 4m. If there is no pinhole in the filter, the straightness became bad. It is important to place the camera in the housing so that the center coordinates do not change even if the spherical housing rolls a little.

The hood is quite important to stop the air flow. The magnets on the girder are usually aligned where the wind velocity is around 0.02 m/s.

The change in temperature is very small in the tunnel. Thus the direction of laser beam is rather stable. The drift of laser beam observed at the distance 5m is usually within 10 μm during a few hours.

One or two planes are made on the magnet for the fiducial ones, and has a hole into which the stage is inserted. The diameter of this hole is 20 mm and its fluctuation among the fiducial planes was over 20 μm. Thus the ball cage is used as shown in Fig.7. It is easy to take the stage in and out the hole.

The reference line used for alignment is 0.5 m upper than the electron beam axis, thus the roll of the magnet is very important. It is difficult to measure the tilt precisely with a tiltemeter if the span between the contact points is short. A means to get good repeatability is necessary.

Since the tolerance between the girder is larger than that of magnets on one girder, firstly, both the end magnets are aligned. The fixed target stage is adjusted only the height, because this position is already aligned. While the magnet is being adjusted, not only CCD camera but also 8 digimatic indicators are used to monitor the magnet shift. The shifted values are displayed on the CRT also. Operators adjust the magnet looking at the indicators. These indicators are useful for moving to an accuracy of several μm.

The adjust of each magnet continues until the displacement at the position of CCD camera becomes within 10 μm on the CRT monitor.

Acknowledgements

We would like to thank Dr. K. Endo, Dr. R. Sugahara, and the personnel of KEK survey alignment group for their useful advice and Dr. A. Ando for discussion. We are much indebted to the staff of our magnet group and also acknowledge to Mr. M. Kawakami, Mr. K. Nakashima, Mr. I. Takeshita and collaborators of Hitachi Plant Engineering & Construction Co., Ltd. for their help.
DEVELOPMENT OF A COMPACT STEERING MAGNET WITH EIGHT-POLE STRUCTURE

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Abstract

A compact steering magnet has been devised. The steering magnet has "eight-pole structure". The strength and its direction of the dipole field can be electrically changed. The outer radius, the bore radius and the length of the magnet are 120 mm, 14 mm and 60 mm, respectively. The effective length is measured to be 97 mm and magnetic field of 0.4 kG is achieved. The steering magnet is very useful under severe space limitation.

1. Introduction

The 7 MeV proton linac at Institute for Chemical Research, Kyoto University consists of 50 keV piroton ion source, 2 MeV RFQ linac and 7 MeV Alvarez DTL. The linac system has been operated since 1992[1]. Unfortunately, the output beam from the DTL has a slight angle against the designed axis, and then the beams are deflected away by quadrupole lenses installed downstream.

A conventional steering magnet system consists of two dipole magnets whose fields are perpendicular to each other, while our facility does not have enough space for two dipole magnets between the exit of the DTL and the quadrupole magnets. Because the direction of the output beam is found to be changed with operating conditions, a short steering magnet system, which has the variable strength and the steering direction, was required. Considering these requirements, we have developed a new type of compact steering magnet which has "eight-pole structure". The main features of this steering magnet and the results of the field measurements are described in the present paper.

2. Concept of the multi-pole structure

It is well-known that a circular distribution of electric current, in which the current density is proportional to the cosine of the azimuthal angle, can produce a perfectly uniform dipole field [2][3]. In analogous way, it also can be shown that a magnet with "multi-pole structure" can produce a dipole field around the axis.

Inside the aperture $r_0$, where there is no electric current (ignoring the beam), the magnetic field can be expressed as the gradient of the magnetic potential $\phi$, i.e.,

$$ \mathbf{B} = -\mu \nabla \phi $$

(1)

The magnetic potential of the perfect $2N$-pole field can be written as

$$ \phi_{2N} = \frac{r_0}{N} k_2 \sin(N\theta) \quad \text{ (2)} $$

where $k_2$ is an appropriate coefficient representing the field strength and $\theta$ is the azimuthal angle relative to the horizontal direction. In order to generate the dipole field ($N = 1$) inside the radius $r_0$, the magnetic potential at $r = r_0$ must have the form

$$ \phi_2 = r_0 k_2 \sin \theta \quad \text{ (3)} $$

The above considerations provide us a guide line for a design of a dipole magnet with "multi-pole structure". The extension to a magnet for higher order field is straightforward.

 Applying the above considerations to an actual magnet, the sinusoidal magnetic potential should be approximated by segments where the magnetic potential is constant and chosen to be proportional to the sine of the azimuthal angle. Further more, coil space should be reserved. Taking these requirements into consideration, we adopt "eight-pole structure" in which the sinusoidal magnetic potential is approximated by eight poles (See Fig. 1 and 2). The magnetic potential on the pole tips is chosen to be proportional to the sine of the azimuthal angle. In this structure, enough space is available for coils and we can get relatively large field strength.

Fig. 1 Schematic view of the eight-pole structure

Fig. 2 Magnetic potential distribution at $r = r_0$

The magnetic potential is linearly interpolated between poles. Broken line: sine curve, solid line: generated by eight poles
We adopt thin poles to reduce leakage flux and have a good approximation of the sinusoidal magnetic potential.

It can be easily derived from eq. (1) and (3) that in eight-pole structure the field strength on the pole tips can be written as

$$B_{rm} = B_0 \cos\left(\frac{n-1}{4} \pi - \Theta\right)$$

$$n = 1, 2, 3, \ldots, 8$$

(4)

where $B_{rm}$ is the field strength on the $n$-th pole tip and $\Theta$ is the azimuthal angle of the dipole field relative to the horizontal direction. The azimuthal angle of the $n$-th pole tip measured relative to the horizontal direction is $(n-1)\pi/4$ radian (See Fig. 1). The excitation current in each coil can be written as

$$I_n = I_0 \left\{ \cos\left(\frac{n-1}{4} \pi - \Theta\right) - \cos\left(\frac{n}{4} \pi - \Theta\right) \right\}$$

$$n = 1, 2, 3, \ldots, 8$$

(5)

where $I_n$ is the excitation current in the $n$-th coil and $I_0$ is a coefficient representing the strength of the excitation current. $N$-th coil is located between the $n$-th and $(n+1)$-th poles (See Fig. 1).

With this structure, we can change the field strength and its direction only by changing the excitation currents and then we can steer the beam in both horizontal and vertical directions by a single element. It is very advantageous under severe space limitation.

3. Field calculation and design

The geometry of the steering magnet is shown in Fig. 3. The outer radius, the bore radius and the length of the magnet are 120 mm, 14 mm and 60 mm, respectively. In order to have long effective length, the length of the pole is longer than that of iron yoke. Its iron yoke is octagonal rather than circular for simple fabrication.

![Fig. 3 Geometry of the steering magnet](image)

![Fig. 4 Flux Plot of a eight-pole magnet](image)

$I_0 = 2.0$ A. Mesh size is 1 mm.

(a) $\Theta = 90^\circ$ (b) $\Theta = 78.75^\circ$ (c) $\Theta = 67.5^\circ$
Fig. 5 Results of harmonic analysis
(a) harmonic field components
(b) azimuthal angle of the generated dipole filed \( \theta \)

Table 1 Main features of the steering magnet

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron pole number of poles</td>
<td>8</td>
</tr>
<tr>
<td>Bore radius</td>
<td>14 mm</td>
</tr>
<tr>
<td>Axial length</td>
<td>56 mm</td>
</tr>
<tr>
<td>Iron yoke axial length</td>
<td>22 mm</td>
</tr>
<tr>
<td>Number of coils</td>
<td>8</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>498</td>
</tr>
<tr>
<td>Cross section</td>
<td>18 \times 40 \text{mm}^2</td>
</tr>
<tr>
<td>Axial length</td>
<td>60 mm</td>
</tr>
<tr>
<td>Excitation current</td>
<td>&lt; 5 A</td>
</tr>
<tr>
<td>Total axial length</td>
<td>60 mm</td>
</tr>
<tr>
<td>Effective length</td>
<td>97 mm</td>
</tr>
<tr>
<td>Maximum field strength</td>
<td>&gt; 0.4 kG</td>
</tr>
</tbody>
</table>

This geometry is designed by PANDIRA[4]. Some results of the calculations are shown in Fig. 4. In the calculations, we found that a steering magnet with eight-pole structure can produce sufficiently good dipole field around the axis, in which higher components of the field are negligibly small. Some results of harmonic analysis are shown in Fig. 5. The harmonic field components are normalized at 10 mm from the axis.

Four DC power supplies feed the excitation current with an accuracy of ± 1%. Main features of the steering magnet are shown in Table 1.

4. Magnetic field measurement

The steering magnet has been fabricated and some characteristics of its magnetic field are measured. The dependence of the field strength at the magnet center on the excitation current strength \( I_0 \) is measured by a Hall probe (FWBELL 4048) (See Fig. 6). The field strength of 0.4 kG is achieved and it is strong enough for the present purpose. Above \( I_0 = 3 \) A, the field strength becomes to saturate. Judging from the results of the two-dimensional calculations with PANDIRA, the nonlinearity is mainly due to the iron saturation in the connection region of the iron pole to the yoke.

The magnetic field distribution on the beam axis is also measured with the Hall probe (See. Fig. 7). The effective length of the steering magnet is calculated to be 97 mm from the measured results, which is considerably larger than the pole length of 56 mm. It provides larger deflection angle for the beams.

5. Summary

A compact steering magnet with eight-pole structure, which has variable strength and field direction has been developed. It has been installed in the beam line. The outer radius, the bore radius and the length of the magnet are 120 mm, 14 mm and 60 mm, respectively. The effective length of the steering magnet is measured to be 97 mm and the magnetic field of 0.4 kG is achieved. The steering magnet with eight-pole structure is very advantageous under severe space limitation.

Acknowledgment

The authors would like to thank Prof. Akira Noda and Prof. Makoto Inoue for their continuous encouragement and support, and all the other members of the accelerator group of Nuclear Science Research Facility for their help and fruitful discussions.

References

ALIGNMENT OF MAGNETS FOR THE SPring-8 SYNCHROTRON

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Abstract

SPring-8 Synchrotron ring is composed of 64 dipoles, 80 quadrupoles and 60 sextupoles. The 80 quadrupoles and the 60 sextupoles are supported on girders. The circumference of the ring is about 400m. Since the tunnel of this ring is very narrow, SMART310, laser tracker for 3D measurements of moving targets, is used for the alignment. This paper will present the alignment method, results and present status.

1. Introduction

SPring-8 Synchrotron ring is under construction now. In June 1995, we began with the first survey of reference points for prealignment. We will finish the alignment of the magnets until January 1996. The alignment method is based on reference points inside the ring since there is no reference points outside the ring. This alignment consists of two levels. The first level is the network which survey and set the reference points of the prealignment for installing the magnets.

The second level is the network for the precise alignment of the magnets.

2. Tolerances

The specification of the tolerance of the alignment is relative precision of ±0.2mm in radial direction, vertical direction and beam direction. And ±0.2mrad in tilt for the magnets. Table 1 shows the deviation of the relative precision of the alignment of each magnets.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Radial</th>
<th>Vertical</th>
<th>Beam</th>
<th>Tilt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>±0.2mm</td>
<td>±0.2mm</td>
<td>±0.2mm</td>
<td>±0.2mrad</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>±0.2mm</td>
<td>±0.2mm</td>
<td>±0.2mm</td>
<td>±0.2mrad</td>
</tr>
<tr>
<td>Sextupole</td>
<td>±0.2mm</td>
<td>±0.2mm</td>
<td>±0.2mm</td>
<td>±0.2mrad</td>
</tr>
<tr>
<td>Correction</td>
<td>±1.0mm</td>
<td>±1.0mm</td>
<td>±1.0mm</td>
<td>±1.0mrad</td>
</tr>
</tbody>
</table>

Table 1 Deviation of the relative precision.

Fig.1 Reference points of SPring-8 Synchrotron
3. Alignment Method

3.1 Reference Points Setting

The first level of the alignment is setting the reference points for the magnets installation to the tunnel and prealignment. We survey the reference points and set them for the proper location.

Fig. 1 shows the reference points of the synchrotron ring. L1 and L2 which are on the injection line from Linac ensure the correct location and orientation of the ring. Based upon them, we set the reference points S1 to S12. These reference points are imbedded in the floor and are able to adjust the X–Y axis of the location. Monuments are set up on the points.

Using L1, L2 and other supplementary points, reference points of the straight line are set.

Since the Tunnel is very narrow and reference points are very few, it is remarkably difficult to realize highly accurate positioning of the reference points by triangle network calculation. For this reason, we use the center location of the 64 dipole magnets as supplementary points. Survey network comprises nearly 80 points of reference points and supplementary points. The objective of the first level alignment is that the deviation of the network calculation of the reference points is less than ±1mm.

The height reference is taken from the Linac injection line. Beam line is 1200mm height from the floor. This height reference is transferred to 1560mm height which is visible after the installing of the magnets. Nearly 10 height reference points like this are set up on the wall along the tunnel.

SMART310, theodolite, N3 and NA2 are used as survey equipment. Direction and Angle are measured by theodolite. Distance is measured with SMART310. Height is measured by N3.

3.2 Prealignment

At the reference points setting, supplementary points of 64 dipoles are simultaneously set, marked and inked on the floor. Magnets are installed in the tunnel according to this markings and inking.

The objective of this prealignment is as follows.

(1) Radial ±1mm
(2) Beam axis ±1mm
(3) Vertical ±0.5mm
(4) Tilt 0.2mm/m

3.3 Precise Alignment

Monuments are set on the reference points. SMART310, Theodolite, N3 and NA2 are used as survey equipment.

Reference points are measured with SMART310 for confirmation.

Fiducials on the 64 dipole magnets are used as supplementary points in order to obtain the accuracy of the network calculation. There are three fiducials on a dipole magnet. "BMU" means up stream, "BMC" means center and "BMD" means down stream. Sphere mounted retroreflector of SMART310 is positioned on the three fiducials.

According to the measurement data, magnets are correctly positioned.

Fig. 2 shows the precise alignment method of the magnets. Using the reference positions as reference, position of the three fiducials are measured. Using the previous data as reference, three fiducials of the next magnet are measured, and so on. After the survey is completed, each position is calculated by triangle network. If the result is not satisfactory, correct the position of the magnets and submit the network calculation again. This precise alignment is made in two rounds of the tunnel.

4. Instrumentation

Due to the narrowness of the tunnel, SMART310 is used for this alignment(see Fig.3). SMART310 is laser tracking system for 3D measurements. This is a single instrument for measuring angles and distances with automatic tracking of freely moving retroreflector.

The following is the instrumentation for this alignment.

(1) Distance
SMART 310 (Leica)
Accuracy
distance resolution ±1.26 μm
Inside Micrometer
1500mm Accuracy max. ±0.04mm
5000mm Accuracy max. ±0.115mm

(2) Direction and angle
SMART310(Leica)
Accuracy
angle resolution 0.7'
Theodolite T2000, T2000S (Wild)
Standard deviation Hz: 0.5°; V: 0.5°

(3) Height
N3, N42 (Leica)
Standard deviation for 1 km ± 0.2 mm

(4) Inclination
DL—D3 (Nigata seiki)
Accuracy 0.01 mm/m

(5) Plumbing
ZNL (Wild) 1:30000

5. Results

In June 1995, we have finished reference points setting.

The deviations which is the difference between designed positions and calculated positions by network calculation were in the range of nearly ± 1 mm.

6. Conclusion

The alignment of SPring-8 Synchrotron is in progress now. 64 BMC's were set on the floor as marking. Applying these markings, positions of all components were inked on the floor.

In August and September 1995, according to the BMC markings and inking, magnets will be carried in the tunnel, and supports and girders will be fixed on the floor. Prealignment will be carried out after that.

Precise alignment will begin in November 1995. It requires three months to complete the second level of the alignment.

Fig. 4 Reference point and supplementary point setting

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Fig.3 SMART310 System
DCCTs for Magnet Power Supplies

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Abstract

This paper describes the operation principle of DCCTs which are used in the magnet power supplies of the TRISTAN main ring.

1. Introduction

The current sensor used in the magnet power supply must be of high precision. In the TRISTAN main ring, high-precision DCCTs comprising 2 Brentford/Hingorani (B.H.-)type DCCTs (direct-current current transformer) are used.

The usual textbooks explain the Kraemer type DCCT, which has a well-known defect: the waveform of the output exhibits "notches" at the peaks of the ac voltage wave. The output therefore has a large ripple of 100 Hz. Although capacitors can be used to smooth out this ripple so as to produce a pure dc component, this sacrifices the response speed.

Dr. Hingorani and Brentford corporation in England developed a modified version of the Kraemer circuit in the early 1960's which eliminated the current notches (refs.1-2). Although any DCCTs of this type are now operational in power supplies, no papers explaining the principle of the B.H.-type DCCT could be found. This paper thus gives both the principle and a procedure for building DCCTs.

2. Brentford/Hingorani-type DCCT

Principle of operation

The B.H.-type DCCT comprises two saturable inductors, four rectifiers and three resistors. The primary and secondary windings are wound on a single core (Fig.1). The core is the key element. A rectangular hysteresis-loop core material is employed to obtain a sharp break between the saturated and unsaturated states. As soon as the flux in the core reaches the saturation region, the impedance of the inductor changes from a high value to a low value. The operation is alike that of the SCR (silicon-controlled rectifier), since the load current can be controlled by firing the saturable core as well as the SCR. The photograph in Fig.1 shows the load voltage. The firing angle can be controlled by the dc current of the primary. The difference between the SCR and a saturable inductor is that the SCR allows the current to pass in only one direction, whereas inductors conduct current in both directions. It is worth noting that the return current is nearly constant. This property depends on the B-H loop, because the characteristics on the integral of the voltage versus the current are almost as sharply rectangular as the B-H characteristics.

B.H.-type DCCTs make use of the flatness of the return current. The circuit in Fig.2 can be regarded as being an equivalent 'circuit of that shown in Fig.1. The resistor (R) in Fig.2 is equivalent to a mixture of the resistors and diodes in Fig.1. The bypass diodes are connected to the resistors in parallel. The rectifiers are switched alternately; the rectified output across the resistor (RL) is shown in Fig.2. We obtain square pulses. The height is proportional to the primary current. Since the region is wider than 180 degrees, a pure dc output can be made from 2 square pulses by means of a circuit functioning as an AND-gate.
In order to fully understand the operation, computer simulations were performed. The circuit shown in Fig. 3(b) was investigated using computer code SPICE. The Jiles and Atherton hysteresis model (refs. 3-4) is listed in the library of SPICE. The model is ferrite so that the hysteresis-loop is not rectangular.

Many computer runs were made in order to obtain a smaller ripple waveform. The resulting ripple, even in the best case, was about 30%. This was caused by non-rectangular hysteresis.

Test of DCCT

The DCCT used for tests has two cores with 6000 turns. The core material has a high permeability and a rectangular-hysteresis loop. The inductance was 980 H, which was almost the upper limit of the LCR meter.

1. The B-H loops in operation are shown in Fig. 4.

2. The ripple of the output was about 8%. This unwanted ripple component is generated by the width of the hysteresis loop.

3. A pulsed current was measured using the DCCT and a precision shunt. Fig. 5 shows the current waveforms. Although the carrier frequency of the magnetization source is 50 Hz, a short pulsed current can be observed, because a core in the unsaturation state serves as an ordinary transformer.
To obtain high stability, a stabilized ac voltage source and a temperature-controlled oven are required. These performances are well documented in the literature, and fulfill the requirements of the storage ring.

Fig. 5 Pulse response of the DCCT

Fig. 6 Circuit of the high-precision DCCT

3. Construction of a high-precision DCCT

The circuit of the high-precision DCCT is shown in Fig.6. There is one primary winding and 3 auxiliary windings. A large dc current for making measurements flows in the primary cable. Four windings for the carrier current are provided in each core; 2 bias windings are provided in each DCCT, which are connected in series. The output of each DCCT is set to the proper operating level by a bias current. The primary cable and compensating winding are wound in opposite directions to each DCCT, and are connected in series. The current to be measured is compensated by the secondary compensating winding current through a high-gain power amplifier with a feedback loop. This control circuit maintains a decrease in the difference between the two DCCTs. The negative-feedback circuit improves the linearity, dynamic range, frequency characteristic, temperature stability, and signal-to-noise ratio. The burden resistor \( V_{\text{be}} \) converts the compensating current into a voltage signal \( V_{\text{out}} \). The voltage is proportional to the primary dc current.

We constructed a high-precision DCCT. Matched DCCTs were chosen for a pair. Although the ripples of about 8% of the DCCTs were canceled in the input of the amplifier, a slight ripple remained in the output voltage. A spike ripple was caused by diodes when the current was turned off. Above a high amplification, an oscillation of 2-3 kHz occurred, and quickly shifted to the voltage limit.

Acknowledgment

The author would like to acknowledge Professor H. Kiwaki of Kyushu Sangyo University for his helpful suggestions.

References

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1. Introduction

The booster synchrotron of the SPring-8 has a circumference of 396.12 m with a FODO lattice of 40 unit cells. The synchrotron ring contains 64 bending magnets. Basic ability have been tested for a preceding magnet. Manufacture of bending magnets have been finished on July in 1995. Field measurements have been performed for all magnets. Based on this results, we discussed sorting of 64 bending magnets in the synchrotron ring to suppress horizontal closed orbit distortion (C.O.D.). Horizontal C.O.D. was calculated by means of the code "SYNCH". In case of the magnets are arranged consideration the phase of betatron oscillation, the C.O.D. decrease to about 1/7 in comparison with the C.O.D. without the above mentioned consideration.

2. Field Measurement

Energy of a electron is increased from 1 GeV to 8 GeV in 0.4 sec by the synchrotron. Following the ramping of the energy, the excitation current of bending magnets were increased by eight times. To estimate the hysteresis of bending magnet, excitation was measured for three preceding magnets. The excitation were measured by means of NMR probe at the center of the pole. It was verified that the magnetic field was nearly in proportion to excitation current within 0.2 % of linearity. Field distribution were measured with a hall-probe for two excitation current ( are equivalent to 1 GeV and 8 GeV ). Horizontal field distribution and integrated field are shown in Fig.1 and 2, respectively. For three preceding magnets, the variation of the former and the latter were less than 2 \times 10^{-4} and 1 \times 10^{-3} for the range of ± 30 mm, respectively.

The integrated field was measured for three excitation current ( are equivalent to 1 GeV, 4 GeV and 8 GeV ) by means of long-flip coil for all bending magnets. The coil has 12 mm width, 3600 mm length and 3 turn. It is flipped by 180 deg during 5 ~ 20 sec. The integrated field was measured along straight line. Consequently, the measurements were performed at 18 mm in the direction of the outside of electron orbit at edge of the pole because sagitta of bending magnet is 35.6 mm. Since the measurement was performed for a half year, a reference magnet was measured in every measurement of a sample magnet to keep long term stability. The deviation from the
average for all bending magnets were obtained as an instrumental error. The instrumental error was less than $\pm 8 \times 10^{-4}$ for three excitation current. Histogram of the instrumental error for 1 GeV was shown in Fig. 3. The instrumental error were divided into eight classes of “A” ~ “H”.

2. Arrangement of the magnets

All bending magnets are excited serially make use of one power supply. Thus, horizontal C.O.D. is generated by the field error of bending magnets. The instrumental error is equal to the field error of bending magnets. Let the direction of electron beam as the s coordinate axis, horizontal C.O.D. $x(s)$ is shown as

$$ x(s) = \frac{\sqrt{\beta(s)} \beta(s_i)}{2 \sin \nu} \cos \left[ \frac{\pi \nu}{\mu(s)} - \mu(s_i) \right] \times (\Delta B/B) \theta $$

where, $s_i$ is position of the field error, $\beta(s)$ is beta function (m), $\mu(s)$ is phase advance (rad), $\nu$ is horizontal tune, $\Delta B/B$ is the field error and $\theta$ is bending angle (rad). From eq. (3-1), a sign of $x(s)$ changes as phase advance to be 180 deg. We assume that the field error is generated at the center of the magnet. If two magnets with same instrumental error were arranged at distance is equivalent to 180 deg, kicked electron by first magnet is returned to design orbit by second magnet. The C.O.D. is canceled except for an interval of two magnets.

3.1 Arrangement of two pairs of magnets

Since horizontal tune is designed to be 11.73, the phase advance of betatron oscillation to be $\sim 105$ deg every one cell. A number, $k$, of cells is equivalent to about 180 deg phase advance are $k = 2, 5, 12, 15, 19, 22, 29, 36, 39$ cells. Distance of two magnets should be short because the C.O.D. remain for an interval of two magnets. It is wished that the phase advance is closer to 180 deg. In this reason, two magnets were arranged with separation distance 5 cells (call first pair).

In order to cancel remained C.O.D., a pair of magnet with opposite sign were put (call second pair). There are two bending magnets every one cell in a normal cell because of a FODO lattice. Let the position of the magnet of upstream in n th cell and that of downstream in n th cell are $(n, u)$ and $(n, d)$, respectively. The first pair were put $(n, d)$ and $(n+5, d)$ and the second pair were put $(n+1, u)$ and $(n+6, u)$. Since the phase advance is approximately 26 deg from $(n, d)$ to $(n+1, u)$, the remained C.O.D. decreases to less than 1/2.

To confirm the above mentioned discussion, the C.O.D. was calculated by SYNCH with following three cases.

1. One magnet with $\Delta B/B = -0.05 \%$ was put at $(4, d)$.
2. First pair of magnets with $\Delta B/B = -0.05 \%$ were put at $(4, d)$ and $(9, d)$.
3. Add second pair of magnets with $\Delta B/B = +0.05 \%$ were put at $(5, u)$ and $(10, u)$ to case (2).

In case of (1), maximum of the C.O.D. was 0.33 mm and root mean square (r.m.s.) of the C.O.D. was 0.18 mm. In case of (2), r.m.s. of the C.O.D. decrease to 0.09 mm. However, maximum of the C.O.D. was 0.45 mm for the interval of two magnets. Thus, the C.O.D. was remained for the interval. In case of (3), maximum and r.m.s. of the C.O.D. were obtained to be 0.16 mm and 0.04 mm, respectively. It was confirmed that the C.O.D. was decreased to about 1/3 for the interval of the first pair due to insert the second pair.

3.2 Arrangement of all magnets

Electron beam size is maximum at 1 GeV and become minimum at 8 GeV. To suppress the C.O.D. at 1 GeV, 64 magnets were arranged based on the result for 1 GeV. For example, two magnets which were taken from class of “B” in Fig. 3 (first pair) were put at the position of $(3, d)$ and $(8, d)$. The second pair were selected from class of “G” and were put at the position of $(4, u)$ and $(9, u)$.

Horizontal C.O.D. was calculated at the
upstream of every quadrupole magnets (location of monitors) by "SYNCH". The C.O.D. against the monitor number was shown in Fig.4 by the solid line. Maximum and r.m.s. of the C.O.D. were 0.35 mm and 0.10 mm, respectively. For comparison, the C.O.D. was also shown in Fig.4 by the dotted line when the magnets were put according to the order of production of magnets. In this case, maximum and r.m.s. of the C.O.D. were 1.71 mm and 0.69 mm, respectively. These results show that the C.O.D. was decreased to about 1/7 by discussion of section 3-1.

Fig.4 Horizontal C.O.D. against the monitor number. Monitor number 1 indicates the position of the inlet of first quadrupole magnet from the injection point of electron beam. Eighty monitors are equivalent to a circumference of the synchrotron. The solid line indicate the C.O.D. for the magnets are arranged consideration the phase of betatron oscillation. The dotted line indicate the C.O.D. without the above mentioned consideration.

4. Conclusion

Integrated field were measured for all bending magnets of synchrotron. The variation of integrated field was less than ± 8 × 10^-4. We decided the arrangement of bending magnets based on the result to suppress horizontal C.O.D.

References

Abstract

HIMAC (Heavy Ion Medical Accelerator in Chiba), which is the first heavy-ion accelerator facility for medical use in the world, is in operation at NIRS. A project of time-sharing-operation of the injector is in progress and a solenoidal magnet with a laminated core is designed and assembled for the time-sharing-operation of the injector. Specifications and results of magnetic-field measurement are described.

Introduction

The HIMAC facility can be divided into three parts; the injector, the synchrotron with two identical rings, and the irradiation system with horizontal and vertical-beam lines. The injector comprises two kinds of ion sources (ECR and PIG), two kinds of linear accelerators (RFQ and Alvarez linac), and beam-transport systems. The linacs accelerate various ions of 8 keV/u, ranging from He to Ar, up to 6 MeV/u. A medium-energy beam line, in cooperation with two pulse-operated magnets, can supply beams to three beam lines, i.e. two synchrotron rings and a medium energy experimental room (see Fig.1), 'simultaneously', changing the beam directions from pulse to pulse.

In order to increase the versatility of the facility, the time-sharing-operation of the injector, i.e. acceleration of different kinds of ions from pulse to pulse, was studied and the project is in progress. In the present case operating parameters of all devices will be adjusted to the optimum values so that ions with values of largely different q/A can be accelerated. All the magnets and monitoring devices in the beam transport line must, therefore, be replaced by those bearing pulsed-operation. Since a solenoidal magnet of DC-operation is installed in the low-energy beam-transport line, in addition to the electro-static quadrupole lenses, a new solenoidal magnet with a laminated core is designed and assembled.

Structure of the solenoidal magnet

Specifications of the solenoidal magnet are listed in Table 1 and its dimensions and structure are displayed in Fig.2. A coil of 288 turns with a current of 350 A generates maximum magnetic field of 6.8 Gauss at the center. A water-cooled coil is made of the hollow copper conductors. A magnet core consisted of two types of segments, Core-A and Core-B (see Fig.2), both of which are made of 0.5 mm thick steel plates coated with electrical insulators. The Core-A is a pile, 25 mm thick, of octagonal plates and is fixed to the Plate-A being made of SUS304. Rectangular plates of 65 mm × 218 mm in size are piled up to form eight pieces of Core-Bs; six of them are 160 mm thick and two of them are 130 mm thick. Each one is tightened by bolts and Plate-Bs, then fastened to the plate-A. The coil is also fixed to the Plate-A with supporting rods.

All the components, cores and the coil, were bolted, and no welding method was employed. It is, therefore, free from the strain induced by the welding. End faces of the coil, which define the spacing between Plate-Bs, were cut with accuracy of ±0.2 mm. Overall accuracy is within ±0.5 mm by controlling torque of the bolts. Omission of the welding process can cancel out the additional cost due to longer machining and assembling processes.

Magnetic-field distribution

Measurement of magnetic-field distribution was carried out. The current source was operated in a DC mode. An example of the field distribution is shown in Fig.3 for the cases of I = 50, 100, 150, 200, 250, 300, 350 A. An effective field length was calculated to be 180 mm. Relation between the maximum magnetic field (Bmax) and the electric currents (I) is plotted in Fig.4.
The $B_{\text{max}}$ values linearly depend on the current values, so that saturation effect inside a core seems to be negligible small. The $B_{\text{max}}$ of 6.915 kGauss obtained with the current of 347 A is strong enough compared to the specification.

Laminated cores of solenoidal magnets have more complicated structure than that of ordinary dipole magnets. Our design of the new magnet can be one of the solution.

References

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The specifications of the solenoidal magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coil length</strong></td>
<td>218 mm</td>
</tr>
<tr>
<td><strong>Bore diameter</strong></td>
<td>110 mm</td>
</tr>
<tr>
<td><strong>Maximum magnetic field</strong></td>
<td>6.87 kGauss</td>
</tr>
<tr>
<td><strong>Maximum magnetomotive force</strong></td>
<td>$1 \times 10^5 \text{ AT}$</td>
</tr>
<tr>
<td><strong>Turns</strong></td>
<td>288 turns</td>
</tr>
<tr>
<td><strong>Maximum current</strong></td>
<td>347.2 A</td>
</tr>
<tr>
<td><strong>Maximum voltage (at 20°C)</strong></td>
<td>34 V</td>
</tr>
<tr>
<td><strong>Maximum power (at 20°C, DC)</strong></td>
<td>11.8 kW</td>
</tr>
<tr>
<td><strong>Cooling water circuits</strong></td>
<td>$8$</td>
</tr>
<tr>
<td><strong>Pressure drop</strong></td>
<td>3 kg/cm$^2$</td>
</tr>
<tr>
<td><strong>Water flow</strong></td>
<td>14.2 l/min</td>
</tr>
<tr>
<td><strong>Water temperature rise</strong></td>
<td>12.5 deg</td>
</tr>
</tbody>
</table>

Fig. 1 Layout of the injector
Fig. 2 Structure of the solenoidal magnet

Fig. 3 Magnetic field distribution

Fig. 4 Relation between $B_{\text{max}}$ and $I$
Simulation of Power Supply for Rapid Cycling Accelerator

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Abstract
This paper presents a simulation of power supply for rapid cycling accelerator. Both the normal and fault condition operations are described.

1. Introduction

In rapid cycling accelerator, magnet circuit is designed into a resonant network because of two important considerations: the need to avoid drawing a large reactive power from the magnet a.c excitation source, and a uniform field intensity in each magnet (1). These requirements are satisfied by the method of connection which is based on the distributed resonance system proposed by M.G. White. The well-known White circuit (Fig.1) were consequently employed on Princeton Pennsylvania Accelerator, Electron Synchrotron NINA, KEK Proton Synchrotron Booster etc.. As for a.c excitation source, pulse method is generally chosen chiefly because of its operational flexibility and reliable performance. An energy storage choke is used to separate a.c and d.c source and the resonant circuit also provides a path for circulating d.c current (but the path for d.c connection is omitted in Fig.1 for simplicity). Here we take the NINA resonant magnet network and power supply as example to carry out the simulation.

2. Normal Operation

(1). Parameters
The parameter of each element is shown in Fig.1. The filter circuit has a resonant frequency \( f_F \),

\[
f_F = \frac{\omega_F}{2\pi} = \frac{1}{2\pi \sqrt{L_F C_F}} = 12.5 \text{ Hz}
\]

and the pulse circuit resonates at frequency of \( f_p \),

\[
f_p = \frac{\omega_p}{2\pi} = \frac{1}{2\pi \sqrt{L_p C_p}} = 150 \text{ Hz}
\]

Assume the resonant frequency of the magnet network is \( f_a \), we have

\[
f_a = \frac{\omega_a}{2\pi} = \frac{1}{2\pi \sqrt{L_M + L_{ch} \cdot C_M}} = 50 \text{ Hz}
\]

The total resonant magnet network a.c power loss is \( P_{a.c} = 950 \text{ kW} \) at maximum excitation.

(2). Operation and simulation results

The cyclic operation of the system can be divided into two periods: charging period and pulse period.

The normal operation is according to the following basic equations provided by J.A. Fox (1).

During the charging period

\[
i_F = \frac{V_s}{L_F \omega_F} \cos(\omega_F t - \pi(\omega_F / \omega_a)) \frac{\sin \beta}{\sin(\omega_F / \omega_a)}
\]

\[
i_F = \frac{V_s}{L_F \omega_F} \left[ 1 + \sin(\omega_F - \pi(\omega_F / \omega_a)) \right] \frac{\sin \beta}{\sin(\omega_F / \omega_a)}
\]

Note: \( V_s = V'_{ch} \)

During the pulse period

\[
i_p = \frac{V_s}{L_F \omega_F} \left[ \cot \beta \left( 1 + \sin \omega p t \right) + \frac{\omega p}{\omega F} \cos \omega p t \right]
\]

\[
i_F = \frac{V_s}{L_F \omega_F} \left[ \cot \beta \frac{\omega F}{\omega p} \cos \omega p t \right]
\]

\[
V_F = V_s \left[ \left( 1 - \sin \omega p t \right) + \frac{\omega F}{\omega p} \cot \beta \cos \omega p t \right]
\]

where \( \beta = \frac{\pi}{2} \left( \frac{2\omega_F}{\omega_a} - \frac{\omega F}{\omega p} \right) \)

With simulation software PSpice53, each waveform of steady-state behavior of the system is obtained as shown in Fig.2.
From the results, we can see that in pulse period the energy-storage-choke primary voltage $V'_{\text{ch}}$ reaches the peak value $V_M/n$, and the energy storage-capacitor voltage $V_F$ is opposed by $V'_{\text{ch}}$, the capacitor $C_p$ is charged twice the $V'_{\text{ch}}$ voltage peak. The peak capacitor voltage of $2V'_{\text{ch}}$ is obtained by cyclic charging through filter choke $L_p$. The choice of $V_s=V'_{\text{ch}}$ makes it possible to discharge the capacitor voltage $V_p$ to zero and utilize the capacity $C_p$ economically.

Thus, the steady-state behavior of the pulse power supply can be described as follows. The rectifier set supplying the d.c voltage of $V_g=V'_{\text{ch}}$, charges the $C_p$ through filter choke $L_p$ to $2V_s$. The pulse thyristor is then triggered to discharge $C_p$ through the pulse choke $L_p$ and the energy storage choke, consequently the resulting half-cycle current $i_p$ occurs symmetrically around the positive peak of the choke primary voltage $V'_{\text{ch}}$. Following self extinction of the pulse thyristor at $i_p=0$, $C_p$ is charged once more and the process is repeated.

3. Fault operations

Under fault condition, such as parameter mismatch, considerable $V_s$ variation, and maloperation of pulse thyristor, the system operation will deviate from the normal operation, and result in large voltage or current swing. In serious case, the system operation will not be recovered.

(1). Parameter mismatch

According to the circuit behavior, the pulse power supply has to provide the pulse of energy, equal to the cyclic ac power loss of the the resonant magnet network. Fig.3 shows the resonant network (1mesh) and it's equivalent circuit. The balance between the average network a.c power loss $P_{\text{ac}}$ and power provided by the pulse power supply can then be expressed as:

$$P_{\text{ac}} = V_s \times i_F(\text{av})$$

where

$$P_{\text{ac}} = \frac{V_{\text{ch-rms}}^2}{R_e} \times 10$$

and the average value of $i_F$ is provided by,

$$i_F(\text{av}) = \frac{V_s}{L_F \omega_F} \left( \frac{\omega_a \cot \beta}{2} + \frac{1}{\omega_p} - \frac{1}{\omega_p^2} \right) \frac{\omega_a}{\omega_F} \pi \frac{\omega_a}{\omega_p} \pi$$

According to circuit parameters, we get $i_F(\text{av})=187A$ and $P_{\text{ac}}=950\text{kw}$.

Accordingly, $R_e=2.164\Omega$, and the Q value is, $\omega_p R_e Q_{CM}=108$.

Now a circuit simulation at $R_e \neq 2.164\Omega$ (Fig.4) shows that $V_F$, $i_F$ and $i_p$ have no change if compared with the normal operation in steady state. But we noted that the related phase changed and desired magnet current will not be reached.

(2). $V_s$ variation

a. Start-up fault operation

Owing to the high Q value of the magnet resonant network, a number of cycles elapse before the magnet current reaches the steady state corresponding to the initial $V_s$. Fig.5 shows a large negative voltage swing on $C_p$ due to sudden starting by the initial value of $V_s$.

b. $V_s$ step reduction

Similar to the starting transient described above, the effect of an unrestrained reduction of $V_s$ is of great severity. The case of a step reduction of $V_s$ to half its original steady-state value is examined. Fig.6 shows the results.

(3). Maloperation caused by pulse thyristor

a. Failure of pulse valve to fire

$V_F$ is limited to a peak value of $2V_s$ according to eq(1) at normal operation. However, should the thyristor fail to fire during any one of the subsequent pulses, $V_s$ will rise to a maximum positive value of $2.64V_s$, and the pulse thyristor will be applied an overvoltage of $3.64V_s$. This process is simulated as shown in Fig.7.

b. Firing impulse 180° out of phase

This occurs when firing impulse triggered the thyristor halfway through the charging cycle. As the simulation (by Micro-cap4) shows(Fig.8), an overswing occurs on $V_F$, and $i_p$ reaches a value of almost twice the normal amplitude.

The knowledge on either the normal operation or the fault condition behavior of the system will be valuable for us in designing control and protection system for this kind of power supply.

Acknowledgement: The author would like to express thanks to Prof.K.Endo, Dr.H.Someya and Prof.Y.Irie for their great helps in this work.

Fig. 1  White circuit for resonant magnet network and pulse power supply

Fig. 2  Steady state normal operation

Fig. 3  Equivalent circuit for 1 mesh

Fig. 4  Parameter mismatch at $R_e = 4k$

Fig. 5  Start-up fault operation ($V_s = 5.07kV$)

Fig. 6  Behavior of step-reduction of $V_s$ ($V_s = 50.7V$)

Fig. 7  Thyristor firing failure ($V_s = 50.7V$)

Fig. 8  Halfway firing ($180^\circ$ out of phase) $V_s = 5.07kV$
Design of Magnet Power Supplies for KEKB Accelerator

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Abstract

A number of magnet power supplies (for Bending, Quadrupole, Sextupole and Wiggler magnet) and about 1800 Steering magnet power supplies will be prepared for KEKB Accelerator. The required specifications for these power supplies, especially the specification for the current stability is very severe. Various measurements have been carried out and in progress at present to try to realize these specifications. In consideration with the results of the measurements the design of power supplies has also been going on.

1. Introduction

There are 4 small and 4 large power supply stations in TRISTAN. 90 main and 520 steering magnet power supplies have been installed in these stations. These existing power supplies will be recycled as far as possible for KEKB Accelerator. Especially almost all of the main magnet power supplies in 4 large power supply stations will be utilized again. But the number of power supplies which have to be prepared for KEKB Accelerator is quite larger than TRISTAN case. Thus 4 new power supply stations for the installation areas of new power supplies will be reserved in the floor of the existing buildings or experimental hall of TRISTAN. The design of power supplies has been put into account in consideration with the room condition of 12 power supply stations which are different with each other.

To investigate the recycling method of the power supplies we altered a power supply of TRISTAN last year which is not in use. We are going to fabricate typical R&D magnet power supplies as well. One is for the 20kW class and the other is for the steering magnet power supplies. We will adopt the switching mode power supplies in both cases.

In this report the design process and its plan will be discussed taking into account the results from the various measured data.

2. Required Specifications for the Power Supplies

Table 1. shows the required current stability and magnetic field ripple content rate of the power supplies. In the Cu vacuum chamber actual magnetic field ripples will be smaller than current ripples because the magnet field ripples will be reduced by eddy current effect of vacuum chamber.

Thus how to realize such high current stability is a most important problem for the design of magnet power supplies.

<table>
<thead>
<tr>
<th>Power Supplies for Magnet</th>
<th>Current Stability</th>
<th>Magnetic Field Ripple Content (P-P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole Mag. (Curved Section)</td>
<td>1×10⁻⁴/year</td>
<td>1×10⁻⁵</td>
</tr>
<tr>
<td>Bending Mag.</td>
<td>5×10⁻⁴/year</td>
<td>5×10⁻⁵</td>
</tr>
<tr>
<td>Sexupole Mag.</td>
<td>5×10⁻⁴/year</td>
<td>5×10⁻⁵</td>
</tr>
<tr>
<td>Correction Mag.</td>
<td>5×10⁻⁴/year</td>
<td>5×10⁻⁵</td>
</tr>
</tbody>
</table>

To estimate the power supply design parameters many kind of measurements have been carried out to attain these current stability and. Later these problems will be discussed in detail.

Table 2 shows the list of power supplies to prepare.

<table>
<thead>
<tr>
<th>Ring Type</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Number of Units</th>
<th>Total Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER Dipole</td>
<td>1400</td>
<td>1250</td>
<td>1</td>
<td>1250</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>1100</td>
<td>2</td>
<td>2200</td>
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<td></td>
<td>130</td>
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<td>2200</td>
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<td></td>
<td>120</td>
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<td></td>
<td>30</td>
<td>1250</td>
<td>2</td>
<td>2250</td>
</tr>
<tr>
<td>Wiggler</td>
<td>400</td>
<td>1100</td>
<td>8</td>
<td>3200</td>
</tr>
</tbody>
</table>
3. Measurement of the Room Condition of the Power Supply Station

The room temperature of the existing 8 power supply stations have not been controlled. But the existing magnet power supplies satisfy the specification of TRISTAN because the control circuits of the power supply have been kept in constant temperature box. We are planning to install all new Sextupole, Steering and several Quadrupole magnet power supplies in 4 existing small power supply stations, and the other new Bending, Quadrupole and Wiggler magnet power supplies in 4 new power supply stations. But in both cases the constant temperature box will not be used by reason of the cost performance. Therefore we measured the room temperature variation at the time of power supply operation. Fig.1 shows the measured data on this summer. As can be seen the room temperature is same as the air outside when the ventilation fan has been operating.

4. Configuration Plan of KEKB Magnet Power Supplies

The KEKB magnet power supplies will be separated into two parts because of the reason mentioned in the previous sections. Namely one is a hardware part not affected by the temperature variation comes from surroundings. The other is a control part which is most important part to satisfy the specification and easily affected by the temperature drift. So the latter part has to be kept in air-conditioned room. Fig.2 shows the configuration plan of the KEKB magnet power supply. All the control units of power supplies will be put together in same air-conditioned room. The temperature coefficient of the head of DCCT will be ignored normally. So it will be installed in hardware part. On the other hand the control circuit of DCCT will be installed in air-conditioned room. In case of steering magnet power supplies the current sensors will be probably kept in air-conditioned room to reduce the cost.

5. Measurement of altered TRISTAN magnet Power Supply

Various measurements have been carried out with the configuration shown in Fig.3 by using altered TRISTAN magnet power supply. DCCT of HOLEC company has been used as the external monitor. 20m length of connection cable between DCCT head and control circuit is guaranteed by the company. So we used it to confirm the specification.
Fig. 2
B, Q and Sx Power Supply Plan for B-Factory

Power Supply Hardware Unit

- DAC
- Error Amp.
- Differential Driver
- DCT Control Unit

Control Unit

Magnet

Fig. 3
Block Diagram of Current Stability Measurement

Altered Power Supply

- GND 0.75mm square cable
- Air-conditioned Container

Temp. constant Box

16bit Digital Signal with Optical Coupling

Twisted Pair

DCCT Control Unit

Monitor

Magnet

Fig. 4 shows a typical measured data. Large drift of DCCT output at warming up was perhaps caused by temp. drift of the resistors which have been used for the differential amplifiers in the current feedback loop. The temp. coefficient of resistors is 100 ppm/degree.

6. R&D Magnet Power Supplies

It proved to be clear that the configuration shown in Fig. 3 has been applicable to KEKB magnet power supplies on the basis of the measurement described in previous sections. Accordingly by this way the fabrication of 20kW class and low power bipolar steering magnet power supplies has been going on as R&D at present. Recently in Europe and USA switching mode power supplies have been introduced for almost all of the power supplies of these classes. For example nowadays it is not difficult to use semiconductor component like IGBT. In Japan switching mode magnet power supplies for accelerator are not so popular. So we would like to adopt switching mode power supplies in both cases which have many merits like very small sizes, high power-factor etc.

7. Magnet Power Supplies for KEKB Accelerator

As pointed out in this report it will be surely possible to fabricate KEKB magnet power supplies which satisfy the given specifications. But here we point out again that how important are the selection of electric parts and the design of electric circuits.

We are now drawing up a detail construction schedule of the magnet power supplies toward KEKB Accelerator operation.
MAGNETS FOR THE HIGH BRILLIANT CONFIGURATION
AT THE PHOTON FACTORY STORAGE RING

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Abstract
The quadrupole and sextupole magnets have been fabricated for the high bright configuration at the Photon Factory Storage Ring. The field measurement of these magnets is now in progress. The shape and thickness of the end-shims in both of the quadrupole and sextupole magnets were determined to correct the higher multipole fields, whose effects were less than \( \pm 1 \times 10^{-4} \) for the quadrupoles and \( \pm 2 \times 10^{-4} \) for the sextupoles at a position of 36 mm from the magnetic center.

1. Introduction
The emittance upgrade for the high brilliant configuration is made by doubling the quadrupole and sextupole magnets in the normal cell section [1]. Severe conditions are however required to these magnets. The space to place the double magnets is limited and they are interfered with the photon beam lines because the bending magnets are fixed. Moreover, they are rather strongly excited than the existing ones; twice for the quadrupoles and ten times for the sextupoles at maximum. Under such conditions the magnets have been designed and fabricated, and the field measurement is now going.

2. Design and Fabrication
2-1. Quadrupoles
Two types of the quadrupoles for QF and QD in the normal cells were designed. Their principal parameters are summarized in Table 1. The schematic drawing is shown in Figure 1. They have same cross-sectional view and are different in core length. The cores are made of soft iron. The coils are water-cooled. Because of the space limitation, not only the core lengths but also the mechanical lengths including coils were made as short as possible. The bore radius (40 mm) is smaller than that of the present quadrupoles (55 mm) to produce field gradient strong enough to realize a 3 GeV operation with the smallest emittance optics. Not to disturb the SR extraction to the existing beam lines, the cores are Collins types. The cores are supported by SUS blocks to keep the field symmetry. The outer SUS supports have several types of shape to fit several types of the SR extraction ports.

2-2. Sextupoles
The core of all the sextupoles are same. Their principal parameters are summarized in Table 1. The schematic drawing is shown in Figure 2. The cores are made of soft iron and are C-shaped for the SR extraction. The coils are water-cooled. The lengths and the bore radius are small because of the same reason on the quadrupoles. The cores are supported by SUS blocks to prevent mechanical deformations, which have several types of shapes as in the case of quadrupoles. The sextupoles have auxiliary windings for vertical steering to save the spaces for correcting magnets. They also have auxiliary windings to correct the field asymmetry which arises from the core shape.

Table 1 Specifications of the magnets

<table>
<thead>
<tr>
<th>Type</th>
<th>QF</th>
<th>QD</th>
<th>SX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Length</td>
<td>0.40 m</td>
<td>0.25 m</td>
<td>0.20 m</td>
</tr>
<tr>
<td>Bore Radius</td>
<td>40 mm</td>
<td>40 mm</td>
<td>45 mm</td>
</tr>
<tr>
<td>Max Field Gradient</td>
<td>24 T/m</td>
<td>24 T/m</td>
<td>600 T/m²</td>
</tr>
<tr>
<td>Max. Current</td>
<td>900 A</td>
<td>900 A</td>
<td>450 A</td>
</tr>
<tr>
<td>Turns/Coil</td>
<td>19 turns</td>
<td>19 turns</td>
<td>17 turns</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>17 kW</td>
<td>13 kW</td>
<td>6 kW</td>
</tr>
<tr>
<td>Water Flow</td>
<td>9.4 l/min</td>
<td>7.2 l/min</td>
<td>4.0 l/min</td>
</tr>
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</table>

3. Field Measurement
The field measurements of these magnets are now in progress using a harmonic coil method [2], which is a standard technique to obtain the main field and the higher multipole components precisely. In this method, the induced voltage is represented as a function of an angular position since a coil is rotated in a magnet. Then the harmonic content of the magnet is directly given as the Fourier components of the induced voltage.

Fig. 1 Schematic drawing of the quadrupole magnet
3.1 Measurement System

Figure 3 shows the schematic view of our measurement system. The system is designed so that we can measure two magnets simultaneously; for example, a pair of quadrupole and sextupole magnets. The length of the coil is within 1 m in consideration of a distortion of the bobbin made of glass-epoxy resin, in which the coil is wound. The bobbin is packed in the rotating cylinder which is fixed by two checking collet. The reproducibility of the cylinder position is less than ±50 μm. The cylinder is rotated by a DC motor whose speed is available to change from 10 to 100 rpm. During rotation an angular encoder mounted in one side of the cylinder outputs an angular position signal, which is used as a trigger of the integration of the induced voltage. The alignment between the geometric center of the magnet and the coil axis is made using a level scope and targets whose center position is marked. Two digital integrators employing a voltage-to-frequency converter (VFC) and a precise amplifier are used in data acquisition. They are controlled by on-line computer through GP-IB interface. The specification of the system are listed in Table 2.

Table 2 Specifications of the harmonic coil measurement system

<table>
<thead>
<tr>
<th>Guarder</th>
<th>material</th>
<th>iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil Support</td>
<td>method</td>
<td>checking collet</td>
</tr>
<tr>
<td></td>
<td>signal output</td>
<td>4 pin rotary connector</td>
</tr>
<tr>
<td>DC Motor</td>
<td>rotating speed</td>
<td>10 ~ 100 rpm</td>
</tr>
<tr>
<td>Angular Encoder</td>
<td>resolution</td>
<td>6000 pulse/turn</td>
</tr>
</tbody>
</table>

3.2 Rotating Coil Probe

Two different set of the rotating coil probe are used in the measurement; one is a radial coil set, and the other is a tangential. The radial coil set is located in the plane of one axis, while the tangential is installed on the cylinder surface.

The radial coil set consists of two separate coils; one is a long coil for measuring the integrated field gradient and the other is a short for the point field gradient, whose parameters are listed in Table 3. The purpose of the radial coil is to measure a precise main field gradient and a deviation of the magnetic center from the geometric center.

Table 3 Parameters of the radial coil set

<table>
<thead>
<tr>
<th>Coil</th>
<th>Long</th>
<th>Short</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>1000</td>
<td>20</td>
</tr>
<tr>
<td>Radius (mm)</td>
<td>29.9</td>
<td>29.5</td>
</tr>
<tr>
<td>Turn Number</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

On the other hand, the tangential coil set is composed of six different coils; φ4, π4, π/2, and 3/2π coils for the quadrupole magnets and φ6, π6, π/2, and 3/2π for the sextupole magnets are connected. The cross section view of coil geometry is shown in Fig. 4. All are long coils to measure the integrated field. Since the main field components reduce with proper angles and turn numbers of the coils listed in Table 4, the higher multipole components should relatively enlarge. For example, the measured data are shown in Figs. 5 for QD and SX types. While the main field components reduced in both magnets, the higher multipole ones are clearly observed; the dodecapole component (n=6) is dominant for QD and the 18 poles (n=9) for SX without a end-shim correction.
Table 4 Parameters of the tangential coil set

<table>
<thead>
<tr>
<th>Coil</th>
<th>ø4</th>
<th>ø6</th>
<th>π4</th>
<th>π6</th>
<th>π/2</th>
<th>3/2π</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>925</td>
<td>925</td>
<td>925</td>
<td>925</td>
<td>925</td>
<td>925</td>
</tr>
<tr>
<td>Radius (mm)</td>
<td>36.0</td>
<td>36.0</td>
<td>36.0</td>
<td>36.0</td>
<td>36.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Angle (rad)</td>
<td>0.206</td>
<td>0.148</td>
<td>π</td>
<td>π</td>
<td>0.5π</td>
<td>1.5π</td>
</tr>
<tr>
<td>Turn Number</td>
<td>10</td>
<td>14</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

3.3 End-Shim Correction

Since large higher multipole fields are undesirable in real operation, it is hopeful to reduce them as possible. In general it is available using a proper end-shim implemented on the magnetic poles. So one of the important purpose in the field measurement is to search parameters of the end-shim. Figures 6 show a field gradient ratio of the dominant higher multipole field component to the main field one. Data were measured by 100 A step of an excitation current and 2 mm step of a thickness using a tangential coil. Since the higher multipole effect depends on the thickness of the end-shim we could easily determine the best thickness to reduce them; 4 mm for QD and QF, and 3 mm for SX. As a result the higher multipole effects were reduced less than ±1×10⁻⁴ for QD and QF and ±2×10⁻⁴ for SX a position of 36 mm from the magnetic center.

Fig.4 Cross section view of the tangential coil geometry

Fig.5-a The integrated induced voltage as a function of an angular position at an excitation current of 900 A on QD

Fig.5-b The integrated induced voltage as a function of an angular position at an excitation current of 450 A on SX

Fig.6-a The field gradient ratio of the dodecapole field to the quadrupole field on QD

Fig.6-b The field gradient ratio of the 18 pole field to the sextupole field on SX

References

Design Study of Sector Magnet for the RIKEN Superconducting Ring Cyclotron (I)


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Abstract

Design study of the sector magnets for a superconducting ring cyclotron, which is adopted as a post-accelerator of the existing ring cyclotron, is carried out. Superconducting main coils as well as superconducting trim coils for rough fitting to isochronous fields are adopted for the sector magnets. Isochronous field distributions and betatron tunes are calculated.

1. Introduction

An "RI beam factory" has been proposed as a next facility-expanding project of the RIKEN Accelerator Research Facility (RARF)1]. The "RI beam factory" aims at production and acceleration of radioactive isotope beams covering the whole mass region. It requires the energy of ion beam to be higher than 100 MeV/nucleon. To meet this requirement, we have adopted a superconducting ring cyclotron (SRC) as a post-accelerator of the existing RIKEN Ring Cyclotron (RRC).

The SRC is expected to boost the energy of ion beam from the RRC up to 400 MeV/nucleon for light heavy ions like carbon ions and 150 MeV/nucleon for very heavy ions like uranium ions. The sector magnet of SRC have to be flexible enough to generate isochronous fields in a wide range of energies and for various q/A's. In this report we describe the feature of the sector magnet together with field calculation and orbit analysis.

2. General Description

The maximum acceleration energy of the SRC was determined by experimental requirements. The maximum energies for typical ions are summarized in table 1. Beam currents are expected to be more than 100 μA for 400 MeV/nucleon light heavy ions such as carbon and oxygen ions and about 0.2 μA for 150 MeV/nucleon uranium ions. The minimum acceleration energy of the SRC is about 60 MeV/nucleon for very heavy ions.
Isochronous field distributions for typical ions are shown in Fig.2. The maximum required field in the sector magnet becomes nearly 4 T. Field difference between at the injection radius and at the extraction radius on the sector axis is 0.7 T for 400 MeV/nucleon ions and 0.1 T for below 100 MeV/nucleon ions. Therefore both main coils as well as trim coils for coarse fitting have to be superconducting.

3. Sector Magnet and Field Calculation

Magnetic fields were calculated by the three-dimensional code TOSCA[2]. For the sector magnet only a quarter of it was modeled because of its symmetry. For the coils a complete set of them in only one sector was taken into account in the calculation. An example of modeled magnet for TOSCA is shown in Fig.3. Strictly speaking, TOSCA requires all conductors of the system to be taken into account. But owing to appropriate selection of reduced potential region, good agreement of the magnetic field on the median plane can be obtained for both the six-symmetry system and the system with only one set. This method shortened the calculation time to be less than 25% of that of the six-symmetry system.

One important point in the design of the sector magnet is to optimize its geometry so that the magnetic forces acted on the main coil can be as small as possible. The expanding force acted on the radial part of the main coil reaches the order of several hundreds tons. One way to support such a main coil is to put the pole in the cryostat and to fix the main coil directly to the pole (cold-pole method). Detailed study has been carried out in ref. 3. In the case of the cold-pole magnet with a sector angle of 23 deg., the excitation current is 2.9 MA/sector.

Conceptual sketch of the superconducting trim coils is shown in Fig.4. If the trim coils can be controlled by many independent currents, fields can be generated flexibly and precisely. But cryogenic system requires the minimum number of current leads to reduce heat load. Three sets of superconducting trim coils thus bring a realistic solution. Maximum excitation current of one set of trim coils is estimated to be 240 kA.

4. Isochronous Field and Tune

Equilibrium orbits and betatron tunes were calculated by the computer program that had been originally developed for the RRC. Results of the field distributions by TOSCA were used in the orbit calculations.

Because of saturation of the iron pole, the field distribution is largely affected by coils' configuration. Examples of field distributions are shown in Fig.5 and Fig.6. In the region of the valley, negative field is
Fig. 5 Field distributions along the sector axis produced with (1) Main coil and (2) Main coil + Trim coil for 400 MeV/nucleon $^{12}$C$^+$ ions.

Fig. 6. Field distribution along the azimuthal direction at (1) $r = 5.5$ m, (2) $r = 4.7$ m and (3) $r = 3.9$ m.

Fig. 7. Tune values at a sector angle of 23.0 deg. for (1) 400 MeV/nucleon $^{12}$C$^+$, (2) 150 MeV/nucleon $^{239}$U$^{90+}$ and (3) 60 MeV/nucleon ions with $q/A = 0.25$.

created. This field brings large flutter and sharp fringing field. Therefore, vertical focusing force is larger than that in a normal conducting ring cyclotron.

Using three sets of superconducting trim coils, it was possible to adjust various distributions of isochronous fields within ±0.02 T. By the optimization of the configuration, it is expected to be less than ±0.01 T. Further fine adjustment will be done with trim coils of room temperature.

In the case of high energy acceleration, vertical tune $v_z$ decreases as the energy increases. The sector angle was selected so that vertical tune value never across $v_z = 1.0$. Smaller sector angle causes larger vertical focusing force. But from the viewpoint of minimizing the maximum field, large sector angle is preferable. Figure 7 shows typical tune values calculated for the sector angle of 23.0 deg. All the tune values are within the range from $v_z=1.0$ to $v_z=1.5$.

5. Summary

Design study of the sector magnet for the superconducting ring cyclotron for the proposed RIKEN RI beam factory has been carried out. Until now, it has turned out that isochronous fields for various ions can be generated by using synchronous fields and superconducting trim coils within ±0.01 T. Detailed design studies and further optimization are under way.

References

Design Study of Sector Magnet for the RIKEN Superconducting Ring Cyclotron (II)


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Abstract

A conceptual design of the superconducting sector magnet for the RIKEN superconducting ring cyclotron is described. A comparison of the warm pole system with cold pole one is discussed. Magnetic forces, coil support system, coil cooling method and cryogenic system are also described.

1. Introduction

The superconducting ring cyclotron proposed for the RIKEN RI beam factory needs six units of superconducting sector magnets, each of which must generate the maximum magnetic field strength of 4 T in the beam orbital area. We use superconducting coils for the sector magnet to obtain a compactness in size and to save electric power and cooling water. The yoke and pole made of magnetic iron are arranged in the sector magnet to reduce the ampere turns of the superconducting coils and to minimize the leakage magnetic flux.

2. Structure of Superconducting Sector Magnet

Figure 1 shows an overview of the sector magnet. A cryostat is not drawn in this figure. The main components of the magnetic elements are superconducting coils, poles and a yoke. We use two kinds of superconducting coils: a pair of main coils and a group of trim coils. Both coils are located upper and lower sides with respect to the mid plane. We have studied two ways of arrangements for the pole. One is a warm pole system and the other a cold pole one. Figure 2 shows the both systems and a cryostat. As for the warm pole system, the poles are directly connected to the yoke in room temperature region, and thus the cold mass at 4.5 K consists of superconducting coils and coil vessels. As for the cold pole system, the main superconducting coil is wound around the pole directly, so the cold mass consists of superconducting coils, poles and coil vessels. From points of view the mechanical rigidity and magnetic force, we have decided to use the cold pole system. However, a serious problem on the cold pole system is the difference of thermal contraction between the pole and the coil vessel during the cooldown of the cold mass from 300 K to 4.5 K. We are currently investigating this problem.

3. Magnetic Field and Forces

A three dimensional display of the magnetic field on the median plane calculated using the OPERA (TOSCA) code is shown in Fig.3. Figure 4 shows the comparison of expanding forces on the straight section of the main coil between for the warm pole system and the cold pole one. It is clear the force in the cold pole system can be reduced by one-third of that in the warm pole system. This effect is due to the short distance between the main coil and the pole in the cold pole system. Figure 5 shows the changing of the maximum magnetic field (at a radius of 6 m on the median plane) and the magnetic forces Fx,Fz in the cold mass (consists of main coils and
cold poles), as a function of the ampere turns of two (a pair of) main coils. The magnetic force $F_z$ in the vertical direction is supported with two coil links which are arranged between the upper cold mass and lower one. The force of 300 tons maximum causes a mechanical deflection of about 4 mm maximum of the cold mass. The magnetic force $F_x$ in the radial direction is generated with a configuration of the six sector magnets. Each cold mass is pushed toward outer radius by the forces from sector magnets at both-side. The maximum force of $F_x$ is estimated to reach about 500 tons per each magnet. It is very difficult to support this force by thermal insulating supports which locate in between the cold mass and the vacuum vessel. To support such a large $F_x$, we are investigating a cold ring of 2.6 m in diameter and 200 mm in thickness which connects the six cold masses in the central region of the ring cyclotron.

4. Superconducting Coils

The main superconducting coil has a triangle shape with two long straight sections of about 4 m length. This force is supported by the coil vessel and the cold pole. It is very hard, particularly for the coil in non-circular shape, to prevent the coil's wire movement that causes a coil quench. However, we should avoid the coil quench, because the total magnetic energy stored in six magnets reaches as much as 300 MJ. Quench-free is indispensable for maintain a reliable long-time operation for the cyclotron. Taking the above matter into account, we apply fully cryogenic-stable cooling for both the main coil and the trim coil adopting a method of conservative liquid-helium bath cooling. The operation currents of the main coil and trim coil are roughly set to be 5000 A and 500 A, respectively. In order to maintain the cryogenic stability, the average current densities of them should be less than 40 A/mm² and 50 A/mm², respectively.

5. Cryogenic System

The total heat leak of six magnets is roughly estimated to be 500 W at 4.5 K.

A helium refrigerator having a capacity of 1 kW at 4.5 K stage will be used for six sector magnets and the beam injection & extraction channels. Weight of the total cold mass of six magnets is about 360 tons. It will take almost one month for the cooldown of the cold mass from room temperature to 4.5 K by the helium refrigerator.

6. Conclusion

Conceptual design of the superconducting sector magnet for the RIKEN superconducting ring cyclotron has been carried out. The arrangement of the coil and pole has been studied, and we have decided to adopt the cold pole system in order to support and reduce the magnetic forces in the coil. We are planing to construct a model of the superconducting sector magnet to confirm our design.

References

1. Y.Yano, "RIKEN RI-Beam Factory Project", This symposium.
2. T.Mitsumoto et al., "Design Study of Superconducting Sector Magnet for the RIKEN Superconducting Ring Cyclotron (I)", This symposium.

Fig.1 Overview of Superconducting Sector Magnet (for three dimensional magnetic field calculation)
Fig. 2 Comparison of Pole Arrangements

Fig. 3 Three Dimensional Distribution of Magnetic Field in Mid Plane

Fig. 4 Comparison of Expanding Magnetic Forces in Coil Straight Section

Fig. 5 Field Strength & Magnetic Forces
FREQUENCY UP-SHIFTS OBSERVED IN MICROWAVE—PLASMA INTERACTION

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Abstract

Frequency up-shifts and some higher frequency components have been observed in the interaction of a high power microwave ($f_0=9\text{GHz}$) with an unmagnetized inhomogeneous argon plasma. The relationship of the frequency up-shift with incident microwave power, plasma density and strength of electric field have also been investigated. The induced frequency up-shift is considered to be related to a rapidly expanding plasma which is created by the ponderomotive force of a strong standing wave.

I. Introduction

Recently, the frequency up-shift (blue shift) has been studied in laser plasma interaction and plasma wake field accelerator [1,2]. Frequency up-shifts in laser–plasma interaction have been observed in recent experiments by Wood et al. and Savage et al [3,4].

The first observation of the frequency up-shift in the microwave-plasma interaction without any ionization front has been reported [5,6]. In this paper, we demonstrate that when a high power microwave is injected into an underdense plasma a frequency up-shift around 2MHz and some other higher frequency components from 2 to 8MHz have been observed.

II. Experimental Arrangement

In the present experiments, a cylindrical, unmagnetized argon plasma column was created by a pulsed discharge between two directly heated LaB$_6$ cathodes in a vacuum chamber (32cm in diameter, 60cm in length) as shown in Fig.1. A typical plasma discharge pulse duration is $t_w=2\text{ms}$ with a repetition rate of 10 Hz. The typical plasma parameters are: maximum electron density $n_0 \leq 1.2 \times 10^{12}\text{cm}^{-3}$ and electron temperature $T_e \approx 3 \sim 5\text{eV}$. The estimated electron-ion collision frequency is $\nu_{ei} \approx 4.5 \times 10^6\text{sec}^{-1}$, and ion-neutral collision frequency is $\nu_{in} \approx 10^5\text{sec}^{-1}$. Within the experimental region of concern, a parabolic density, $n_0 = n_{\text{max}}[1-(z-z_0)^2/L_z^2]$, is observed in the z direction. Here $L_z$ is the half-width of the density profile along the chamber axis, $n_{\text{max}}$ is the maximum plasma density during the experiment and $z_0$ is the position of the maximum density layer, while in the radial direction there is a quite weak linear density gradient. In the present experiments, the $L_z$ is around 25cm and $L_r$, the gradient length in radial direction, is around 300cm.

III. Experimental Results

Pulsed microwave ($f_0=9\text{GHz}$) with a risetime of $\tau \approx 100\text{ns}$, maximum power of 250kW and a typical pulse width of $\tau \approx 3\mu \text{s}$ is radiated synchronously with the discharge pulse through a rectangular horn antenna (aperture area= $13.5 \times 10.5\text{cm}^2$) from the lower density side of the plasma along the chamber axis (z direction). The ratio of the electric field energy to the plasma energy is $\varepsilon_0 E_0^2/4\pi n_c K T_e \approx 0.1$, where $E_0$ is the amplitude of the electric field of the incident microwave, $n_c = 1.0 \times 10^{12}\text{cm}^{-3}$ is the plasma density of critical layer and $K$ is Boltzmann's constant. Because the pulse width of the microwave is short enough for the ionization or plasma heating, these effects can safely be neglected. The plasma density perturbation and rf signal in the plasma are detected by a plane Langmuir probe and a cylindrical probe, respectively.
at \( z = 11 \text{cm} \) where plasma density \( n_0 = 0.5n_c \) with two different incident powers. Here \( z \) is a distance from the horn antenna aperture. The dashed and solid lines represent the spectra of rf signals of 35 and 250kW, respectively. It can be seen that the up-shift is 2.5MHz when \( P_1 \) is 250kW, but is 0.5MHz when \( P_1 \) is decreased to 37kW.

The relationship between the upper frequency components and the incident power is plotted in Fig.3. We found that as the incident power of the microwave \( P_1 \) is increased from 0 to 250kW, the frequency up-shift \((f_1)\) and the higher frequency components \((f_m, m=2, 3)\) can only be observed when \( P_1 \) is higher than 7.9kW, i.e. the threshold power for the present phenomenon is around 7.9kW. This result is the same as that we obtained before [5,6].

![Fig.2 Frequency spectra of microwave for different incident power.](image)

![Fig.3 Frequency up-shift and higher frequency components vs. incident power.](image)

The relationship between the frequency up-shift and plasma density has also been investigated. Figure 4 shows the dependence of the frequency on plasma density. It can be seen that when the plasma density \( n_0 \) is increased from 0 to \( 0.9n_c \, (n_c = 1 \times 10^{14} \text{cm}^{-3}) \) the up-shifted frequency increases from 0 to 2MHz, and the higher frequency components increase from 0 to about 8MHz proportionally to the plasma density.

![Fig.4 Frequency up-shift and higher frequency components vs. plasma density.](image)

As mentioned in Ref[5,6], the up-shifts are due to moving plasmas which are created by the ponderomotive force of the incident wave. So, the frequency up-shifts should have a relation to the strength of the electric field of the incident wave. In order to verify it, a moveable reflecting plate is put near the end wall of the chamber \((z_r=0 \text{cm})\) for investigating the dependence of frequency spectra on the intensity of the electric field. The the electric field intensity of the incident wave \(|E|^2\) and frequency spectra are observed at a fix point \( z=11 \text{cm} \) while the reflecting plate is moved from \( z_r=0 \) to 9cm with a step \( \Delta z=0.4 \text{cm} \).

![Fig.5(a) Electric field intensity vs. reflecting position.](image)
The electric field intensity $|E|^2$, frequency up-shifts and higher frequency components observed as a function of reflecting position are shown in Fig.5(a) and Fig.5(b). It is obvious that the frequency up-shifts and higher frequency components have been observed at which the electric field intensity is strong.

IV. Discussion

Frequency up-shifts have been verified experimentally in the interaction of high power microwave and plasma. As shown above, the observed up-shifted frequency and higher frequency components depend not only on the incident power of the microwave and the plasma density but also on the strength of electric field. According to Refs.[5,6], the frequency up-shifts are due to moving plasmas arising from ponderomotive force and the velocity of the expanding plasma can be written as

$$v \approx \frac{2P_i \omega_0^2}{cL \omega_0^2} - K(T_i + T_e) \nabla n_0 \nu (m_i n_0),$$

(1)

where $A$ is the irradiation area of the microwave, $c$ is speed of light in vacuum and $m_i$ is ion mass. $T_i$ and $T_e$ are ion temperature and electron temperature, respectively. If we take $P_i=250$ kW, $f_0=9$ GHz, $T_e=3$ eV, $A = 5 \times 10^{-2}$ m$^2$, $\nu=3 \mu$s, $l=8 \times 10^{-3}$ m, the velocity of the expanding plasma is estimated to be $v \approx 7.5 \times 10^6$ cm/s.

When the incident wave encounters such a moving plasma, a part of it is reflected by the plasma, and the rest transmits through the moving plasma. In the frame of the moving plasma (the prime frame) the frequency of the incident wave is $\omega'_i = \gamma(1 + \beta)\omega_0$, where $\gamma = (1 - \beta^2)^{-1/2}$, $\beta = v/c$. Performing an inverse Lorentz transformation to get back to the lab frame, the wave frequency for the reflected wave is

$$\omega_r = \gamma^2(1 + \beta)^2 \omega_0^2.$$

while for the transmitted wave, it is found that

$$\omega_t = \gamma^2(1+\beta) \left[ 1 - \beta \left( 1 - \frac{\omega_0^2}{\omega_0^2 \gamma^2(1 + \beta)^2} \right)^{1/2} \right] \omega_0,$$

(3)

Substituting $v = 7.5 \times 10^6$ cm/s (experimental result) into Eq.(2), the frequency up-shift of the reflected wave is $\Delta f_r = 2\Delta f_0 \approx 4$ (MHz), and for the transmitted wave, the frequency up-shifted is $\Delta f_t = 1\Delta f_0 \approx 2.1$ (MHz). These results are in good agreement with the experimental results. Since the up-shifted frequency signal interacts with the moving plasmas several times within one pulse duration of the incident wave, higher frequency components could be observed in the experiments.

V. Conclusion

In summary, the frequency up-shift around 1 ~ 2 MHz and some other higher frequency components in the range of 2 MHz to 8 MHz have been demonstrated again experimentally in the interaction of microwave ($f_0=9$ GHz, $P_i=250$ kW) with underdense plasma. It has been predicated theoretically that a frequency up-shift may occur when an electromagnetic wave interacts with an underdense ionization front [7]. This mechanism is verified by our experiments of microwave-plasma interaction when there is no ionization front. It means not only an underdense ionization front but also a moving underdense plasma can be used to up-shift the frequency of a microwave radiation. In the present case, because a strong standing wave is established in the chamber, the plasma is expanded rapidly by the collective ponderomotive force arising from the electric field gradient of the standing wave. The reflected and transmitted waves interact with the moving plasmas, and the frequency is up-shifted due to the Doppler effect.

References

Formation of duct in Plasma by High Power Microwave and Self-Focusing

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Abstract
The first experimental demonstration of ducting of high power microwave in a preformed density channel is studied. The microwave remains trapped and guided in a preformed density channel. These results are in good agreement with a numerical model describing the microwave propagation.

1. Introduction
One of the most interesting topics is the application of the laser to plasma based particle accelerators with a ultrahigh gradient. A number of ways to excite plasma waves having gradients as high as several ten of GeV/m have been proposed so far. A laser driven accelerator that has a number of attractive features is the laser wakefield accelerator (LWFA) [1,2]. But LWFA has the fault that the acceleration distance is severely limited to the diffraction length, or Reyleigh length. This phenomenon is particularly interesting for processes requiring a long interaction length such as x-ray lasers [3] and laser-driven accelerators. More recently numerous theoretical works on this subject [4,5] have been performed and experimental results [6,7] have also been presented.

2. Theory of optical guiding
One approach to the guiding of an intense electromagnetic waves uses the effect depending on self-induced modulations of the plasma refractive index. In a plasma there are two types of optical guiding mechanisms. One is the self optical guiding due to the ponderomotive force of an intense electromagnetic wave and the other is the optical guiding due to the relativistic effect. The former utilizes the dependence of refractive index on the plasma, which is given by

\[ N = \sqrt{1 - (\frac{\omega_p}{\omega_0})^2}, \]

where \( \omega_0 \) is the incident-wave frequency, \( \omega_p = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2} \) is the plasma frequency and \( n_e \) is the electron density. With the preformed density channel along the pass of electromagnetic wave, it propagates in this channel over distances exceeding Reyleigh length. The latter results from the increase of the refractive index due to the relativistic quiver motion of electrons. Because the refractive index has the largest peak on the axis where the intensity of electromagnetic wave has a maximum, the distribution of refractive index is the same as that of an optical fiber. Such relativistic self-guiding occurs when the incident-wave power \( P \) exceeds a critical power [8,9] given by

\[ P_c = 16.2\left(\frac{\omega}{\omega_p}\right)^2 \text{GW}. \]

3. Experimental Set up
The experimental arrangement used in the present studies is shown in Fig.1. A cylindrical, unmagnetized argon plasma is produced in a stainless-steel chamber of 60 cm length by 32 cm diameter covered with a number of multipole permanent magnets for a plasma confinement.

![Fig.1 Experimental apparatus](image-url)
a plane Langmuir probe. The typical plasma parameters are the maximum electron density \( n_e \approx 2.0 \times 10^{12} \) cm\(^{-3}\), electron temperature \( T_e \approx 3 \sim 5 \) eV in an argon gas pressure \( P_0 = 3 \sim 4 \times 10^{-4} \) Torr.

The pulsed microwave with frequency \( f_0 = \omega_0/2\pi = 9 \) GHz and a maximum power of 250 kW and the pulse duration of 1 \( \mu \)sec in FWHM is irradiated from a rectangular horn antenna (aperture area= 13.5 x 10.5 cm\(^2\)) with a metal lens located at a lower end of plasma density toward a higher density area along the chamber axis.

4. Experimental Results

The density channel is formed by inserting the Polyimide film sheet with 240 mm length by 15 mm width and 125 \( \mu \)m thickness at the center of the chamber filled with the plasma. In the present experiment, the sheet is inserted from the higher density to 15 cm position from the edge of metal lens. We may estimate that the radius of density channel is about 1 cm.

When the microwave pulse is injected into this density channel, Fig.2 shows an axial profile of observed electric field pattern as a function of incident power. We observe that with increasing the incident microwave’s power the microwave pulse propagates deeper along the density channel and that the electric field also becomes stronger. The electric field tends to be confined around the axis (\( r = 0 \) cm) as the microwave pulse propagates along the channel. We can measure that the spatial separation of three peaks (\( \alpha, \beta, \gamma \)) appear in Fig.2 (a) is about 2.2 cm. Three peaks can be visible as the incident power increases. We know that the wave length of the fundamental TE mode in the wave guide (WRJ-10: 2.29 x 1.02 cm\(^2\)) is \( \lambda_g = 4.8 \) cm. If we assume that the observed wave in the experiment is the fundamental TE mode, we suppose that the standing wave of the mode is formed in a density channel.

5. Discussion

In order to interpret the observed behavior, we calculate a transverse profile of the microwave in the density channel. We assume that the microwave pulse is weak enough to neglect the relativistic effect. We use a propagation model approximated by that in an optical fiber with refractive index \( N_1 \) inside and \( N_2 \) outside. Because the microwave field is axially symmetric, we can look for the fundamental TE mode solution of Maxwell’s equations. In a slab geometry, this solution [10] is given by

\[
E_\phi = \begin{cases} 
E_0 \cos(k_y y) \exp(-jkz) & (|y| \leq a), \\
E_0 \cos(k_y a) \exp[-p(|y| - a)] \exp(-jkz) & (|y| > a), 
\end{cases}
\]

where \( k_y^2 = N_2^2 k_0^2 - k^2 \), \( p^2 = k^2 - N_2^2 k_0^2 \) and \( k_0 = \omega_0/c \), \( c \) is the speed of light and \( a \) is the channel radius. Applying the continuity condition of magnetic field \( H_y \), we obtain the characteristic equations

\[
p = k_y \tan(k_y a), \quad p^2 + k_y^2 = k_0^2 (N_1^2 - N_2^2). \tag{3}
\]

This numerical calculation enables us to determine the transverse profile for propagation of microwave in the plasma channel.

We assume that the channel radius is \( a = 1 \) cm from the experimental result. Because the plasma density of channel outside is overdense, we may put

\[
z = 19 \sim 20 \text{ cm}, \quad \text{while the field amplitude has maximum on the axis. Therefore, we can say that the microwave pulse is focused at } z = 19 \sim 20 \text{ cm.}
\]

Figure 3 (b) shows the half width of the field radial profile as a function of the incident power. Fig.3 (b) indicates that the half width has a minimum at the maximum power \( P = 250 \) kW. It is evident from Fig.3 (b) that the half width tends to decrease with increasing the incident power.
$N_2 = 0$. We carry out the calculation as a function of the refractive index $N_1$. Figure 4 shows the transverse profile of the microwave calculated for abovementioned conditions and the observed experimental results. Note that experimental and numerical values are normalized. Solid lines and dashed lines are results calculated for the cases of $N_1 = 1$ (in vacuum) and $N_1 = 0.5$, respectively. One can see that there is a fairly good agreement between experimental and numerical results. The experimental result at the lower density (Fig. 4 (a)) is more agreement with the numerical result of $N_1 = 0.5$ than that of $N_1 = 1$, while at the higher density (Fig. 4 (b)) the observation shows better agreement with $N_1 = 1$. These results obtained for Fig. 4 can understand as follows. As the microwave propagates along the plasma channel, the electric field of microwave in the channel is maximum around $z = 19$ cm. Therefor, the refractive index of channel increases, since electrons in the channel are pushed out of the channel by the enhanced ponderomotive force. As a result, the refractive index of channel changes gradually along the plasma channel. We can say the results indicate that the ducting of the microwave is formed and that the microwave propagates along the channel.

Fig. 4 Normalized radial field profiles. Each curve represents numerical results. The parameters are channel radius $a = 1$, refractive index $N_2 = 0$, and $N_1 = 0.5$ (dashed line), $N_1 = 1$ (solid line). Axial positions (a) $z = 17$ cm, (b) $z = 19$ cm.

The variation of refractive index is very important and the motion of the electron has to be taken into account. The plasma is modeled using no relativistic cold fluid equations. Using the momentum and continuity equations, we can estimate that $\delta n/n_e$ is directly proportional to the incident power. The half width has $\Delta r \approx 1/k_p$. Using equation (3), the half width is approximated by $\Delta r \approx 1/k_p \sim 1/N_1$. Because the channel refractive index is given by $N_1 = (1 - n/n_e)^{1/2} \sim \sqrt{P}$, where we put $n = n_e - \delta n$, the half width is given by

$$\Delta r \sim 1/N_1 \sim 1/\sqrt{P}. \quad (4)$$

On writing in this result on Fig. 3 (b) by solid lines, the experimental and the theoretical results are in good agreement. But this comparison can only be qualitative.

6. Conclusion

We have demonstrated that the ducting of the microwave is formed and the microwave pulse remains trapped and guided in the plasma channel at the fundamental TE mode. The comparisons of the experimental observations with the theoretical calculations produce good agreement for both the transverse profile of the electric field and the dependence on the incident power of the half width $\Delta r$. We have shown that the experimental result can be explained by the concept on the "optical guiding".

Acknowledgement

We would like thank Mr. X. Xu for his corporation on establishing the experimental device. This work was supported by a Grant-in-Aid for Scientific Research from Ministry of Education, Science and Culture, Japan.

References

Experimental Demonstration of $V_p \times B$ Acceleration Scheme with Use of Transverse Electromagnetic Waves

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Abstract
Electron linear acceleration, using a slow transverse electromagnetic wave (TE wave) supplemented with a crossed static magnetic field, has been demonstrated. An energy gain of 3.5 keV is measured for electrons with a 64 keV incident energy, in a 0.5 m long accelerator, when an external magnetic field of 0.67 G is applied. The results show the feasibility of a high gradient, compact accelerator using TE mode intense laser or short wave length microwave without slow wave structure or mode converter.

I. Introduction
An accelerator is proposed in which a TE-mode wave is used to drive charged particles in contrast with the usual linear accelerators based on the $V_p \times B$ acceleration mechanism in which longitudinal electric fields or TM-mode waves are supposed to be used. Using TE mode as a driving wave allows higher gradient and more compact accelerators, because the slow wave structure, or mode converter, is not necessary for high energy accelerators. In this paper, we report results of proof of principle experiments on the $V_p \times B$ acceleration scheme using the TE wave in vacuum. In order to couple particles with the transverse wave we use a slow wave structure created waveguide composed of parallel dielectric materials and of conductors.

II. Theory
Suppose that the transverse electromagnetic wave which has a maximum electric field $E_x$ and a maximum magnetic field $B_y$ in the $x$ and $y$ direction, respectively, propagates with a phase velocity $v_p$ in the $z$ direction (see Fig. 1). When an external static magnetic field $B_0$ with an amplitude smaller than $B_y$ is applied in the $y$ direction, there exist two magnetic neutral points (A and B) where the electric field is non-zero. Around point B, the Lorentz force acts on the particles with its velocity, $v \approx v_p$, which are accelerated by the electric field in the $x$ direction, in the $z$ direction as restoring force. Therefore the particles bunch there and are accelerated by the wave electric field in the $x$ direction, continuously.

The motion of a charged particle with the rest mass, $m$, and charge, $q$, in the above-mentioned system is described by the equation of motion. The trapping condition is obtained by the balance of the equation of motion in the wave propagation direction ($z$ direction) such as,

$$|B_y| > \gamma_p^2 B_0.$$  \hspace{1cm} (1)

where $\gamma_p$ is the Lorentz factor measured with the wave phase velocity, $v_p$. Inequality represents the unlimited acceleration condition. In other words, if this condition is satisfied, electrons can be accelerated continuously without detrapping from the wave trough.

III. Experimental set-up and results
A schematic view of the experimental set-up is shown in Fig. 2(a). The injected electrons with beam
Table I. Dimensions of the dielectric wave guide.

<table>
<thead>
<tr>
<th>Dielectric materials</th>
<th>Macrol and Folsterght</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator length</td>
<td>48 cm</td>
</tr>
<tr>
<td>thickness Ad</td>
<td>50 mm</td>
</tr>
<tr>
<td>width 2i</td>
<td>50 mm</td>
</tr>
<tr>
<td>separation 2d</td>
<td>13~33 mm</td>
</tr>
<tr>
<td>height (2d + 2Ad)</td>
<td>113~133 mm</td>
</tr>
</tbody>
</table>

The electrons accelerated through the accelerator are analyzed by a magnetic field bending type energy analyzer which has a uniform magnetic field of 200 G. The electrons are detected by a microchannel plate (MCP) electron multiplier with a slit of 2 mm in front of it. The MCP is scanned spatially in the analyzer and the position at which the signal is detected from the MCP corresponds to the energy and the signal intensities to the electron fluxes. The maximum resolution of the energy analyzer is less than 0.1 keV. This instrument is calibrated with the above-mentioned electron beam source. The calibration is carried out by changing the acceleration voltages without RF power before and after the main experiments. In the experiments, the orbit of the electrons is bent by the applied magnetic field. When the electron energy was measured, the energy analyzer is adjusted such that the electrons are injected normal to its slit inlet.

A pulsed electromagnetic wave, with a 10 kW maximum power, is generated by a magnetron which is triggered by an external timer with a typical pulse width of 5 μs with repetition of 10 Hz. The generated microwave is absorbed by a nonreflection dummy load after going through the slow-wave structure.

The static, vertical magnetic field for the $v_p \times B_0$ acceleration is generated by a pair of saddle-shaped external coils. Uniformity less than 3% covers length of 32 cm (40 cm for 5%) in the $z$ direction and 5 cm in the $y$ direction. A maximum field strength of 10 G is measured at the center of the accelerator. This value is high enough to demonstrate the $v_p \times B_0$ principle with TE mode under the present experimental parameters.

![Fig.2](image)

**Fig.2.** Experimental apparatus and the crosssectional view of the wave guide loaded dielectric material. (a) Experimental apparatus for the proof of the principle of the electron accelerator using TE wave. (b) Schematic drawing of the dielectric wave guide.

![Fig.3](image)

**Fig.3.** Energy increment, $\Delta e$, as a function of the incident electron energy, $e_0$, without external magnetic field. Incident microwave power: $P = 10$ kW. The solid lines indicate the calculated maximum energy increment, at the maximum electric field value of $E_x = 20$, 30 and 40 kV/m.

Figure 3 shows the electron energy increment as a function of incident electron energy $e_0$ with no externally applied magnetic field. The maximum electron...
energy increment, $\Delta E = 1.3$ keV, is observed when the incident electron energy $E_0$ is 64 keV. This implies that this slow wave structure is resonated with the frequency of 2.45 GHz, and the phase velocity is corresponded to the energy of the order of 64 keV. The vertical error bars indicate the variation in electron energy due to the instability of beam transparency arisen from the induced space charge on the dielectric surface through the wave guide. The resonance at the electron energy of 64 keV is slightly smaller than the designed value of 66 keV. The results show that an efficient acceleration is occurred when the wave phase velocity is slightly larger than the beam velocity. A strong deceleration is observed for electrons with an energy $E_0 = 60$ keV. In Fig. 3 the calculated results of the electron energy increment are also displayed by solid lines when the wave electric field is $E_x = 20, 30$ and $40$ kV/m (shown in the next section).

![Graph showing electron energy increment as a function of static magnetic field](image)

**Fig. 4. Energy increment, $\Delta E$, as a function of the static magnetic field $B_0$ with $P = 10$ kW. The solid lines show the calculated values when $E_0 = 20, 30$ and $40$ kV/m. Symbols $\bigcirc$ and $\Delta$ stand for $E_0 = 64$ keV and 66 keV, respectively.**

Figure 4 shows the electron energy increment as a function of an external applied magnetic field. Symbols $\bigcirc$ and $\Delta$ stand for values of the incident electron energy of $E_0 = 64$ and 66 keV, respectively, and solid lines are the calculated results with an electric field amplitude $E_x = 20, 30$ and 40 kV/m. In Fig. 4, as the static magnetic field is increased, the electron energy increases until $B_0 = 0.67$ G at $E_0 = 64$ keV. A maximum energy increment of 3.5 keV is observed at the incident energy of 64 keV with an external magnetic field of 0.67 G.

IV. Discussion

The energy increment is computed by solving the equation of motion of an electron for the parameters of the present experiment, assuming $v_p = 0.461c$, $E_x = 20, 39$ and $40$ kV/m and $\tau = 3.2$ ns, where $\tau$ is the time that the electrons travel throughout the wave guide. The electric field strengths are estimated from the distribution of an incident microwave power in the wave guide. The Runge-Kutta method is used to these calculations with 100 test particles uniformly distributed initially in the phase space. Although the profile of the electric field amplitude in the wave guide depends on the position, we select the value on the axis of the waveguide, because almost all electrons propagate through the center of the wave guide in the present experiments. In the present experiment, the trapping condition inequality (Eq. (1)) is violated, because it takes more than 20 ns to reach the steady state. When $E_x = 30$ kV/m, it is good agreement with the experimental data in Fig. 3. Therefore the assumption on the intensity of the electric field is reasonable to energy increment the electron motion in the wave guide. In Fig. 4, the observed energy increment is larger than the calculated value. This discrepancy is not clarified yet. The condition of the transient state, however, should be taken into consideration for more precise explanation of the experimental results.

V. Conclusion

Electron acceleration using a slow transverse electromagnetic wave (TE wave) supplemented with a static magnetic field has been demonstrated. An energy gain of 3.5 keV for electrons is observed from an incident energy of 64 keV in a 0.5 m accelerator, when an external magnetic field of 0.67 G is applied. The results show the feasibility of high gradient compact accelerator using an intense laser or short wave length microwave without slow wave structure.

Acknowledgment

Vivid discussions with Prof. S. Takeuchi were greatly appreciated. Part of the present work was supported by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture of Japan. A part of the work and the construction of the machine were supported by IDX Co., Tokyo, Japan.

References

Continuous Beam Monitoring for Charged Particle Therapy


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Abstract
Continuous beam monitoring can ensure beam stability during beam irradiation for charged particle therapy. It can also detect the beam which is not synchronized with a patient's respiratory in case of treatment of an organ moving with respiratory. A MWPC was adapted to these purposes. It was used in air to not disturb beam. The effective thickness of the MWPC with respect to the beam is only that of wires. Therefore, scattering the beam and losing the energy of the beam in the MWPC is sufficiently small so that they do not affect charged particle therapy. The MWPC was proved to be useful by use for biology experiments.

Introduction
The Heavy Ion Medical Accelerator in Chiba (HIMAC) at National Institute of Radiological Sciences is the first heavy ion accelerator complex dedicated for charged particle therapy1,2). Charged particle therapy severely requires controlling dose of beam and safety assurance. In the HIMAC, the dose is measured by using two monitors, an ion chamber and a secondary electron monitor, at the same time. Occurrence of any abnormal conditions interlocks the beam irradiation through a global interlock system.

Furthermore, the continuous beam monitoring is one of strong means to ensure beam quality as follows. The first is assurance of stability of beam profile and position, because they affect beam intensity distribution at an isocenter. The second is detection of the beam which is not coincident with a patient's respiratory during the treatment of an organ moving with the respiratory. When such a beam spill is detected, the treatment is interrupted in order to make beam extraction coincident with the respiratory. Thus the continuous monitoring shall be one of the activities of quality assurance for the charged particle therapy.

Beam monitor for medical use
A multi-wire proportional chamber was in use for the continuous monitoring. The MWPC is same as that developed for beam monitors used at the high energy beam transfer lines (HEBT) of the HIMAC3). A picture of the MWPC is shown in Fig.1.

![MWPC used in air](image)

Fig.2 Configuration of the BIOLOGY beam course

![Configuration of the BIOLOGY beam course](image)
Rare gases or organic gases are generally used to obtain high amplification factor of the MWPC. In these cases, thin windows are necessary on the MWPC to have gas tight structure. Our purpose is focusing to use the MWPC as a sort of non-destructive monitors, so that the MWPC should have no window on it. Eventually, air is used as the sensor gas of the MWPC. Therefore the beam passing through the MWPC has a probability to collide with only the wires. We describe the effects of the collision as an average thickness of the wires, that is approximately 8x10^-2g/cm^2. This is corresponding to water equivalent thickness of only 0.8mm. This value is negligibly small in comparison with thickness of a margin on a target volume in a body.

The MWPC was installed at the end of BIOLOGY beam line as shown in Fig.2. The MWPC is located between the end of beam duct and Wobbler magnets. The beam intensity is uniformly distributed at the isocenter by a pair of Wobbler magnet and a scatterer. Each wobbler magnet sweeps sinuously the beam in horizontal or vertical direction. Combination of both motions of the beam results in rotational motion. The rotating beam is scattered by the scatterers. In this way, the beam of maximum diameter 22cm become uniform within ±5% at the isocenter. Scattering effect at the MWPC affects the uniformity. However, the effect evaluated by a calculation is only less than 1x10^-3%. Eventually the MWPC can be regarded as the non-destructive monitor for the charged particle therapy.

Electronics

We used the same electronics with that used for the beam profile monitors of the HEBT^3). Generated current on a wire of the MWPC is integrated on a capacitor in the integration circuit.

The electronics gives us good performance as follows. Typical noise level is 1 digit of full scale 2048-digit. The noise level is independent of the time width of integration. It means that leak currents in electronic elements do not contribute to the noise, or are very small. A simple estimation shows that the leak currents are supposed to be less than 0.1nA each channel. Cross talk between adjacent channels is less than -60dB. Because of the low noise level and the small cross talk, the beam profiles can be observed clearly even though the peak height of the profile is less than 0.1V.

Tests and results

In order to test the MWPC under various beam conditions, the MWPC was installed in BIOLOGY beam course as mentioned above. The BIOLOGY beam course is used for biology experiments and not therapy.

Fig.3 shows dependence of the gas amplification factor on applying voltage. It was measured at C^6+ 290MeV/u beam. The amplification curve is normalized to 1 at plateau region. Because the amplification factor should be 1 at the plateau region. The curve shows the amplification factor is about 20 at -2.7kV the maximum voltage of the MWPC. The amplification factor 20 is small compared with that of same type profiles monitors used at the HEBT. They gain more than 5,000 filling with Ar-CO2 mixed gas^4). Comparatively small amplification factor results from quenching effect due to oxygen. An oxygen component of air strongly quenches electron avalanche even under a considerably strong electric field. Charged particle therapy is performed using the beam intensity of 3.6~3.2x10^8pps. In order to observe such a beam, the MWPC does not need to obtain a wide intensity range. This condition does not require the MWPC to have high amplification factors.

Dynamic range of this MWPC system spans from 1 to 2,000. This results from that the range of amplification factor of the MWPC is from 1 to 20, and the dynamic range of the electronics is from 0.1V to 10V as mentioned already. Then the intensity range of observable beams is estimated, for instance of C^6+ 290MeV/u beam, to be from 3x10^6pps to 6x10^9pps. It is sufficiently wide to cover the intensity range necessary for charged particle therapy or related measurements except for measuring LET.

A beam profile of C^6+ 290MeV/u beam observed by the MWPC is shown in Fig.4. The MWPC is located at downstream from the last triplet quadrupole magnets of the BIOLOGY beam course. The triplet quadrupole
Magnets are forming 10mm diameter beam at the isocenter 11m downstream. Therefore, the beam has an approximate round shape as shown in the figure.

Although an exposure of a film to the beam and scanning the density measured the beam uniformity, difference of the uniformity was undetectable as expected. High voltage of -1kV was continuously applied to the MWPC for about 3 months. An approximate amount of total beams was 1.314 particles. No damage due to radiation is found on the MWPC at present.

Conclusions

We summarize the results of the MWPC and these tests as follows.

1) The MWPC worked stably in air and gained the amplification factor of about 20 at -2.7kV. The total dynamic range including that of the electronics is from 1 to about 2,000. It is sufficiently wide to monitor the beam for charged particle therapy and related measurements.

2) Disturbance of the beam was negligibly small so that it was supposed not to affect charged particle therapy and related measurements.

We do not test the MWPC to detect the beam which is not synchronized with a patient's respiratory, because the irradiation coincident with a patient's respiratory is in a test stage at present. However, we know that the response of MWPC is sufficiently fast to interrupt the irradiation within acceptable dose ambiguity.

We can conclude the MWPC system is working as a non-destructive beam monitor with versatility to ensure the quality of treatment. A damages due to radiation of a long term, however, must be watched continuously in future.

Acknowledgment

We would like to express our gratitude to the other members of Research Center of Charged Particle Therapy of NIRS for helpful discussion. We also wish to thank the members of Accelerator Engineering Corporation for their warm support.

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DEVELOPMENT OF AN ANALOG SWITCH GATING A SINGLE BUNCH

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1. Introduction

Most storage machines require a multi-bunch operation in order to achieve a high intensity. KEKB\cite{1} also requires a multi-bunch operation, where about 5000 bunches will be filled in rf buckets with a period of 2 ns. It is not guaranteed that stored bunches have always the same intensity and the same position. Therefore, it is important to measure the beam parameters of each bunch. There would be two methods to obtain the beam information on each bunch. The first one is to sample successive bunches with a rate of more than 500 MHz and store data in a memory bank after digitalization. The second as an alternative method is to pick up a specified bunch with a ultra-fast gating switch. A gated signal is slowly processed within one revolution. A switching time should be much shorter than a bunch spacing time. Changing timing of a gate pulse responds to other bunches. The former is applied for the bunch-by-bunch feedback system\cite{2,3}. However, it would be technically difficult to convert sampled data to a normalized position signal in real-time. The latter technique using a gate is described here. This technique is adequate for measuring a specified bunch in real-time, but cannot measure all bunches at the same time.

2. Analog Switch

In order to pick up one bunch under a multi-bunch operation, a switching time of less than 1 ns is required in the KEKB. However, commercially available analog switches using PIN diodes and GaAs FETs do not satisfy the requirement. A fast analog switch using Si-bipolar transistors with $f_T$ of 10 GHz has been developed\cite{4} for a burst modulator. A switching time was obtained to be 1.2 ns. The on/off isolation was more than 60 dB at 200 MHz. Circuit configuration of the switch has been kept and the transistors used in the circuit were replaced by those with higher $f_T$ of 35 GHz in order to shorten the switching time. Fig.1 shows the circuit of the ultra-fast analog switch. The circuit consists 12 transistors. The transistors from T3 to T6 control the switch by comparing the voltage externally applied at J1 with the $V_{R1}$. In order to pick up one bunch under a multi-bunch operation, a switching time of less than 1 ns is required voltage $V_{R1}$. The switch is off when the voltage at J1 is zero and on at -0.7 V. An rf signal passes through from J2 to J3. The bias voltages VCS1 and VCS2 are used for adjusting offset voltages of an output signal.

![Fig. 1 Circuit of analog switch.](image)

3. Performance

The switch has been manufactured as a monolithic IC and packaged in a case of 9.3 mm square with 21 pins. A frequency response was measured using a network analyzer. Fig. 2 shows transmission loss (S21) with on and off. The insertion loss is about 11 dB up to 1 GHz. The on/off isolation is about 40 dB at 500 MHz and is getting worse as frequency increases. The isolation is worse than that expected in a simulation, which may be due to stray capacitances.

A transient response was tested. A continuous rf wave of 508 MHz was prepared and divided into two ways. One is applied to the switch input J2 and the other to a frequency divider. The divider produces a pulse corresponding to the revolution frequency by doing 1/5120, where 5120 is the harmonic number of KEKB. An output pulse of the divider is used as a trigger of a gate pulse. Rise and fall times of the gate pulse which synchronizes with the rf wave should be much faster than the bunch spacing time. The switching time was less than 200 ps. Switching noises were observed in an output signal of the switch. The noises shaping a spike were reduced by a low-pass filter of 800 MHz. Fig. 3 shows an example of the transient response. We may notice that a continuous wave is converted to a mono-pulse. Table 1 summarizes specifications of the analog switch.
Fig. 2 Frequency characteristics. Horizontal frequency range is 0.05 GHz to 2.05 GHz. Vertical scale is 10 dB/div.

Table 1 Specifications of the switch.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
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<tr>
<td>Input/Output Impedance</td>
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<tr>
<td>Input Amplitude</td>
<td>0.7 V p-p max.</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>1.0 MHz to 1.0 GHz</td>
</tr>
<tr>
<td>Control</td>
<td>0 to -0.7 V</td>
</tr>
<tr>
<td>Switching Time</td>
<td>200 ps max.</td>
</tr>
<tr>
<td>ON/OFF Isolation</td>
<td>40 dB min. at 500 MHz</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>11 dB</td>
</tr>
<tr>
<td>Power Supply</td>
<td>200 mW</td>
</tr>
</tbody>
</table>

Fig. 3 Transient response of the switch. Upper trace shows an input rf signal of 500 MHz with 400 mV/div. Middle one is a gated output signal with 50 mV/div. A low-pass filter of 800 MHz is used. Lower one is a gate pulse with 1 V/div. All traces are swept with 1 ns/div.

4. Signal Processing

Two techniques to detect a beam pulse are widely used. One is a narrow-band method, where a specified frequency component of a beam pulse is detected with a band-pass filter. The other is a wide-band technique, where a pulse height or area of a pulse is detected. Let's compare the S/N in both techniques assuming that one bunch is gated with 2 ns gate width and the signal process is carried out within one turn (10 μs). The bandwidth is more than 100 kHz. The thermal noise level is proportional to square root of the bandwidth. On the contrary, a signal amplitude in the frequency domain is approximately reduced to the duty factor (2x10E-4) in the time domain. Therefore, the wide-band detection in the time domain has an advantage for the S/N ratio in a turn-by-turn measurement.

One example of the turn-by-turn measurement is shown in Fig. 4. The apparatus will be able to measure the betatron tunes as used in TRISTAN[5]. A beam pulse is picked-up by a button electrode and will be stretched out by a coaxial cable. Low-pass filters also stretch the beam pulse further so as to not overlap successive bunches. A low noise amplifier is needed in order to compensate the loss occurred at the gate. The BOD[6] (Bunch Oscillation Detector) samples the gated beam pulse with a self-produced pulse and holds its peak voltage. The BOD can detect AC components of a normalized beam position with a help of an AGC (Automatic Gain Control) loop. The betatron tune measurement is very important especially in the components of a normalized beam position with a help of an KEKB since the beam-beam tune shift gives us a transverse beam size at a colliding point.

![Fig. 4 Block diagram for detecting the betatron tunes.](image)

As a summary, we have developed an analog switch for gating a single bunch. The gating switch has the switching time of 200 ps. The on/off isolation was 40 dB at 500 MHz. This switch would be used for monitoring a bunch intensity and the betatron tunes in real-time.

References

Analog Processor for Emittance Monitor in SPring-8 Linac


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Abstract

The analog processor for the emittance monitor in the SPring-8 linac is composed of a charge sensitive amplifier with gain control, a sample/hold circuit and an isolation circuit. The charge sensitive amplifier detects pulsed charge from the wire scanner. The sample/hold circuit maintains the signal to which can be accepted by an A/D converter on VME computer. It is designed as 1V/pC, 0.1V/pC or 1V/nC. The linear region was measured as -5V~5V of output. Fluctuation of output for 200 seconds was ~1.5mV of 6σ. However voltage drift was observed for 150 hours. But this is acceptable for emittance measurement.

1. Introduction

Profile monitors are generally used for emittance measurement. There are many kinds of profile monitors for example a wire scanner, a scintillation screen, an OTR monitor and so on. In the SPring-8 linac, a wire scanner is employed for the emittance monitor [1]. When an electron beam impinges on the wire, secondary emission charge and the bremsstrahlung are generated. Both are proportional to the charge of incident electron beam. An analog processor which detects the secondary emission charge is employed for the emittance monitor in the SPring-8 linac. However the efficiency of secondary emission charge from incident charge is reported as 6-7% for total surface at 30MeV~1GeV. Because of this low efficiency, a high gain charge sensitive amplifier is required. The analog processor has a sensitivity of 1V/pC nominally. The minimum charge is expected as <0.01pC/pulse at the positron mode (Ins width and 10mA peak current). Therefore the minimum signal output is expected as <10mV. The fluctuation of output signal is must be comparable (~10mV of 6σ) to measure the positron beam profile.

Because an A/D converter on VME computer only acquires DC voltage, the output signal of the charge sensitive amplifier is processed to DC voltage by a sample/hold circuit.

Fig. 1 Photograph of the analog processor.
frequency by the PLL circuit. Then the frequency is transferred through an isolation transformer to the second PLL circuit. Finally the frequency is restored to a DC voltage by the second PLL circuit.

3. Examination of Analog Processor

The analog processor was adjusted and examined using a simulated pulse. An appropriate reference capacitor $C_i$, 10pF, 100pF or 0.01µF, was connected to the input of the analog processor. When a step voltage $V_i$ was applied, a corresponding charge $-C_iV_i$ was generated on the reference capacitor. At the same time the charge flowed into the analog processor. This means the charge of $C_iV_i$ was transferred to the feedback capacitor of the charge sensitive amplifier. Fig. 3 shows the CS-507 outputs when various charges were applied. Due to the charge $C_iV_i$ on the feedback capacitor, the CS-507 generated the voltage of $CS_i$. However the charge was released exponentially through the resistor. Once the exponential curve was obtained, the peak voltage would be calculated by the curve fitting at the value at t=0. Fig. 4, Fig. 5 and Fig. 6 show the peak voltage of CS-507 output when the various charges were applied. The variation of DC output is also plotted. The region where the output is proportional to the input within ±1% is named linear region. The linear region was measured as -5V~+5V of DC output. The linear region will be extended to -10V~+5V of DC output if further adjustment will be performed. The sensitivity and the offset voltage are calculated by the curve fitting in the linear region. These measured characteristics are summarized in Table 1.

![Fig. 2 Block diagram of analog processor.](image)

![Fig. 3 CS-507 output when the simulated charge is applied from -10pC to 10pC by 1pC step.](image)

The fluctuation (standard deviation) of DC output for 200 second (100 samples) was measured as shown in Fig. 7. The correlation between the input charge and the standard deviation means that this fluctuation was caused by the PLL circuit. The average is ~1.5mV (1σ).
This value can be acceptable to measure the positron beam profile.

Fig. 8 shows the fluctuation for 150 hours. Each data was acquired in different run. The maximum difference of CS-507 output is $-3.5 \text{mV}$. On the other hand the maximum difference of DC output is $-85 \text{mV}$. The sample/hold circuit and the isolation circuit may be affected by room temperature drift.

5. Reference


### Table 1

<table>
<thead>
<tr>
<th>Output</th>
<th>Linear Region</th>
<th>Sensitivity</th>
<th>Offset of DC Output</th>
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</thead>
<tbody>
<tr>
<td>CS-507 High</td>
<td>-6 to 10 [nC]</td>
<td>-0.7324 [V/pC]</td>
<td>NA</td>
</tr>
<tr>
<td>DC Output High</td>
<td>-6 to 6 [pC]</td>
<td>-1.0046 [V/pC]</td>
<td>10.1 [mV]</td>
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<tr>
<td>CS-507 Medium</td>
<td>-50 to 100 [pC]</td>
<td>-0.09795 [V/pC]</td>
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<tr>
<td>DC Output Medium</td>
<td>-50 to 60 [pC]</td>
<td>-0.10030 [V/pC]</td>
<td>6.35 [mV]</td>
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<tr>
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<td>-5 to 10 [nC]</td>
<td>-0.9920 [V/nC]</td>
<td>NA</td>
</tr>
<tr>
<td>DC Output Low</td>
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<td>-1.0038 [V/nC]</td>
<td>13.55 [mV]</td>
</tr>
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</table>

4. Conclusion

The analog processor achieved as designed characteristics. The fluctuation for 200 second can be acceptable to measure the positron beam profile. However the fluctuation for 150 hours is rather large. This means that measurement must be performed in few minutes. The linear region is $-5 \text{V}→+5 \text{V}$ of DC output. This can be extended to $-5 \text{V}→+10 \text{V}$.
Horizontal COD measurement and correction system in HIMAC synchrotron


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Abstract

A horizontal COD measurement system has been made which has twelve electrostatic pick-up monitors beside focusing quadrupole magnets. The measured horizontal COD has maximum value of 14mm, and is corrected down to 2mm with simple way by use of twelve steering magnets which have been set at same places of the monitors.

I. Introduction

HIMAC synchrotron[1] has been designed to accelerate heavy ions from He to Ar. Injection energy is 6MeV/u and maximum energy is 800MeV/u for ions of e/m=0.5. The maximum required beam intensities for each ion species are determined to have dose rate of 5Gy/min. In the carbon case which is being used for cancer treatments now, required beam intensity is 4x10^9 ppp. To obtain this value in the synchrotron, the multturn beam injection scheme is adopted. Hence, horizontal and vertical acceptances of the ring are 260µm and 260µm mrad, respectively. Slow beam extraction with third order resonance is used, and this process requires extra horizontal space for last three turn. To determine the sizes of vacuum chambers and good field regions of magnets, additional spaces for residual COD after the correction are added. Hence the maximum apertures are ±122 and ±28mm in horizontal and vertical directions, respectively. Non uniform contraction and deformation of base concrete after final alignment deteriorate its accuracy, and increase the COD. To correct these horizontal CODs and maintain the machine acceptance large, the horizontal beam position monitor and the steering magnet systems have been constructed.

II. Electrostatic pick-up monitors

To measure the horizontal COD, electrostatic pick-up monitors with triangular right and left electrodes have been made. The electrodes that are 260mm long are made of stainless steel SUS316L. The aperture is 238 mm wide and 32mm height, which is defined with window frames to prevent the noise due to lost beam hitting. The capacitance is 110pF and its balances between the right and left electrodes in each monitors are adjusted within 2 pF with a movable ground plate (see Fig.1).

Fig.1 Electrostatic pick-up monitor together with steering magnet.

To check the output, test signal with a rod in the monitor chamber has been used. Amplitudes of
output signals from right and left electrodes ($V_R$ and $V_L$) have been measured as a function of the rod position. With simple assumption the position ($x$) is given as follows:

$$ X = \frac{(W/2)(V_R-V_L)}{(V_R+V_L)} \tag{1} $$

where $W$ is electrode width. In Fig.2 the measured values of $\frac{(V_R-V_L)}{(V_R+V_L)}$ are plotted versus the horizontal rod position, and show linear dependence on $X$ in the full aperture with 24% larger value of the coefficient $W$ (294mm) than the geometrical electrode width (238mm). If there are unbalanced capacitances or setting errors of right and left electrodes, measured beam position has offset error. If this error was larger than 0.5mm, we adjusted the capacitance balance to reduce the measured position at the center.

III. Monitor electronics

Monitor electronics is similar to the one[2],[3] in an acceleration system except for following points.

1) Between pick-up electrode and first FET amplifier, there is semi-rigid cable of 40cm which has resistor of 100Ω in the middle. As shown in Fig.3 this attached resistor permit to amplify the beam signal without distortion by the signal reflection. And this cable permit to attach the first amplifier away from the vacuum chamber and to decrease radiation damage of the FET amplifier.

2) There is only one beam signal processor for position detection, and the beam signals from twelve monitors are selected with diode switches. Isolation between input channels are better than 62dB, which value is good enough for our purpose. Switching speed is 200ns and this fast speed make it possible to measure twelve horizontal beam positions in a short time as flat base period.

At the end of signal processor a low pass filter of 1kHz is used to reduce the white noise. The measured output values are shown in Fig.4. In this monitor system, frequency range of input signal is from 1 to 8MHz, and gain range from 0 to 60 dB (range used in daily operation). With difficulty of the fine adjustment in the wide range of frequency and gain, monitor electronics have offset errors of ±2mm. Owing to the wide horizontal aperture of ±122mm, this error is acceptable.

IV. Steering magnets

Twelve steering magnets have been installed at the same place as monitors to correct the horizontal COD. The magnets have been made with laminated core to make possible the pattern operation for COD.
correction at flat top. Maximum field strength is determined to correct the expected CODs at the flat top field which are 16 mm. The value is 800 Gauss with the magnet length of 10 cm. The magnet power supplies are controlled with pattern data of 12 bits.

V. COD measurement and correction

To check the monitor, beam positions were measured for different RF capture frequencies (see Fig.5). Changing RF frequency ($\delta f$), the beam position ($\delta x$) varies as follows:

$$\delta x = \eta \gamma^2 \gamma_u (\gamma U^2 - \gamma^2 \delta f^2)$$

where $\eta$ is dispersion at the monitor, $\gamma$ is the energy in units of the particle rest energy, and $\gamma_u$ is the value at the transition energy. In the HIMAC synchrotron $\gamma_u = 3.67$, $\gamma = 2.5 m$, and $\gamma = 1.0$ at injection. By use of these parameters,

$$x = 2.7 \times \delta f^2 (m)$$

and this coefficient is consistent with the measured value of 2.8 m.

Measuring the displacement of beam position at the monitor with excitation of one steering magnet, this matrix elements of $A$ can be determined experimentally.

At the flat base the COD could be reduced to the value smaller than 2 mm (see Fig.6) with steering magnets, whose field strengths were calculated with an equation-(5).

VI. Acknowledgements

The authors would like to appreciate engineers of Iwatsu electric co., LTD and Sukegawa electric co., LTD for their effort to produce the nice components in this system, they are also grateful to the operating crews of AEC for their skillful assistance.

VII. References

Development of a Beam Pulse Monitor for the JAERI AVF Cyclotron

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Abstract

A beam pulse monitor has been developed for timing information about pulsed beams produced by the JAERI AVF cyclotron. This monitor provides fast timing signals for beam pulses of proton and heavy ions using a micro-channel plate, which detects secondary electrons and photons yielded by interaction between the beam and a target. In addition to using a wire target, we adopted a thin aluminum foil target for increasing the amount of electrons and photons. The monitor has been tested in 45 MeV proton and 260 MeV neon beams.

1. Introduction

The JAERI AVF cyclotron (K=110) accelerates various ion beams from proton to xenon in a wide range of energies mainly for materials science experiments. The extracted beams from the cyclotron are pulsed at the same frequency as the RF of the cyclotron and thinned out at an interval (1μs-1ms) by a beam chopping system for time-of-flight experiments and time-resolving analyses.

The timing information on the beam pulse is needed for tuning parameters of the chopping system to a required condition of the beam pulse. Use of a trigger signal produced by detection of the beam pulse allows higher time-resolution experiments than that of a signal originated from the RF because of fluctuation of phase difference between the beam pulse and the RF. We have a plan in which the cyclotron beam energy will be measured by a time-of-flight method with fast timing counters to calibrate an analyzing magnet.

For these purposes, a beam pulse monitor, detecting the beam pulse with high time resolution and high sensitivity, has been constructed and tested using 45 MeV proton and 260 MeV neon beams.

2. Beam Pulse Monitor

The beam pulse monitor provides a fast timing signal of the beam pulse by detecting secondary electrons and photons emitted from a target inserted into the beam. A structure of the monitor is shown in Fig. 1. A foil target, having a large interaction area with the beams, has been adopted for detection of high-energy light ion beams. A wire target was also mounted for detection of low-energy heavy ion beams so as to minimize the degradation of the beam.

The foil target is a 3 mm thick aluminum-foil strip with 5 mm width, and the wire target is a tungsten wire 0.3 mm in diameter. The foil and the wire targets are placed in front of the MCP at a distance of 50 mm and 94 mm, respectively. The foil and the wire targets are stretched in parallel with the MCP and at a right angle to the beam direction. They are positioned away from each other in the beam direction so as not to disturb a flow of the secondary electrons from the wire target. The foil target is tilted at an angle of 45 degrees to the beam line.
beam axis for efficient detection of secondary electrons and photons emitted from the surface of the foil.

Secondary electrons are collected into a micro-channel plate (MCP, F4655-10, Hamamatsu photonics Ltd.) through a slit using an electrostatic field. The operational voltage of the MCP is -2.4 kV, a recommended maximum voltage.

The collection field for secondary electrons, biased up to -6 kV relative to the entrance of the MCP, is produced with seven sets of electrodes. The electrodes are spaced at 20 mm by insulator rods of Al₂O₃. Each electrode is connected with neighbor ones by dividing resistors to form a uniform electrostatic field. A floating high-voltage power supply with two outputs is used for adjustment of the collection field independently from the MCP voltage. One of the outputs serves a potential of the MCP and the other serves a potential of the top of the electrode relative to the MCP.

The entrance face of the MCP, and the surfaces of the wire and the foil targets were evaporated with CsI for optimizing the emission of secondary electrons.

The monitor was installed in a chamber at the end of the beam line, where the pressure is around 10⁻⁹ Pa.

The output signal from the MCP was amplified by a fast preamplifier (Ortec VT120) and fed into a constant fraction discriminator (Ortec 935) to produce fast timing signals. A time to amplitude converter (TAC) was started by the MCP signal and stopped by the RF signal with a divided rate. The output of the TAC was fed into a CAMAC analog to digital converter (ADC) and analyzed on a personal computer with a data taking system, “K-max”.

3. Results and discussion

Time spectra for 45 MeV H⁺ and 260 MeV ⁸²⁰Ne⁺ beams at a collection voltage of -4 kV are shown in Fig. 2 and 3. Each spectrum shows the time structure of the beam having one or two peaks in this case. Difference between the peak widths measured with each target indicates that the time resolution using the foil target is superior to the one using the wire target.

The expansion of the peak width for the wire target suggests interference with the secondary electrons emitted from the wire target. A flow of secondary electrons from the wire target may be disturbed and widen in time when passing through the field near the foil target.

At a collection voltage of 0 V, the peaks of the spectra appear at faster positions on time axis than the peaks of the spectra at collection voltages of more than a few kV. An example of the peak shift is shown in Fig. 4.

The results of the test suggest that the main particles collected into the MCP are photons at 0 V and electrons at -4 kV. Adjustment of the collection voltage allows the selection of the particles detected with the MCP.
4. Conclusion

We have developed a beam pulse monitor which provides a fast timing signal for light and heavy ion pulsed beams produced by the JAERI AVF cyclotron using a MCP. An aluminum foil and a tungsten wire can be used for producing electrons and photons originated from the beam pulse. In this arrangement of the targets, the foil target is superior to the wire one in time resolution.

References

We report here diagnostic measurements of accelerated protons of 400MeV in RCNP Ring Cyclotron.

1. Introduction

To clear the problems on the extracted beam qualities concerned with accelerated beam dynamics in RCNP Ring Cyclotron, we developed a beam viewing system with TV camera and a phosphor covered scintillation plate. It enable us to take a continuous picture of beam position and size in full radius of acceleration. The scintillation plate is mounted in front of the copper beam stopper of the main probe head. From these measurements, we can deduce the vertical and radial oscillation frequencies in each radial positions.

2. T.V. camera and scintillation plate

The phosphor plate which has scintillating surface obtained by spraying ZnS on an aluminum plate(1mm thickness) is mounted in front of the copper beam stopper( on the main probe head for an integral current monitor). The viewing ports for this is set at the valley region beyond the one sector magnet from the main probe location. The T.V. monitor camera outside the vacuum chamber views the inside mirror inclined 45-degree to the median plane of the accelerator. In order to look over the whole view for the radial range of the main probe, the setting of the mirror and T.V. camera should be changed several times. One measurement for that radial range is about 600mm. The scintillation plate on the main probe moves at the speed of 20mm/sec by taking a picture for the monitor TV with POLAROID camera at B-mode. The observed vertical oscillation is shown in Fig. 1.

3. Main probe

A main probe measures the current and the transverse shape of the beam in the Ring Cyclotron. It consists of a tomography head of three thin platinum wires and an indirectly cooled beam stop. The probe can be adjusted for the probe head to face the tangential direction of the beam orbit at any radius. The driving speeds can be chosen between 20mm/sec and 200mm/sec. At the beam tuning, the current measured with this probe is about 10nA. Thus the efforts to get good signal to noise ratio for weak beam current down to 1nA are being made. A 30 Hz 5th order(30dB/Oct.) low pass filter is used. Moreover, the attenuation of 30dB for 60Hz was
achieved by using an integrated circuit of switched capacitor filter LTC1062.

4. Results and discussion

(1) Both from the observed pattern for the vertical beam oscillation and from the recorded turn numbers obtained with the three wire tomography monitor, we can deduce the turn numbers in each oscillation cycle. Thus, there are two results when the cycle is estimated from the successive top peak positions or from the bottom peak positions in the observed figures. Specified radial length in Fig. 2 shows this oscillation intervals and specified ones are described at the middle of the cycle in the radial axis. The betatron oscillation frequency can be estimated from the reciprocal number of turns in this cycle plus one. Less than about 1500mm in radial, the pattern of tomography monitor can be distinguished in turn by turn, although some of them are a little overlapped each other which introduced more errors.

With these procedures, we can obtain vertical betatron oscillation frequency at each radial intervals as shown in Fig. 2.

![Fig. 2. Deduced vertical oscillation frequency](image)

(2) We assume that the betatron oscillation of the beam is enhanced with mismatching in the injection to the Ring Cyclotron and purely introduces the unequal separation in successive turns. Thus, we measured $dr$ separation in each turn of the radial spectra observed with vertical wire of the tomography monitor from injection to the distinguished turn about 1600mm where we can put the turn number 260-revolutions. Thus, we plotted $dr$ separation to this revolution numbers. It shows oscillatory pattern with a increase of the radial position as shown in Fig. 3.

![Fig. 3. Measured $dr$ separation in each acceleration turn](image)

Between the successive $dr$ maxima or $dr$ minima in this figure we can measure the turn numbers in the one cycle from which we estimated radial betatron frequencies. Over the 1000mm in radius the figure shows an irregular pattern mixed with two or three cycles of oscillation intervals. Even taking into account the regular increase of the radial betatron oscillation frequency, the observed structure was somewhat disturbed with several processes such as unequal
acceleration process in beam phase, imperfect isochronous field and considerable amount of beam dispersion in energy.

As a result, we can deduce radial betatron frequencies from injection to almost full acceleration radius as shown in Fig.4.

Compared with the betatron frequencies calculated from the data of magnetic sector field, these observed values are roughly consistent with their radial response for both betatron oscillation frequencies[1]. However, vertical oscillation frequency rapidly increases at around 1500mm over \( v_r = 1.0 \) which may suggest the unstable behavior of accelerated beam induced from magnetic field structure and trim coil parameter optimization. This phenomena is coincided with the measurement of induced radio activities remained in acceleration gaps of three cavities. Although this oscillation have not brought about a fatal situation for obtaining the full transmission from the injection to the extraction, it needs precise tuning the isochronous field shape and the beam injection phase.

Acknowledgments
The authors wish to express their thanks to RCNP cyclotron operation crews for the various tuning of machine for the accelerator development.

References

Correcting Slanted Beam Profiles in Superconducting Storage Rings.

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Abstract

In the Super-ALIS superconducting storage ring for synchrotron radiation, the electron beams have been suffering from slanted profiles. These profiles degrade the uniformity of exposure in X-ray lithography. The most possible reason for this slanting problem is x-y coupling originating from the combination of the sextupole components and the vertical closed orbit distortion (COD) in the superconducting bending magnets. In this work, we present the results of correcting profiles in the Super-ALIS by reducing COD and canceling out the sextupole components.

1. Introduction

Compact storage rings for synchrotron radiation (SR) have recently been developed [1,2]. The magnetic fields in superconducting bending magnets for these machines generally have a large amount of sextupole components. In these sextupole fields, vertical closed orbit distortion (COD) creates skew-quadrupole components whose strength is where is the strength of the sextupole kick and is the vertical COD. Such localized skew-quadrupole components make the principal plane of the betatron oscillations slanted to the ordinary (x,y) axes [3]. This means that the beam profiles become slanted. Especially in the condition close to the difference resonance, this problem becomes serious.

Such slanted beam profiles are undesirable for experiments using SR. In X-ray lithography beamlines that generally adopt toroidal mirrors, the asymmetry of the beam profiles are much emphasized on the exposure plane and the uniformity of exposure is therefore seriously degraded. In beamlines using monochromators, the intensity is decreased because the slit of the monochromator must be narrow for fine resolution.

Especially in the Super-ALIS superconducting storage ring [4], the slanting of beam profiles is serious because the operation point of the machine must be set close to the difference resonance to increase the beam lifetime. In this work, we present the methods and results of correcting these distorted profiles in Super-ALIS.

2. Sextupole components of Super-ALIS

Super-ALIS is a compact storage ring for SR as shown in Fig. 1. The machine parameters are shown in Table 1. This machine has two superconducting 180-degree bending magnets; BM1 and BM2. The magnets have a maximum magnetic field of 3 tesla. The uniformity of the field is not much better than that of normal conducting magnets. Therefore, these magnets have cancellation coils for multipole components.

The measured magnetic field at the center of BM1 excited to 3 tesla is shown in Fig. 2(a). The solid line is the field produced without employing cancellation coils. The solid line in Fig. 3 shows the sextupole components along the orbit in BM1. The sextupole component in the magnet is about -1.8 T/m except for the edges. At the edges, the

Table 1. Super-ALIS machine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. energy</td>
<td>600 MeV</td>
</tr>
<tr>
<td>Max. bending Field</td>
<td>3.0 T</td>
</tr>
<tr>
<td>RF frequency</td>
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<td>Peak RF voltage</td>
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<tr>
<td>Betatron tune, vertical</td>
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<tr>
<td>Synchrotron tune</td>
<td>~0.003</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>9.35x10⁻⁷ π m rad</td>
</tr>
<tr>
<td>Circumference</td>
<td>16.8 m</td>
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</table>
3. Correction of the beam profiles

Before profile correction the sextupole components were present and the vertical COD was large as represented by the solid line in Fig. 5. The beam profiles in this condition are slanted as shown in Fig. 6. The profile was observed from BL9 SR port in BM2. The SR light extracted from the port was telescoped and monitored by a CCD camera.

To cure the slanted profiles, two methods can be proposed: reducing vertical COD and canceling the sextupole components by cancellation coils. In practical reducing COD seems to be easier than canceling sextupole components. However, we must take into account the high sensitivity of COD to profile slanting.

Fig. 4. Simulated beam profile at the 135-degree position in BM1. The betatron tunes are (1.585, 0.583) and the CODs are assumed to be -1 mm in BM1 and +1 mm in BM2. The initial horizontal emittance is $4 \times 10^{-6} \text{ m rad}$. The field distribution is quite different as shown in Fig. 2(b). The effect of these sextupole components on the beam profiles is very serious. As shown in Fig. 4, beam tracking simulations including the sextupole components with the corresponding COD show that even 1-mm vertical COD is critical.

By using cancellation coils, the sextupole components can be reduced to one tenth (except for the edges) as shown by dotted lines in Figs. 2 and 3. At the edges, however, the sextupole components become large even if the cancellation coils are used.

Fig. 2. Radial distribution of the magnetic field on the median plane in BM1. (a) at the center and (b) at the entrance edge.

Fig. 3. Sextupole components of BM1 along the designed central orbit.

---

### Table 1: Parameters of BM1

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Tune</td>
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<td>Emittance</td>
<td>$4 \times 10^{-6} \text{ m rad}$</td>
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<tr>
<td>Sextupole</td>
<td>uncorrected</td>
</tr>
<tr>
<td>COD</td>
<td>uncorrected</td>
</tr>
</tbody>
</table>

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Fig. 5. Bending angle in BM1 [degrees].

---

Fig. 6. Simulated beam profile at the 135-degree position in BM1.
as described in Section 2. If the sextupole components are not reduced, COD must be reduced with 0.1-mm precision. However, such a high sensitivity is not preferable for stable operation of storage rings. Moreover, such precise COD reduction might be technically difficult especially in superconducting bending magnets. This is mainly because the median plane of the magnetic field, which is mainly determined by the shape and position of the coils as well as the yoke geometry, may be slightly displaced from the geometrical median of the iron yoke. The restricted number of steerings also makes precisely reducing COD difficult.

To correct the beam profiles, therefore, we first reduced the vertical COD as small as possible and then canceled the sextupole components. The vertical COD was reduced as shown by the dotted line in Fig. 5. The resulting beam profiles are shown in Fig. 7. The slant angle of the beam profiles was completely corrected and the intensity distribution on the exposure plane of the X-ray lithography beamline was greatly improved.

4. Summary

We can draw the following conclusions about slanting beam profiles in superconducting SR rings.

1) The vertical COD in the large sextupole component of a superconducting bending magnet generates large x-y coupling. This coupling seriously distorts beam profiles.
2) Theoretically, this problem can be corrected by either reducing vertical COD or the sextupole components.
3) In a real machine, however, using both methods makes it easier to correct the profiles and to ensure stable operation of the machines.

References

Refinement of Calibration Procedure for Beam Position Monitors

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Abstract

Experimental studies to examine calibration accuracy of beam position monitors (BPM's) with an RF-antenna were conducted as an R & D for the BPM's of the SPring-8 storage ring. The antenna was optimized so as to generate the electric field similar to that carried by an electron beam. The accuracy was evaluated better than ± 1 % for the position sensitivity after correction of systematic error due to the effect of the finite diameter of the antenna, and within ± 56 µm for the offset of electrical center.

I. Introduction

To measure the position of an electron beam with a BPM, it is necessary to calibrate precisely the offset of electrical center, and the relation between imbalances of signals from pickup electrodes and the deviation of the electron beam from the electrical center. The imbalances are expressed by position sensitivities U and V (Fig. 1).

![Fig. 1 Conceptual drawing of a BPM and definition of position sensitivities U and V.](image)

We studied the calibration procedure with an RF-antenna as an R & D for the BPM's of the SPring-8 storage ring. Since the electric field around a relativistic electron beam is contracted into a thin disk perpendicular to the direction of motion, the electric field from the antenna has to be dominated by a transverse component at the position of a BPM. We optimized the antenna to generate a TEM field and examined the accuracy of position sensitivity and offset measurements with the antenna.

II. Equipment for BPM Calibration

A. RF-Antenna

The RF-antenna is made of a straight semi-rigid cable with an inner conductor bared at the tip (Fig. 2). The outer diameter of the cable is 3.6 mm and the length of the coaxial cable is chosen to be 295 mm which is a half wavelength of 508 MHz sinusoidal wave fed to the antenna. The frequency of 508 MHz is the RF frequency of the SPring-8 storage ring and the BPM electronics of the storage ring detects the 508 MHz component of the electric fields excited by an electron beam. The antenna is supported by a long rod which is fixed to a three-dimensional moving stage.

![Fig. 2 Structure of the RF-antenna.](image)

B. BPM Chamber

Two BPM chambers have been prepared for the present study. One has a circular cross section of 30 mm in radius. The chamber has been made to have symmetry of rotation. Its dimensions have been measured with a precise coordinate measuring machine. This chamber was used to define the reference point for BPM calibration. The other has an ideal elliptical cross section of the beam chamber of the SPring-8 storage ring. Since the electric field around a relativistic electron beam is transversal to the direction of motion, it can be modeled as two-dimensional electrostatic field from a line charge of infinite length located at the mass-center of the electron beam. We can calculate it numerically by the two-dimensional boundary element method (BEM) [1] imposing the boundary condition of the elliptical cross section of the chamber, and calculate the dependence of the output voltages of individual pickup signals upon the beam position. We measured the output voltages by moving the antenna in this chamber, and investigated its systematic difference from the calculation.
III. Experiments and Results

A. Distribution of Transverse Electric Field

Because uniformity of the coaxial structure, which is composed of the antenna and the elliptical BPM chamber, is broken at the tip of the antenna, many modes of electric field may exist there. However, only the TEM mode can propagate through the coaxial structure since the cutoff frequency is higher than 500 MHz.

To find the maximum point of the transverse electric field, we investigated the longitudinal distribution of transverse electric field along the antenna [2]. Changing the longitudinal position of the BPM with respect to the antenna, we measured the voltage of a pickup signal which is proportional to the transverse electric field. The transverse electric field reaches a minimum at the tip of the antenna and a maximum at about 130 mm (Fig. 3). We decided to use the maximum point at 130 mm for BPM calibration.

We measured the dependence of the output voltages of individual pickup signals upon the antenna position in the transverse plane in order to verify if the distribution of the electric field around the antenna is consistent with that of the TEM mode. The voltages measured with the antenna moving on the horizontal and vertical axes are shown as open circles in Fig. 4. They are normalized to be unity at the electrical center. We can calculate the expected voltages for the TEM mode by BEM, assuming an indefinitely long charged metal rod of 3.6 mm in diameter (solid curves). The position dependence of the measured voltages agrees with the calculation quite well.

The theoretical voltages for an electron beam are calculated by assuming an infinitely long line charge (broken curves). Small systematic errors are found in the measured voltages. We conclude that the electric field around the antenna is consistent with that of the TEM field, but is slightly different from that of an electron beam because of the finite diameter of the antenna.

B. Position Sensitivity

Moving the antenna by 1 mm step in a central square of 10 mm by 10 mm within the elliptical BPM chamber, we measured the position sensitivities U and V (open circles in Fig. 5).

Crosses represent the sensitivities calculated for the electron beam by BEM at the same points. We found small systematic errors in measured sensitivities. They are caused by the finite diameter of the antenna. In order
to evaluate the systematic errors $\Delta U$ and $\Delta V$ quantitatively, they are plotted as a function of the theoretical sensitivity, respectively (Fig. 6). According to least squares fit to a straight line, the systematic errors are evaluated to be $\pm 2.8\%$ in horizontal sensitivity $U$ and $-2.2\%$ in vertical sensitivity $V$. After correction of the errors, residual systematic errors are $\pm 0.3\%$ for $U$ and $\pm 0.6\%$ for $V$. Taking account of the random error of $0.2\%$ caused by the repeatability of measurement, we conclude that the total accuracy of position sensitivity measurement is $\pm 0.5\%$ for $U$ and $\pm 0.8\%$ for $V$.

![Graph showing systematic errors of position sensitivities](image)

Fig. 6 Systematic errors of the position sensitivities measured with the RF-antenna.

C. Offset of Electrical Center

To measure the offset of the electrical center of a BPM, we have to locate the antenna at the reference point whose location is definitively identified. We defined it as the rotational center of the circular BPM chamber.

Owing to the measurement of its dimensions, location of the rotational center of the circular BPM chamber is known (crosses in Fig. 7). The position where we can set the antenna directly, however, is not the rotational center, but the electrical center (a solid circle in Fig. 7 (a)). If we know the distances between the rotational center and the electrical center, we can identify the location of the rotational center through the electrical center. In order to find out the distances, we rotated the chamber to the configuration shown in Fig. 7 (b), and measured the displacements of the electrical center (an open circle) from the position measured in case of the setup in Fig. 7 (a). Since the rotational center is at the midpoint of the electrical centers thus measured, we can identify the location of the rotational center, i.e., the reference point.

![Diagram showing measurement of distances](image)

Fig. 7 Measurement of the distances between the rotational center and the electrical center of the circular BPM chamber. The midpoint between two electrical centers in setups (a) and (b) corresponds to the rotational center.

After setting the antenna at the reference point with the circular BPM chamber, we slide the antenna away from the chamber and replace it with a BPM chamber which should be calibrated. Then the antenna is slid into the chamber, and the offset of the electrical center is measured.

The precision of the reference point and that of the electrical center of the elliptical BPM chamber were $\pm 24\mu m$ (full error) and $\pm 15\mu m$ (full error), respectively. The total accuracy of offset measurement is evaluated to be $\pm 54\mu m$ (full error), which is the sum of the precision of the reference point, the precision of the electrical center and the residual errors of the characterization of the signal processing circuits.

IV. Conclusion

We studied the calibration procedure for BPM's and evaluated the calibration accuracy. An RF-antenna was optimized so that the distribution of electric field around it was consistent with that of TEM mode. The position sensitivities were calibrated with accuracy of within $\pm 1\%$ after correction of systematic errors due to the finite diameter of the antenna, and the total accuracy of offset measurement was evaluated to be within $\pm 54\mu m$.

References

Beam Position Monitor for an Orbit Feedback System

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Abstract

We have developed a stripline type beam position monitor system. This system was intended to be used in the beam study on the orbit feedback system which will be used in the KEKB. Characteristics of the monitor system were investigated in both bench tests and beam tests. We succeeded to detect these positions with enough accuracy of a few micron using the system.

1. Introduction

An orbit feedback system is vital for maintaining an optimum collision condition at a B factory where two beams circulate in separate rings. For this purpose the beam-beam deflection technique, pioneered at the SLC, may be utilized to detect an offset of the two beams. Methods of applying this technique to a ring collider are described in a previous paper [1]. Feasibility study of the technique has already conducted successfully by using beams of the TRISTAN Main Ring. Details of this beam test were shown in another paper [2].

In this paper we focus on characteristics of the beam position monitors developed for the beam test. Results of bench tests and beam tests on the characteristics of the monitors are described in detail.

2. Stripline Monitor

Stripline electrodes, which are also called directional coupler pickup electrodes, are essentially transmission lines with a well-defined characteristic impedance. Since we want to pickup the signal of two beams separately, we chose this stripline monitor with four electrodes. In addition, the stripline has the advantage of the higher signal level in comparison with button type electrode.

The design value of the characteristic impedance is 50 Ω. The length of the stripline electrodes was chosen as 148 mm to maximize signal amplitude at the detection frequency of 508 MHz. Directivity of stripline electrode can help us to distinguish a signal of one beam from that of the other. To avoid degradation of accuracy due to insufficient directivity of stripline electrodes, we have worked out two countermeasures. First, the locations of the monitors were carefully selected as shown in Fig. 1 so that Fourier components of this signal are not disturbed, very much by the counter-rotating beam at the detection frequency. Second, we designed the structure of the monitors so that the characteristic impedance of the dipole mode matches to 50 Ω taking account of the electromagnetic coupling with the other electrodes. Details of the two countermeasures are described in a previous paper [3].

The schematic view of the stripline monitor we finally adopted is shown in Fig. 2.

![Fig.2 Stripline monitor](image)

Matching of the characteristic impedance of electrodes was measured by using a time domain reflectometer (TDR), as shown in Fig. 3. A mismatch of the stripline electrode itself seems small. A large mismatch exists at the part of line to connect the stripline and the center conductor pin of the feedthrough. Although this mismatch can not be avoided, the directivity is hardly influenced by this at the detection frequency. To obtain the beam position, we convert the electrical position (H, V) to the geometrical position (X, Y) following the first order approximation as:

\[ X = k_x H, \quad Y = k_y V \]
where $k_x$ and $k_y$ are coefficients of conversion which are determined from the geometry of the monitor chamber. And the electrical positions are given by the normalization procedure as follow:

$$H = \frac{(A-B-C+D)}{(A+B+C+D)}$$
$$V = \frac{(A+B-C-D)}{(A+B+C+D)}$$

where $A, B, C$ and $D$ are the induced voltages of the four electrodes.

We aimed at obtaining much better resolution than that in the TRISTAN. The configuration of position monitor electronics is shown in Fig.5. Eight output signals from a moniter chamber are sent to the local control room (D10) through their own coaxial cables. The signals are selected by RF switches and processed by a common front-end circuit. A programmable attenuator adjusts the signal level to match to the circuit. The front-end circuit consists of a triple stage super-heterodyne circuit, a synchronous detector and a 20 bits ADC.

These circuit components were made as CAMAC modules such as an RF switching module and a programmable attenuator module. We are able to control these modules from the central control room. A pick up frequency was chosen as 521MHz which is the 5267th harmonics of the revolution frequency (99.9KHz). This frequency was determined experimentally so that we can mitigate the effect of insufficient directivity. We mention this frequency choice in more detail in the next section.

The position resolution of this system is designed to be a few micron and this value was actually achieved in the beam test. The time which is needed to get beam positions of the two beams at one position monitor is about 3 sec. The time is mainly determined by A/D conversion, the typical value of which is around 120msec per conversion.

3. Electronics

We developed new electronics for the beam position monitor. We adopted basically the same signal processing method as that for the BPMs of the TRISTAN Main Ring.
4. Measurement

We measured beam positions repeatedly by using the monitor system to check performance of the electronics and to observe an orbit change. Fig.6 shows a history of the beam positions at 8 GeV for about three hours. We confirmed that the monitor system has a high position resolution of a few micron. We also measured repeatedly beam positions of the two beams at 29 GeV as shown in Fig.7. We observed some fluctuation of the beam positions. Those were changing with a period of about 150 sec and about 50 min. The FFT analysis of those data reconfirms those periods as shown in Fig.8.

![Fig.6 History of beam position at 8 GeV.](image)

To see an influence of the counter-rotating beam on the beam position measurement, we made measurements in the following two conditions. First, with the positron beam we observed the signals coming from the upstream port of each electrode. Secondly, with the two beams we observed the signals from the same port. In the measurements the beam current was 1.2 mA for the positron beam and 0.8 mA for the electron. Fig.9 shows results of the measurements. The vertical axis is the difference of the signal levels in the two conditions. If the directivity of the stripline is perfect, the voltage shift should be zero. In reality, however, the signal levels do change due to the influence of the counter-rotating beam as seen in Fig. 9. The horizontal axis is the relative bucket difference of the two beams. The zero bucket shift corresponds to the situation where the two beams collide at the nominal collision point. We intended that the voltage shift should be zero with the zero bucket shift at the design detection frequency of 500 MHz by choosing the locations of the monitors correctly. However, in the experiment the shift of 15 RF buckets were needed to minimize the voltage shift. We have not yet understood the reason for this. In the experiment on the beam-beam deflection[2], the detection frequency was changed temporarily to 521 MHz to minimize the voltage shift.

![Fig.9 Influence of the counter-rotating beam observed at four stripline electrodes](image)

6. Acknowledgments

We wish to thank KEK Vacuum Group for helping the construction of BPM chambers. We also wish to thank Dr. N. Hiramatsu, Dr. K. Satoh for useful some comments and K. Mori, Y. Suetsugu and K. Hanaoka for assisting with carrying out experiments.

References

Development of a Single-Bunch Selector for the Riken Ring Cyclotron

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Abstract

We have developed a single-bunch selector with fast repetition rate (1 MHz) for the RIKEN Ring Cyclotron. The system is compact due to use of a beam chopper for the beam with low velocity. Moreover by operating the buncher for injection in the AVF cyclotron with a sub-harmonic mode, a purity of the single-bunched beam was raised up. The obtained purity of the beam is more than 99.7%.

1. Introduction

A single-bunched beam is often demanded to measure a time spectrum in very short range (< 1 ms). To fulfill the demand a single-bunch selector has been developed. In the first step a beam chopper was installed at the injection line of the AVF cyclotron (AVF). We could get the almost single-bunched beam. A purity, that is a ratio of the current of the desired bunch to total one including undesired bunches, is about 90%. However the purity is not enough for the experiment to measure the time spectrum with a low background. In the next step we tried to raise up the purity by operating the buncher with sub-harmonic frequency of the AVF.

In similar cyclotron, the single-bunched beam is normally produced at downstream of the cyclotron where the beam energy is relatively so high. For the case the purity is independent of extraction of the beam but the system is very large and needs a high power. On the other hand, for the present method a single-turn extraction is needed. As the beam can be extracted from the AVF and the RIKEN Ring Cyclotron (RRC) 1), the present method can be applied in our facility. Since single-bunched beam can be produced at low energy the whole system can be small and of low cost

2. Principle

Figure 1 shows the method for production of the single-bunched beam. The single-bunched beam can be produced by sweeping undesired bunches.
wide enough to include the tail, the single-bunched beam with the purity of 100% can be produced.

3. Devices

The electrodes of the beam chopper connect with a DC power supply via a switching module. The repetition rate of the switching module is 1 MHz that is demanded from a typical experiment.

A schematic drawing of the circuit of the switching module is shown in Fig. 2.

![Schematic drawing for the circuit of the switching module](image)

The switching module has two trans-coupled switches with repetition rate of 1 MHz (HV 1000 P, N), which are bought from DEI inc in USA. One is for the charge-up of the electrode and the other for the discharge. To avoid an electrical oscillation between two switches and the electrode, we inserted several resisters there. Two pulses for the switches are made by a pulse generator located at upstream of the switching module. One is a leading pulse which is sent to the switch for discharge and the other is a delayed pulse which is sent to the one for charge. The difference of time when each pulse arrives at each switch corresponds to the duration for the base of the single-bunched beam. Characteristics of the pulse made by the switching module are summarized in Table 1. The choppers are installed on the two injection line. One is from the ECR ion source (ECRIS) and the other is from the polarized ion source (PIS).

Table 1. Characteristics of the pulse made by the switching module.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>0 ~ 500 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>&lt; 1 MHz</td>
</tr>
<tr>
<td>Rise time</td>
<td>15 ns</td>
</tr>
<tr>
<td>Duration time</td>
<td>100 ~ 250 ns</td>
</tr>
</tbody>
</table>

We used the buncher that has been already installed. In order to operate the sub-harmonic mode we must use the buncher with low frequency (4 ~ 8 MHz). For the purpose we made a new frequency divider that an amplifier and a phase is controllable. A wave made by the divider is sent to the buncher via the wide-band amplifier. A shape of the voltage is sin-curve. For the single-bunch operation, the range of phase to be compressed is wider than that for the normal one. In this case, even the sin-shape can compress the phase efficiently because the sin-shape is approximately a straight line for the main region of the phase to be compressed.

4. Performance Study and Result

A performance study of the single-bunch system was carried out for the 7.45 keV H$_2^+$ beam from the PIS which was accelerated to 7 MeV/nucleon by the AVF with an RF frequency of 16.3 MHz and to 135 MeV/nucleon by the RRC with an RF frequency of 32.6 MHz. The setup is shown in Fig. 3.

![Setup for a performance test of the single-bunch system](image)

The duration that the voltage between the electrodes was switched off was 150 ns. Voltage of the electrodes was 470 V. The variable delay connected with the switching module was adjusted so as to get the purest single bunched beam for the RRC. Time structures of the beam after the AVF and RRC were measured by using a time of flight (TOF) between a reduced RF signal and a timing signal of micro channel plates (MCP's) with a target 3). In this study we operated the buncher with the normal mode because the frequency divider had not been installed by that time.

Figure 4a shows a typical example of the TOF spectrum of the AVF. The main peak in Fig. 4a is due to a single bunched beam to be extracted.
The peak next to the main one is due to the next bunch of the main one. The existence of the other two peaks means that the same bunch inside the AVF is extracted with two-turns. Production mechanism of those peaks is explained in Fig. 5a. The result of the many peaks in the spectrum might be caused by the adjustment of the variable delay that is suitable to the RRC. In fact, using the system we obtained the single bunched beam as shown in Ref. 1 by adjustment of the variable delay for the AVF and by single-turn extraction from the AVF.

Figure 4b shows a typical example of the TOF spectrum of the RRC. The main peak in Fig. 4b is made by the single bunched beam to be extracted. The peaks next to the main one are due to the next bunches of the main one. The two small peaks correspond to another turn of the RRC (right side) and that of the AVF (left side). The purity of the single bunched beam is ~80%. Production mechanism of those peaks is explained in Fig. 5b. As shown in Fig. 5b, in principle, the other turn of the AVF gives a bad effect to the single bunched beam extracted from the RRC but the peak of the turn is not so strong. This might be due to bad transmission of the RRC for the turn.

Recently, the whole system including the new controller was used to make a single-bunched beam for the deuteron beam from the ECRIS which was accelerated to 4 MeV/nucleon by the AVF with an RF frequency of 12.3 MHz. For the beam we used the buncher with an frequency 4.1 MHz. The purity of the single-bunched beam is 7% by using the only buncher with the sub-harmonic mode. Using the whole system we obtained the beam with the purity of 0.3%. The current of the beam was about 100 enA.

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Single-Pass Measurements of Injection-Beam Position at the Photon Factory Storage Ring

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Abstract

A single-pass beam position monitor (BPM) system that monitors injection-beam positions is under development. A signal extracted through a button electrode was detected using a high-speed digitizer. Waveform of the button signal was recorded by real-time sampling. The waveform could be measured with enough sensitivity even for positron beam as well as electron beam. The beam position was determined with a resolution of a few hundred microns.

1. INTRODUCTION

Photon Factory ring (PF ring) is a 2.5 GeV electron/positron storage ring dedicated to a synchrotron radiation source. In 1997, reconstruction for a lower emittance lattice is scheduled. [1] The reduced emittance is achieved by replacement of quadrupoles and sextupoles in FODO cells. The brilliance of synchrotron radiation will be increased by a factor of 10. In the normal-cell sections, vacuum ducts are replaced by new ones, and the number of quadrupole magnets and BPMs are doubled. All electronic components related to COD measurements will be also updated. [2]

In the low-emittance configuration, there is a weak point of a small dynamic aperture. The small aperture would demand a strict correction of the injection beam path. A COD correction in advance of beam storage will be inevitable. So a BPM system to monitor the injection beam is being prepared for the sake of efficient commissioning after the large reconstruction. In following sections, we will report about a single-pass measurements of button signals using a digitizing oscilloscope and results of a preliminary position measurement.

II. MEASUREMENT PROCEDURE

We have installed three BPMs in a beam transfer (BT) line between the injector linac and the ring. A schematic cross section of the BPM is shown in figure 1 (a). It has a circular cross section of 38 mm diameter. Four button electrodes of 10 mm diameter are placed as in the figure. In the storage ring, a vacuum duct has a polygonal cross section. Each BPM of the PF ring has six electrodes of 30 mm diameter. The four electrodes numbered in figure 1 (b) were used in the present measurement. An output voltage of these large buttons is estimated to be a factor of four higher than that of the small buttons in the BT line.

A bunch signal extracted by a button electrode was led to a digitizing oscilloscope through a double screened coaxial cable of 20 m long. The cable has an attenuation factor of 3 dB/10 m at the frequency 1 GHz. The digitizing oscilloscope (Tektronix TDS684A) has four channels with four digitizers. Each channel is a 8-bit digitizer with a maximum sampling rate of 5X10^6 samples/s and a analog bandwidth of 1 GHz. The signals from four buttons were simultaneously recorded in the four channels by a real-time sampling. A time base for the measurement is a trigger pulse of an injection kicker magnet. A maximum record length was 15,000 for each channel. 10 turns of bunch signals that revolving at a period of 625 ns could be recorded turn by turn with a sampling rate of 2.5x10^6/s.

A beam position is calculated from the peak-height ratios, U and V.

\[ U = \frac{(V_2+V_3)-(V_1+V_4)}{(V_1+V_2+V_3+V_4)} \]

\[ V = \frac{(V_1+V_2)-(V_3+V_4)}{(V_1+V_2+V_3+V_4)} \]

Figure 1. Dimensions of button BPMs installed in the beam transfer line (a) and the storage ring (b).
where $V^#_n$ means a peak height of the $n$-th electrode's signal. Because the injection beam position would change with a large amplitude, nonlinear behavior of the ratios has to be taken into account. For the BPM of the storage ring, $U$ and $V$ were computed in a range, $0 \text{ mm} < X, Y < 16 \text{ mm}$. Figure 2 shows the $U$ vs. $V$ plot. We determine the beam position using following quadratic equations.

$$X [\text{mm}] = (12.4 U^2 + 21.8 - 17.7 V^2) U.$$ $$Y [\text{mm}] = (-79.0 U^2 + 65.5 + 71.3 V^2) V.$$

These approximations are valid up to 16 mm with an error of about 3%. For the BPM in the BT line, following equations are adopted. These are valid up to 10 mm with an error of 10 %.

$$X [\text{mm}] = ( 13.5 U^2 + 12.4 - 15.0 V^2 ) U$$ $$Y [\text{mm}] = ( - 15.0 U^2 + 12.4 + 13.5 V^2 ) V$$

**III. MEASUREMENT RESULTS**

An injector of the PF ring is a 2.5-GeV linac. Positron or electron beam is available for usual operation. Measured waveforms for electron and positron pulses are shown in figure 3 (a) and (b), respectively. These were records of the first-turn's signals observed with one button in the storage ring, while RF acceleration system was not powered. Solid squares in the graphs are the sampling points at a rate of 5X10^9 samples/s, and the solid lines are curves drawn by a 3rd order spline interpolation. Charge per bunch for the electron beam was about 2X10^10 C, that was estimated from an output of a current transformer in the BT line. Charge of positron beam was an order of magnitude less than that of electron beam. The waveform of the positron bunch was measured with an amplifier of 20 dB gain and 1 GHz bandwidth. The amplifier was located in the neighborhood of the BPM in order to keep a good signal-to-noise ratio. Compared with simulated waveforms of the button signals based on a Gaussian approximation, bunch lengths (standard deviation) of the electron and positron beams were estimated to be about 0.4 ns and 0.7 ns, respectively. For the both injection beams, the present measurement system had a enough sensitivity to deduce peak heights from the button signals.
aperture. Rapid attenuation of the peak heights were observed in the several turns.

![Figure 4](image)

**Figure 4** The first 9-turn signals from four electrodes of one BPM in the ring measured with usual condition (a) and with abnormally high octupole fields (b).

Beam positions of the first nine turns deduced from the records in the figure 4 (a) were plotted in figure 5. The BPM used in the present measurement was located just upstream the injection point. Numbers beside the solid circles means the data of the N-th turn. The peak heights were determined by interpolated curves for the sampled data, and the approximation equations described above were adopted to the calculation of positions. A horizontal injection bump generated by the kicker magnets had a duration of about 5 us. A timing of the injection pulse was adjusted to the center of the bump duration. The bump would disappear just before the fourth-turn pulse go back to the injection point. It seems that a large horizontal oscillation occurred after the bump disappeared. A resolution of the position measurement was estimated from variations of data in measurements for large number of injection pulses. For the BPM of the ring, the resolution for horizontal and vertical measurements were 0.3 mm and 0.8 mm, respectively. The poor value for the vertical was mainly due to a rectangular arrangement of the four electrodes. It is not the case for the BPM in the BT line that has the same position sensitivity for both directions.

![Figure 5](image)

**Figure 5.** The first 9-turn beam positions deduced from the peaks in the figure 4 (a).

**IV. SUMMARY**

In the present measurement, it would be confirmed that the button signal of the injection beams could be measured with good sensitivity to determine the beam position. Now, we are going to develop single-pass BPM systems for the BT line and the storage ring on the basis of the present method. When any number of button signals from different BMPS are combined to one channel, the peaks for every buttons can be recorded at the same time. [3] So using a small number of high speed digitizers, the BPM system that extended over the whole ring would be constructed.

**V. ACKNOWLEDGMENTS**

The author would like to thank M. Tejima, T. Kasuga, and K. Shinoe for their support and useful discussion. I also acknowledge Y. Hori and Y. Takiyama for their support in installation of BPM heads in the BT line.

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Stability study of ATF 80MeV injector linac


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Abstract

A beam stability test was carried out at ATF 80MeV injector linac. The test was performed by taking data of each monitor in pulse to pulse base. A data acquisition system which consists of a PC and a GPIB network was used for the test. In order to analyze the data, 'Correlation plot' method is used which is effective to find out some source of the observed beam fluctuation. This paper describes the result of the stability measurement and the comparison between ATF injector and SLC injector.

1. Introduction

The Accelerator Test Facility (ATF) consists of a 1.5 GeV linac and a damping ring which is under construction in KEK. The purpose of the ATF is development of accelerator components to realize future Linear Collider. The injector part of the linac consists of a thermionic gun, two SHBs (357MHz), seven cells of buncher following to a 3m long S-band (2856MHz) accelerating structure (AS). The energy of beam is 80 MeV at the exit of the AS when 60 MW of RF power is fed into the AS. The diagnostics of the injector are an amorphous core current transformer (CT), an integrated current transformer (ICT), wall current monitors (WCMs), beam position monitors (BPMs), fluorescent screen profile monitors (PRMs) which measure the beam size and the relative position, optical transition radiation monitors (OTRMs) which measure a bunch by bunch beam profile using a fast gate camera and a bunch length using a streak camera and a photomultiplier (PMT) with a scintillator which measure a beam loss.

In order to produce a stable beam at the injector is a key issue for a stable operation of ATF. 4% of the fluctuation of beam intensity at the injector is measured which should be reduce to less than 1%. In order to investigate a source of the fluctuation, the test was performed by acquiring the pulse to pulse data from each monitors in each position. The data acquisition system consist of a PC and a GPIB network which connect between the PC and the data acquisition devices. The acquired data are treated statistically and analyzed by 'Correlation plot'. The correlation coefficient which is evaluated in the correlation plot exhibits a strength of connection between the two measured quantities. This technique is used at SLC beam tuning. 2)

2. Data acquisition system

System configuration

The configuration of the data acquisition system is shown in Fig. 1. Two scopes for electrical pick up signals, a streak camera for bunch length measurement and a pulse generator for generating a system trigger signal, are connected to a PC through a GPIB network. A video analyzer for the energy and the energy spread measurement at PRM4 not yet have the interface software. The beam trigger signal starts the beam emission of the electron gun which is distributed to each acquisition device as the acquisition trigger signal in order to acquire at same

Fig 1 ATF injector linac and acquisition system
The acquisition sequence is following, the pulse generator generates a single pulse for the system trigger by the software, the other devices acquire each points of monitors at same timing, the acquired data are recorded to the PC and then the pulse generator generates a next single pulse for next data acquisition. For each test, 100 data are recorded and used for the analysis. The acquisition speed was 5-10 sec. per data. The size of data was 10k~20kbytes per data. The software used in this system are VEE for the GPIB control and MATLAB for the data processing and analysis.

**Monitoring beam signals**

Following signals were used for the test.

a) Gun high voltage: The gun use a pulsed high voltage of 3 μsec which is made by a PFN and a thyratron circuit. The fluctuation of this voltage will affect to the beam intensity and the beam optics directly.

b) Beam intensity: The CT and the WCMs measure the micro-pulse of beam intensity. The ICT measure the total beam intensity of multi-bunch.

c) Beam loss: The PMT detects the beam loss at the down stream of the accelerating structure.

d) Beam position: The signals from BPMs are stretched by the head amplifiers and recorded its wave forms. The beam position are calculated by using the peak amplitudes which are estimated by polynomial fittings for the sample hold points of the scope. The sum of the opposing electrode signals is proportional to the beam intensity approximately.

e) RF phase: The RF phases of two SHBs and a AS are measured by a mixer at the output level of φ-crossing.

f) Beam energy and energy spread: The PRM4(OTR) is located after a 90 degree bending magnet. The horizontal position and width of the profile show the beam energy and the energy spread. The video analyzer acquires the video signal and calculates the projection of the profile.

g) Bunch length: The light from the PRM5(OTR) is fed to a streak camera. The bunch length is measured by the projection of the swept image of the light.

**3. Result**

The beam parameter for the test were following, beam mode: single bunch, charge number $-1.5 \times 10^{10}$ electrons, beam energy: 80 MeV. None of machine parameters were changed during each test.

**Signal distribution**

The examples of the signal distribution are shown in Fig.2. Fig.2a), b), c) show the distribution of RF phase of SHB1(SHB1φ), RF phase of AS(ASφ) and beam intensity by ICT, respectively. The sigma values of the fitted gaussian distribution were SHB1φ: 0.16deg., ASφ: 0.73deg., ICT: 4%. Some data points which were deviated from the main distribution were observed in the phase distribution of SHB1. It's assumed to the possibility of discharge at inside of the
cavity.

**Correlation plot**

The examples of the correlation plot are shown in Fig.3. Fig.3a), b), c) show the correlation plot of AS0-ICT, SHB10-ICT and ICT-BPMsingle signal. The correlation coefficients were 0.12, 0.40 and 0.90, respectively. A correlation of 0.2 or lower is hard to find out the causality. Correlation of 0.3 or more are assumed to be the causality between two observed quantities. In the case of Fig.3c), the beam intensity monitored two different monitors exhibits a strong correlation.

Same measurement were repeated for each signals. The result are summarized in table 1 and 2. The tables are presented in the form of correlation coefficients matrix with one-sigma of the distribution in the diagonal. In the table 1, correlation can be seen between SHB20-BPMposition and SHB20-BPMSum. No other correlation except for between the same physical value. It’s assumed that the change of the RF phase of SHB2 affect to the beam position and the intensity.

**4. Summary**

The stability of ATF injector is compared to the stability of SLC injector in table 3. The ATF data is two times to several times larger than the SLC data. The one of reason come from the noise from klystron modulator. The small correlation coefficient was observed even between two current monitors that is a evidence of the noise effect. The noise cure is significant problem to realize the stable beam at ATF.

The unexpected distribution of RF phase of SHBs were observed in the result. The fluctuations were assumed to be correlated to the beam current and the position. The after the test, we could find the evidence of the discharge at the vacuum shield ceramics of the couplers when open the cavities.

**5. Acknowledgment**

This study was executed in a framework of an exchange program of SLAC and KEK collaboration. We would like to express our thanks to Professors Y.Kimura and K.Takata for their encouragement. We also thank other members of ATF group and Mr. S.Morita of ATC Corporation for their support.

**6. References**

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<table>
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<tr>
<th>Table1. example of correlation coefficients and one-sigma distribution. (SHB2 Ø, BPMs, streak camera)</th>
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<td>BPM8 sum</td>
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<td>BPM9' single port</td>
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PRESENT STATUS OF NAR
Masayuki NAKAJIMA, Koji YAMADA, and Teruo HOSOKAWA
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Abstract
Transverse coupled bunch instability, ion trapping effect, and closed orbit distortion are shown to be fundamental problems of NTT normal-conducting accelerating ring (NAR), which adopted extremely low injection energy (15 MeV). Elucidation of these problems as well as present status of NAR are presented.

1. Introduction
NTT LSI Laboratories have constructed their own synchrotron radiation (SR) facility to develop X-ray lithography system. The facility consists of two storage rings, NAR and Super-ALIS, and injector LINAC. NAR is a multi-purpose ring which functions as a booster synchrotron for Super-ALIS and as a storage ring for SR applications.

To minimize the size and cost of injector LINAC, low injection energy (15 MeV) is adopted. Therefore, beam dynamics in low energy region had to be clarified to attain enough beam current. Outline of NAR is shown in Fig. 1 and fundamental parameters are listed in Table 1.

Operation of NAR started in November 1987. We succeeded in extracting SR in May 1988. A beam current was about 20 mA at the beginning and stayed the same level for a few years. At injection energy, because of the short life time and the lack of appropriate monitors, we had difficulties in analyzing the phenomena and improving the beam current. Closed orbit distortion due to small magnetic fields or magnet displacement also offered serious problems. With difficulty, transverse coupled bunch instability and ion trapping effect were shown to be current limiting factors. As a result of solving these problems, as much as 120 mA could be stored.

On the other hand, we succeeded in extracting high energy electrons to inject Super-ALIS in 1992. Super-ALIS, which could have stored 200 mA with low energy injection scheme, attained more than 700 mA by injecting high energy electrons from NAR.

In this paper, improving process and present status of NAR are presented. Problems peculiar to low energy injection are also described.

2. Improvement Process and Present Status of NAR
Improvement process of NAR beam current is shown in Fig. 2. At the beginning of the operation, current limiting factors were not clear and suitable parameters were surveyed without any reference. In May 1991, the beam current increased by adjusting RF modulation pattern during acceleration but the reason why the modulation is effective was not clear. We can explain now that transverse coupled bunch instability was avoided by this modulation. The alignment of magnets suddenly displaced in October 1991 and then re-alignment were performed immediately.

Closed orbit distortion was also corrected again both at injection and during storage. Octupole magnets were newly installed in April 1993 because transverse coupled bunch instability was shown to limit the beam current of NAR. After all, we can store maximum 120 mA. Although it is not shown explicitly in this improving process, the decrease of vacuum pressure also seems to contribute to the current increase because ion trapping effect became somewhat suppressed. These problems are described later.

In NAR, six beamlines have been constructed and are used. Normally, three days a week (Wednesdays, Thursdays, and Fridays) are used for machine study or system maintenance of NAR and/or Super-ALIS.

3. Problems of Low Energy Injection Scheme
Through the machine study of NAR, several problems of low energy injection scheme were shown. These problems are summarized here.

As lower energy electrons are more liable to be affected...
by electromagnetic fields, collective phenomena such as beam instabilities are apt to be induced. However, in such low energy as adopted in NAR, radiation damping time is so long that large beam size at injection preserves over a long period. Large beam size may weaken the collective phenomena. Therefore, the effect cannot be estimated simply from electron energy. For example, average beam size of NAR at injection is estimated as large as ($\sigma_x, \sigma_y$) = (5 mm, 2 mm) by simulation while the size in final energy is calculated as ($\sigma_x, \sigma_y$) = (1.2 mm, 0.35 mm) from theory. Longitudinal beam size (bunch length) at injection is also much larger than that in storage. This beam size difference affects drastically in case of transverse coupled bunch instability or ion trapping effect. The analyses are described later.

Concerning single particle behavior, closed orbit distortion due to small magnetic fields such as geomagnetism or residual fields is fatal. More than a few tens milli-meters closed orbit distortion is roughly estimated. Meanwhile, the velocity of low energy (15 MeV) electrons is not so close to the light velocity that the electrons in NAR can be accelerated without radio frequency modulation. The reproducibility worsens at injection in case of NAR because the stability limit required to magnet sources is determined supposing the stability in final energy.

4. Transverse coupled bunch instability

Abrupt loss of electrons is often observed just after injection or in the middle of acceleration. Whether the electron loss occurs or not or when the loss occurs depends on various injection conditions. Furthermore, once the loss occurs, electrons are lost immediately. These factors made it difficult to examine the case.

Judging from the symptom, the phenomena were supposed to be due to transverse coupled bunch instability. To ascribe this assumption, it is difficult to use conventional method, that is, observing the corresponding peak in RF pick up signal with spectrum analyzer because the loss occurs faster than the scanning speed of spectrum analyzer. Fortunately, the higher order mode of RF cavity was measured before the installation and TM110-like mode was supposed to cause the instability. RF pick up signal was observed with a spectrum analyzer triggered by injection pulse. The center frequency was set nearby 493.5 MHz (the corresponding frequency of TM110-like mode) and the frequency span was set to 0 MHz. The timing of beam loss was monitored by fundamental mode frequency component of RF pick up signal. As shown in Fig. 3, the frequency component near by TM110-like mode appears in the beam signal in coincidence with beam loss. This is a distinct proof that the beam loss is due to transverse coupled bunch instability induced by TM110-like mode RF cavity.

As a result of above experiment, we decided to introduce four octupole magnets. Then we could store more than 100 mA. Meanwhile, transverse coupled bunch instability shows an interesting aspect in low energy region. The strength (growth rate) of the instability is expressed by the following formula:

$$ \frac{1}{\tau_{\text{inst}}} = \frac{eI\beta_w}{2E} \text{Re} Z(f_{\text{inst}})F(f_{\text{inst}}) $$

where $e$ is the electron charge, $I$ is the beam current, $\beta_w$ is the betatron frequency at the RF cavity, $E$ is the electron energy, $\text{Re} Z$ is the real part of transverse coupling impedance and $F$ is the form factor. $F$ represents the frequency components of an electron bunch. The center of $F$ is determined by chromaticity of the ring while the width of $F$ is inversely proportional to the bunch length. The value of $F$ at higher order mode frequency determines the strength of transverse coupled bunch instability. From the shape of $F$ distribution, it is clear that the instability is slightly dependent on chromaticity in final energy whereas it has strong dependence at injection energy. Fig. 4 is the chromaticity dependence of the transverse coupled bunch instability observed in NAR at injection energy. The strength of the instability is measured by the octupole current required to suppress the instability. That is, direct observation of the form factor distribution became possible in low energy injection storage ring.

As the electron energy increases, the bunch length shortens and the width of the form factor becomes wide. Accordingly, even though the transverse coupled bunch instability can be avoided by controlling the chromaticity, it cannot help occurring in the middle of acceleration. This is one of the reasons why transverse coupled bunch instability occurs at rather high energy.

5. Ion Trapping Effect

NAR has 12 button type electrodes to clear trapped ions. The high voltage of 200 V and 800 V is applied to the electrodes during injection and storage. They are effective but seem to be insufficient to clear ions completely.

At injection, the life time is much shorter than expected from vacuum pressure. This is supposed to be due to trapped ions which may be stored in neutralization pocket even if clearing electrodes are used. This phenomenon seems to limit the beam current of NAR.

6. Closed Orbit Distortion

In NAR, which adopted 15 MeV injection energy, closed orbit distortion due to geomagnetism, residual fields from magnets, and leakage fields from Super-ALIS can be more than a few tens mm without correction.

For geomagnetism, assuming the flat distribution of geomagnetism of 0.3 tesla in the straight section of 3.5 meters long, 15 MeV electrons are kicked about 2.1 mrad. Therefore, electrons cannot circulate the ring without correcting the effect of geomagnetism. To cancel the geomagnetism, solenoid coils are set at the two long straight section reserved for insertion devices. However, it is impossible to cancel the geomagnetism which exists narrow spaces between the magnets. Then, closed orbit distortion is corrected by the steering magnets together with the effects of residual fields or alignment errors of multi-pole magnets of 0th order.

The effects of residual fields of magnets are also examined. NAR consists of several kinds of magnets which have iron poles. The injection energy of NAR is 1/50 times as small as the final energy. As a result, residual fields of the iron poles are not observed in NAR at injection energy. The strength of the instability is measured by the octupole current required to suppress the instability. That is, direct observation of the form factor distribution became possible in low energy injection storage ring.

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**Fig. 3.** RF pick-up signal with the occurrence of transverse coupled bunch instability

**Fig. 4.** Chromaticity dependence of transverse coupled bunch instability

[Graphs and diagrams are not rendered here for text-only display.]

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**Table:**

<table>
<thead>
<tr>
<th>Sextupole Current (arb. units)</th>
<th>Unstable</th>
<th>Occasionally Unstable</th>
<th>Stable</th>
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<tr>
<td>-2000</td>
<td>x</td>
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</tr>
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Then, closed orbit distortion can be corrected by steering magnets demagnetized before routine operation. The other magnets with negligible after magnetization. Even if the sextuple magnets or is sent properly, the closed orbit distortion due to the leakage field uni-polar power sources’ are used after the same magnetization magnets which are connected to bipolar power sources are magnetized. The residual field reaches a few gausses. Accordingly, can be roughly corrected.

Stage complicated is bad reproducibility of injection experiment. One of the problems that makes machine study at early stage complicated is bad reproducibility of injection experiment. One of the distinct reasons is the offset change of magnet power sources. Power sources of bending or quadrupole magnets are designed to achieve 10^4 stability against maximum output. However, this stability correspond to as much as 0.5 % against injection level. Moreover, the accuracy and stability of 10^4 are secured by the feedback system from the output current monitors (DCCT) to power sources but the offset value of this DCCT shows long term shift which results in the bad reproducibility of output current.

Another reason which affect the reproducibility is the characteristic change of LINAC. Energy, current, or position of electrons from LINAC changes slightly per pulse. After an interval, LINAC sometimes shows larger characteristic shift. In consequence, adjustment of microwave output is required in routine operation.

The reproducibility at injection is determined by various conditions but main factors are focused on the reasons described above.

7. Reproducibility

One of the problems that makes machine study at early stage complicated is bad reproducibility of injection experiment. One of the distinct reasons is the offset change of magnet power sources. Power sources of bending or quadrupole magnets are designed to achieve 10^4 stability against maximum output. However, this stability correspond to as much as 0.5 % against injection level. Moreover, the accuracy and stability of 10^4 are secured by the feedback system from the output current monitors (DCCT) to power sources but the offset value of this DCCT shows long term shift which results in the bad reproducibility of output current.

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The reproducibility at injection is determined by various conditions but main factors are focused on the reasons described above.

8. Magnet Displacement

Another factor which made machine study more difficult is the displacement of the magnets. When we measured the vertical alignment of the magnets a few years after the installation, more than a few millimeters alignment errors were found out (Fig. 5). These alignment errors are very large considering the error limit at initial installation is less than 0.1 millimeters. When this displacement happened is not clear. As the operation condition was adjusted under these alignment errors, no correction was made even though these alignment errors were detected.

Moreover, the alignment suddenly changed in September 1991 (Fig. 5). The change must have happened in a week during which no-one used SR. An earthquake which happened in the middle of this interval might have caused this displacement. Fig. 5 shows the similarity between the original magnet displacement and the second alignment change. This similarity suggests that these displacements are caused by the same reason.

The second alignment change result in decrease of injection current and movement of SR position which could not be corrected satisfactorily with steering magnets. In consequence, the vertical re-alignment was performed and closed orbit distortion was re-corrected with steering magnets both at injection and during storage.

9. Shortening of Life

During the storage, sudden change of beam life is observed. Two kinds of life shortening seem to exist. One of them is thought to be caused by dust particles trapped in electron beam. In this case, the life can be recovered by changing the electron orbit with steering magnets. The response time of steering magnets is so slow that lighter particles such as ions cannot escape. No distinct change in beam profile is observed before and after the shortening and the life changes sharply.

The other seems to be related to ion trapping. According to the beam profile monitor, the vertical beam size changes before and after shortening of life. The life seems to be determined by toschek life from its dependence on RF voltage. This phenomenon is interpreted as follows. Trapped ions causes the coupling between horizontal and vertical oscillation. As a result, the enlargement of vertical beam size and the increase of bunch volume make toschek life longer. Trapped ions happen to escape and the decrease of vertical beam size and bunch volume shortens toschek life. In this case, the life cannot be cured by changing electron orbit with steering magnets and the life changes gradually.

10. Summary

After the first SR from NAR was extracted in 1988, it took about five years to improve the beam current and achieve more than 100 mA. The machine study at injection was complicated and difficult because a couple of factors limited the beam current and the reproducibility was not good. After all, the current limitation could be attributed to individual factors, i.e., transverse coupled bunch instability, ion trapping effect, and closed orbit distortion. At present, these phenomena can be examined independently.

While low injection method required several efforts, some interesting phenomena such as chromaticity dependence of transverse coupled bunch instability can be observed because the electron beam size is large in such low energy.

Acknowledgment

The authors would like to thank the technical staffs of Toshiba Corporation who collaborated the design and construction of NAR. They also would like to express their appreciation to SR operators and users who were helpful and encouraging in improving NAR.

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Present Status of PNC High Power CW Electron LINAC

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Abstract

Pre-commissioning of the PNC high power electron accelerator, a 10 MeV CW (Continuous Wave) TWRR (Travelling Wave Resonant Ring) electron linac, has been started. All the major components of the injector are installed and aligned. After pre-commissioning, the rest of six accelerating TWRR tubes will be installed by the end of the 1996 fiscal year. Commissioning of the entire machine will begin in April 1997.

1. Introduction

Design and construction of a high power CW electron linac to study feasibility of nuclear waste transmutation [1] was started in 1989 at PNC.

A high power L-band klystron and a prototype high power TWRR accelerating tube were built and successfully validated many of design concepts by the end of 1992 at KEK facility. The injector, first accelerating tube and utility equipments were installed. These portion is ready to accelerate beam by winter 1995 at beam energy of 3 MeV. The whole facility will be completed in March 1997 at energy of 10 MeV.

The accelerator facility building has been completed in August, 1991. The facility has three floors, where there are the accelerator in the basement, klystrons and their power supply in the first floor. The accelerator room is surrounded with 2.3 m concrete shielding on its roof and wall. The utility facility such as a gas processing equipment and a cooling-water system are in the basement and first floor, respectively. A schematic isometric view of the building is shown in Fig. 1A.

PNC linac is a 10MeV, 20mA (average current, 20% duty) CW accelerator with eight normal conducting TWRR disk loaded accelerating tubes[2]. The linac uses 1249.135 MHz constant frequency very critical. A copper made cavity was fabricated with the results of prototype. The beam dump core and cooling plumbing is shown in Fig. 1(D) without a vacuum jacket.

The cooling-water system for the accelerating tubes and the klystrons has been optimizing for the injector test.

The new klystron designed specifically for this project and the rf power supply, 90kV 4 msec 50Hz, can be produced the power of 200kW. The klystron development includes much effort to make a L-band 1MW CW klystron with one pill-box type rf window. The klystron is able to handle continuous power of about 1MW at factory test. Fig. 1(B) shows picture of the klystron and the power supply in the klystron gallery.

Fig. 1(G) shows the electron gun and power supply. At present, the electron gun is under the conditioning up to 200kV. The injector is shown in Fig. 1(E) and 1(F) with view of solenoid coils and TWRR. To reduce the transverse momentum to the part of beam, the rf chopper cavity is driven at fundamental frequency with TM_{401} mode and second harmonic with TM_{304} mode, and DC magnetic bias. Adjusting rf field amplitude and phase, a superposed magnetic field can be equal to nearly zero on the beam center line in 120 degree phase length[3]. The aluminum mock up cavity has shown good results but the feeding rf power and tuning the cavity with different frequency very critical. A copper made cavity was fabricated with the results of prototype. The beam dump core and cooling plumbing is shown in Fig. 1(D) without a vacuum jacket.

The beam line components such as profile monitors, position monitors, and current monitors were installed and have been adjusted. The injector beam acceleration test (as pre-commissioning) will be started with short pulse (~100μsec) and few repetition rate (~1Hz) to avoid the temperature changes of accelerating tubes by feeding high power rf.

3. Summary

All components for the injector has been adjusted and tested at the PNC site to confirm the performance toward injector test.

Presently the PNC accelerator facility is coming to the injector commissioning. This partial operation is necessary for verification of a few new ideas such as two frequency driven rf chopper and the studies of the accelerator that has no existence in the past.

After commissioning of the injector, the rest of six accelerating TWRR tubes are going to be installed by the end of the 1996 fiscal year.

References

Fig. 1 Schematic isometric view and recent pictures of PNC facility.
Abstract

Generation of subpicosecond single electron pulse with the charge of 1 nC have been succeeded at the S-band (2856 MHz) linear accelerator of the university of Tokyo. 34.8 MeV electron pulses with the pulse width of 10 ps have been compressed by the achromatic magnetic pulse compression system. 890 fs (FWHM) single pulse have been generated with the charge of 1 nC through a 3 μm slit. No satellite of the main pulse could be observed.

1. Introduction

The development of short pulse electron accelerator enables direct observation of ultrafast dynamics of electron-matter interaction. In 1977, a 10 ps electron single pulse was first generated at the 35 MeV S-band linear accelerator of the university of Tokyo, and then the pulse radiolysis system was established. Since then, ultrafast phenomena such as excitation, ionization and relaxation of atoms and molecules have been investigated in picosecond regime with the time resolution of a few couple of ten picoseconds. In the case of photoinduced reactions, investigation on ultrafast phenomena in femtosecond region have been started by using femtosecond laser. On the other hand, the time resolution of pulse radiolysis remains a few couple of ten picoseconds. Recently, generation of subpicosecond pulse (900 fs, 150 pC/pulse, 7.1 mm X 11 mm) was succeeded at the university of Tokyo. However, the charge was too little to detect radiation-induced reactions. We attempted to generate high intensity subpicosecond pulse.

2. Experimental Setup

2-1. Achromatic pulse compression system

The achromatic pulse compression experiment was carried out at the 35 MeV S-band linac of the uito twin linacs. This linac has two accelerating tubes (ACCI and ACCII). The experimental setup is shown in Fig. 1. The achromatic pulse compressor consists of two 45° sector magnets and four quadrupole magnets. The upstream sector magnet was also used as an energy analyzer magnet. The longitudinal distribution of electron pulse was modulated for pulse compression by adjusting RF phase of ACCII.

2-2. Induction system

The injector consists of an thermionic electron gun (Y-796) and a d-c biased grid-cathode pulse generator placed on a -90 kV high potential deck, a 476 MHz (1/6 of the main accelerating microwave frequency of
2856 MHz) subharmonic buncher (SHB), a 2856 MHz traveling wave type 6 cell prebuncher and focusing system. The accelerating potential of the electron gun is provided by 90 kV pulses of 8 μs duration. The duration of flat top is 4 μs. The velocity of the electron beam injected from the electron gun is modulated by the electric field at a gap of the SHB. In order to generate an isolated pulse without satellite, a fast rise-time, low jitter trigger pulse synchronized with the accelerating RF waves is required. Up to now, a single pulse has been generated by the grid pulser, whose voltage is 300 V with the pulse width of 1 ns. A higher voltage pulser was purchased by Kentech corporation. The output voltage of the new pulser is 1 kV and the pulse width is 1 ns. We attempted to increase the charge of emission from the Y796 electron gun using this pulser.

2-3. Measurement of pulse shape
Pulse shape of emission from electron gun with the energy of 90 keV was measured by co-axial beam catcher at a distance of 2.5 cm from the anode. The time-resolution of co-axial beam catcher is less than 50 ps. The charge of emission was measured by Faraday cup.

Pulse width of relativistic beam was evaluated by measuring Cherenkov radiation emitted by the relativistic electrons in air at the beam ports. Cherenkov radiation was measured by using a femtosecond streak camera which has a time resolution of 200 fs (HAMAMATSU). The optical measurement system is shown in Fig. 1. All data were acquired by single shot measurement to avoid effects of jitter by accumulation. Beam sizes were measured by using phosphor screens (Desmarquest AF995R) at the beam ports.

3. Results and Discussion
3-1. Magnetic pulse compression at achromatic system
In the magnetic pulse compression experiment, the RF phase in ACCI was tuned so as to minimize the energy spectrum of the pulse. Its energy and energy spread are 19.1 MeV and 0.26 %, respectively. The RF phase in ACCII was tuned so as to accelerate electrons in the early phase of the pulse more than those in the later phase of the pulse. The best RF phase in ACCII was adjusted so as to make the shortest pulse monitoring its width by using streak camera. The peak electric field in ACCII was 10 MV/m. The charge passing through a 3 μ slit at the straight beam port was 700 pC/pulse. A typical measured pulse shape of compressed pulse riding on the phase of 72° is shown in Fig. 2. The pulse width is 850 fs and the horizontal

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Fig. 2. Measured pulse shape of compressed single pulse generated by using the 300 V grid pulser.

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Fig. 3. Calculated longitudinal phase space distributions and beam sizes after energy modulation and after pulse compression.

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At the downstream exit of ACCII

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At the Beam Port

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- 180 -
and vertical beam sizes of the compressed pulse were 3.3 mm and 5.8 mm, respectively. The charge was 208 pC/pulse. Also, 900 fs single pulse with the beam size of 3.3 mm X 3.0 mm was measured at the RF phase of 61.5°. Figure 3 shows the results of simulation. The simulation parameters are 100 μm mrad as 90% normalized emittance, 19.1 MeV as the energy and 0.26% as the energy spread at the exit of ACCI. Both the pulse width and the beam sizes are agreed with the experimental results.

3-2. Change of Grid Pulser
By increasing applied voltage to the grid up to 900V from 80V, the emission from Y-796 electron gun was increased up to 11A with the pulse width of 1 ns. With the increase of the emission, the SHB power was increased up to 2.8 kW from 2.0 kW so as to form a single pulse. The electric field of SHB cavity was increased up to 0.029 MV/cm from 0.024 MV/cm. Figure 4 shows the pulse shape at the beam port in the straight direction. The satellite of the main pulse could not been observed within 10 ns before and after the main pulse. The charge of the original pulse passing through 3 <ϕ> slit was 2 nC/pulse. The charge was increased more than twice. This pulse was compressed by achromatic pulse compression system. Figure 5 shows the typical pulse shape of subpicosecond single pulse with the energy of 34.8 MeV passing through 3 <ϕ> slit. The charge was 1.04 nC. The charge of the compressed pulse passing through 5 <ϕ> slit was 1.36 nC. About 20 percent of the initial charge before compression is lost by the energy modulation. Furthermore, a part of the charge is lost at the slit of the beam port.

4. Summary
34.8 MeV electron pulses with the pulse width of 10 ps have been compressed by the achromatic magnetic pulse compression system at the university of Tokyo. 890 fs single pulse have been generated with the charge of 1 nC through 3 <ϕ> slit. The satellite of the main pulse could not been observed. Subpicosecond pulse radiolysis system is under construction to investigate radiation chemistry and physics in a subpicosecond time domain.

References
Abstract

Construction of the photon storage ring, a novel free-electron laser has been started at Ritsumeikan University. The optimized scheme is composed of a 50 MeV exact circular electron storage ring having 155.8 mm orbit radius, and a concentric optical cavity surrounding the orbit. The beam injection is a 2/3 resonance method. We will start with lasing of 31.2 μm wavelength, although the final goal is of a few μm.

1. Introduction

The idea of photon storage ring (PhSR) was originated in Japan in 1989.[1] The PhSR is based on an exact circular electron storage ring and a concentric barrel shaped optical resonator surrounding the electron orbit. This instrument may be categorized in a compact free-electron laser (FEL), but an undulator is not introduced at all. Stimulated emissions occur due to interactions between electrons in the circular orbit and the synchrotron radiations accumulated in the optical cavity when the phase velocity of the radiation in the electron velocity direction and the electron velocity is matched. TE(pj) mode is concerned to be built in the circular resonator.[2] A large gain is demonstrated by an analytical formula as well as simulations[3], which is common to a circular FEL[4] and a magnetron[5]. The minimum obtainable wavelength is determined by the quality of the electron beam. The use of relativistic electrons possibly leads to an oscillation in a few micron wavelength range[6]. One another advantage of the PhSR is that coherent synchrotron radiations[7] are generated in this small storage ring[8]. The estimated bunch length is the order of 0.1 mm, which leads to coherent radiations of a tens micron wavelength.

Therefor the lasing start with this coherent radiation in the PhSR, while it start with noise signal in an conventional FEL.

In this paper we discuss the designing of a 50 MeV version photon storage ring. We have started the construction of the ring and will be completed by 1997. We will have lasing at 31.2 μm wavelength, but the final goal will be a few micron.

2. Ring parameters

The machine parameters of the electron storage ring is determined as follows. The laser growth rate of the PhSR is inversely proportional to electron energy, γ, and energy distribution, \((dy/\gamma)^2\). In the case of the weak focusing exact circular ring \((dy/\gamma)\) is proportional to \(\gamma^2/\rho\), where \(\rho\) is the central orbit radius. Consequently the growth rate is inversely proportional to \(\gamma^2\), which suggests that lower electron energy gives higher growth rate in principle. In the low energy ring, however, the emittance grows due to the intrabeam scattering, and the damping rate decreases. When we want to construct the ring with a normal conducting magnet, we find that the emittance becomes smallest at 50 MeV under 1 T magnetic field. We are concerned that in this case the Touschek lifetime becomes smallest value, around 1 sec, but this value is large enough for the lasing as well as for the injection of beam. Another concern to be made is the practical problems to construct the ring. The 150 mm electron orbit radius for the 50 MeV ring is almost the smallest size to install the acceleration cavity and the perturbator for the resonance injection.

One of the advantage of the PhSR is there in its beam injection method. The resonance injection method keep the beam in the central orbit undisturbed over more than 10 mm radial width.[9] This enable us continuous injections during FEL oscillations in PhSR.
Table 1 Machine parameter of 50 MeV ring under following conditions: RF-voltage=120 keV, coupling constant=0.1, harmonics=8. The growth rate is calculated for 100 μm wavelength. Correction for intrabeam scattering(ibs) is calculated at 1A beam current.

<table>
<thead>
<tr>
<th>parameters</th>
<th>n-value</th>
<th>0.01</th>
<th>0.1</th>
<th>0.3</th>
<th>0.5</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>emittance (π·mm)</td>
<td>natural</td>
<td>3.58E-07</td>
<td>3.85E-06</td>
<td>1.45E-06</td>
<td>1.88E-06</td>
<td>1.03E-06</td>
</tr>
<tr>
<td>energy spread (ΔE/E)</td>
<td>natural</td>
<td>9.05E-06</td>
<td>4.36E-04</td>
<td>4.76E-06</td>
<td>1.11E-03</td>
<td>1.36E-03</td>
</tr>
<tr>
<td>RMS bunch length (mm)</td>
<td>0.247</td>
<td>1.22</td>
<td>0.317</td>
<td>3.9</td>
<td>0.425</td>
<td>4.9</td>
</tr>
<tr>
<td>horiz. bunch size (mm)</td>
<td>0.235</td>
<td>1.16</td>
<td>0.317</td>
<td>0.58</td>
<td>0.047</td>
<td>0.545</td>
</tr>
<tr>
<td>vert. bunch size (mm)</td>
<td>0.074</td>
<td>0.355</td>
<td>0.0033</td>
<td>0.055</td>
<td>0.0047</td>
<td>0.066</td>
</tr>
<tr>
<td>growth rate (1)/turn</td>
<td>14.7</td>
<td>0.266</td>
<td>13.5</td>
<td>0.021</td>
<td>12.2</td>
<td>0.006</td>
</tr>
<tr>
<td>growth rate (2)/turn</td>
<td>23.5</td>
<td>0.426</td>
<td>22.2</td>
<td>0.034</td>
<td>19.5</td>
<td>0.013</td>
</tr>
<tr>
<td>power loss/turn</td>
<td>0.014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: growth rate (1):cylindrical resonator growth rate (2): barrel shaped resonator

The field index of the ring may be selected to near the integer, 2/3, 1/2, or 1/3 resonance values. Since the field index affects the laser gain, we have studied the n-value dependence of the beam parameters and the growth rates for a 100 μm wavelength as shown in Table 1. Both natural values and corrected values for the intrabeam scattering are listed. It is clear from the table that the smaller index gives higher gain. The use of the integer resonance is recommended. The problem of the integer injection is that the damping speed is slower, and the injection efficiency could be relatively smaller.

3. Optical resonator

We use TE(pj1) mode with large azimuthal, p, and radial, j, mode numbers, and axial mode number of one as the operating mode. The whispering gallery mode, which has fundamental mode numbers, (p,1,1), is inadequate for PhSR, because the optical cavity has to be set too close to the electron orbit within millimeter, and also the power loss due to the ohmic loss becomes too large. The radial mode number dependence of the power loss is shown in Fig. 1, together with the integrated power in the resonator. We can find that the filling factor decreases as the radial mode number increases, but the power loss is reduced more dramatically than the decrease of filling factor.

In order to increase the filling factor the resonator is made in a barrel shape. Strictly speaking the curvature should be specified for each wavelength. This implies that the changing wavelength for not optimized wavelengths is not easy, while it is easy with a simple cylindrical mirror. If enough large gain is observed, we will switch it to the cylindrical resonator.

The optimized curvature of the barrel shape has been obtained by the Gelerkin technique in incorporating with the quasi-optics approximation.[10] For 31μm wavelength we have selected the mirror width, D=20 mm, the curvature in axial direction, Ro= 207 mm, and the mirror radius, R= 155.8 mm. The mirror has a 2x10 mm² slit on the surface for injecting beams as well as extracting laser radiations. Mode mixing due to this slit has already been analyzed.[10]

Fig. 1 Radial mode number(j) dependence of power loss and integrated power.

4. Basic structure of the ring and injector
We have introduced several new features in this ring in comparison with AURORA, the first exact circular ring. The ring is made of normal conducting magnet. The vertical cross sectional view is shown in Fig. 2. In order to generate 0.94 T magnetic field in 120 mm rather wide pole gap, the pole is made in grating shape. Six trim coils are placed in the groove of the grating. Instead of using inflectors and magnetic channels, a field clamp is introduced.

Major components in the ring magnet is one perturbar and two RF-cavities. The RF-cavity is of 2.45 GHz, which serves 8 harmonics. We have already succeeded in fabricating a prototype cavity which has a 10 mm wide slit in the median plane for extracting laser beam.[11] We are planning to use a CW magnetron as a RF source. We are working on a techniques for stabilizing magnetron.

The perturbar is a one turn coaxial coil. To provide 12 kA peak current, we use pulse compression technology based on a non-linear amorphous core for generating a 0.1µsec width pulse train at 50 Hz repetition rate.

Injector is a s-band linac. One accelerator column and pre-buncher, which load 50 MeV beam, will be transferred from KEK. A 30 MW klystron, which will also be transferred from KEK, provides power to both the pre-buncher and the accelerator column. We will operate this at a 0.1 µsec macro pulse, a 50 Hz repetition rate, and 1 A peak current. Note that a long macro pulse is unnecessary for PhSR, which is normally required for a conventional free-electron laser.

5. Project goal

The initial target of the lasing wavelength is around 30µm. This wavelength was chosen because the laser growth rate drops dramatically at shorter wavelengths. The growth rate increases as the beam current increases. Lasing of 30 µm wavelength requires about 100 mA beam current, and for 10 µm wavelength, nearly 10A. We have a experiences of accumulating 1A beam current with AURORA[12], but 10 A beam current sound too large. We hope, however, the number of electrons in bunches are order of 10^{10} in the present case, which is comparable to the 1 A in AURORA, since the circumference of this ring is smaller.

Our first objective is an accumulation of 10 A beam current with such a small and low energy ring, which must be a first experience in the world, and our success in lasing short wavelengths will be influenced by this result. An introduction of gas into the beam duct is a proposed method to accumulate large beam current without increasing beam size, as it was observed by using AURORA at 150 MeV operation. [11]

Generation of coherent synchrotron radiation in a range of 10 to 100 µm wavelength is the target before installing the barrel shaped optical resonator. All these experimental studies are planned to be held in early 1997. We hope to complete machine by the end of next year.

References
PRESENT STATUS OF THE ACCELERATOR DEVELOPMENT AT THE ICR KYOTO UNIVERSITY

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Abstract

The injection system of the 7MeV proton linac has been improved to transport the high intensity beam. A measurement device for the longitudinal emittance of the 7MeV proton beam has been developed. A 100MeV electron linac has newly assembled to study electron-photon beam physics. An electron storage ring will follow this linac. A heavy ion 4-rod RFQ linac was completed and has been moved to the cooperating company to perform acceleration test for industry. The cold model study of the improved DAW structure for the high energy linac was done and a power test model has been designed. A medical synchrotron design has been also studied. An untuned cavity for this synchrotron has been constructed and a new RF power feeding scheme has been tested. Theoretical studies of the space charge effect and an improved 4-rod RFQ structure are in progress. An accelerator-based reactor which consists of a proton linac and a subcritical assembly has been proposed as a pulsed neutron source.

1. Introduction

It may be necessary to use a large accelerator for high energy physics, nuclear physics, photon factory or neutron factory. Only at a national laboratory we can construct such large machine. While at universities accelerator physicists are now disappearing in this country because of the concentration of the budget into the national laboratory. But it is very important to study fundamental accelerator physics or beam physics at universities in order to develop advanced technology and educate younger generation. Our laboratory was a nuclear physics center with a cyclotron more than thirty years ago. But now it becomes a unique accelerator laboratory developing small accelerators and promoting accelerator physics or beam physics at the university.

2. Proton linear accelerator

Our 433MHz RFQ linac accelerated the first beam of 2MeV protons in 1991. Since January 1992 we have obtained 7MeV proton beam from a 433MHz Alvarez linac which follows the 2MeV RFQ linac. So far intensity of the beam has been limited by small aperture of the injection line. Recently we have replaced a bending magnet (a mixing magnet to-be) by a newly designed one which has a larger gap and an entrance angle against the sector focusing. We can now transport a wider envelope beam, which reduces space charge effect. Not only the high intensity beam transportation during the injection line but also beam matching to the RFQ acceptance is necessary to increase the accelerated beam intensity. For this purpose a permanent magnet symmetric lens (PMS) has been designed. The injection line is shown in Fig.1. The designed beam envelope in this injection line is shown in Fig.2. To ensure the beam matching a measurement system of the emittance of the extracted beam from the ion source is now designed.

![Fig. 1. The injection line of the proton linac](image1)

![Fig. 2. The matched beam envelope between einzel lens and PMS section at current of 20mA (TRACE-3D calculation).](image2)
3. Electron linear accelerator and storage ring

On the occasion of the shut-down of the JAERI electron linac and the storage ring JSR some components have been kindly transferred to our laboratory. We have designed a 100MeV electron linac and our storage ring KSR for the study of the electron and photon beams using these transferred components and additional parts.

The calculated beam envelope is shown in Fig. 5. The first beam acceleration test is planned in September 1995.

Table 1. Characteristics of the electron linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Electron Beam</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1 μsec</td>
</tr>
<tr>
<td>Max. Repetition</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Electron Gun (Pierce type)</td>
<td></td>
</tr>
<tr>
<td>Cathode assembly</td>
<td>Y-796 (Eimac)</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>-100 kV DC</td>
</tr>
<tr>
<td>grid voltage (typ.)</td>
<td>100 V</td>
</tr>
<tr>
<td>Accelerating structure</td>
<td></td>
</tr>
<tr>
<td>Mode</td>
<td>2GHz, Constant Gradient</td>
</tr>
<tr>
<td>Number of Cells</td>
<td>85</td>
</tr>
<tr>
<td>Bore Radius</td>
<td>11.74 - 13.4 mm</td>
</tr>
<tr>
<td>Length</td>
<td>3 m</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>2857 MHz</td>
</tr>
<tr>
<td>Shunt Impedance</td>
<td>53 MW/m</td>
</tr>
<tr>
<td>Maximum Electric Field</td>
<td>15 MV/m at 20 MW input</td>
</tr>
<tr>
<td>Klystron (ITT-8568)</td>
<td></td>
</tr>
<tr>
<td>Cathode</td>
<td>250 kV, 250 A</td>
</tr>
<tr>
<td>Output RF Power</td>
<td>21 MW</td>
</tr>
<tr>
<td>Gain</td>
<td>53 dB</td>
</tr>
</tbody>
</table>

Table 2. Design parameters of the storage ring KSR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum energy</td>
<td>300 MeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>25,689 m</td>
</tr>
<tr>
<td>Lattice structure</td>
<td>Triple bend doubly achromatic lattice</td>
</tr>
<tr>
<td>Superperiodicity</td>
<td>2</td>
</tr>
<tr>
<td>Bending angle</td>
<td>60°</td>
</tr>
<tr>
<td>Radius of Curvature</td>
<td>0.835 m</td>
</tr>
<tr>
<td>n-value</td>
<td>0</td>
</tr>
<tr>
<td>Size angle</td>
<td>9°</td>
</tr>
<tr>
<td>Length of long straight section</td>
<td>5.619 m</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>10</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>116.7 MHz</td>
</tr>
<tr>
<td>Number of Bessel Oscillations</td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>2.75</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.75 (1.25)</td>
</tr>
<tr>
<td>Critical wave length from dipole</td>
<td>17 nm</td>
</tr>
</tbody>
</table>

4. Boron beam acceleration with the 4-rod cw RFQ linac

At the ICR Kyoto University the 4-rod cw RFQ linac was constructed and the first beam was obtained on December 25, 1992. At the University He, N and C ion beams were accelerated to test the operation of the system. After one year test the linac system was moved to Kuzo factory of Nissin Electric Co., Ltd. to continue the acceleration test of the boron ion beam which would be used in the process of semiconductor industry. The characteristics of the 4-rod RFQ linac are listed in Table 3 and a schematic plan view is...
Table 3. Characteristics of the 4-rod RFQ heavy ion linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion source</td>
<td>Freeman type</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>504 kV max.</td>
</tr>
<tr>
<td>Mass analyzer</td>
<td>90° magnet with octupole correction</td>
</tr>
<tr>
<td>Focusing elements</td>
<td>Four magnetic quadrupole lenses and one Eustel lens</td>
</tr>
<tr>
<td>Beam optical length</td>
<td>2.5 m, including a beam monitor</td>
</tr>
<tr>
<td>RFQ:</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>feed frequency &quot;modified&quot; 4-rod</td>
</tr>
<tr>
<td>Frequency</td>
<td>33.2 MHz (design)</td>
</tr>
<tr>
<td>Average bore radius</td>
<td>0.8 cm</td>
</tr>
<tr>
<td>Focusing strength</td>
<td>0.79</td>
</tr>
<tr>
<td>Inter-electrode voltage</td>
<td>54 kV</td>
</tr>
<tr>
<td>Change to mass ratio</td>
<td>551 (design)</td>
</tr>
<tr>
<td>Injection energy</td>
<td>2.7 MeV/µA</td>
</tr>
<tr>
<td>Output energy</td>
<td>85.3 MeV/µA (two half-cells)</td>
</tr>
<tr>
<td>Length of electrode</td>
<td>327 mm (two half-cells)</td>
</tr>
<tr>
<td>Cavity inner diameter</td>
<td>60 cm</td>
</tr>
<tr>
<td>of power</td>
<td>30 kW max.</td>
</tr>
<tr>
<td>Operation mode</td>
<td>cw</td>
</tr>
<tr>
<td>Transmission</td>
<td>249%</td>
</tr>
</tbody>
</table>

Fig. 6. Experimental setup of the 4-rod RFQ linac system shown in Fig. 6. We have obtained the singly charged boron beam intensity of 330 mA with total beam transmission of 80%5). The measured beam emittance was about 10πmm-mrad at the accelerated beam energy of 0.92 MeV.

5. DAW cavity

The disk-and-washer (DAW) structure of the linac has been studied in our laboratory. Recently a biperiodic L-support structure has been proved to have high quality without the mode overlapping problem. MAFIA and SUPERFISH calculations and cold model studies have been made6). Then a power model is now under construction for S-band electron linac because the S-band RF power sources have become available as mentioned above.

6. Medical proton synchrotron

A compact 230 MeV proton synchrotron with a combined function lattice has been designed for medical use. A proton linac like our existing 7 MeV linac may be used as an injector. Slow beam extraction of diffusion-resonant scheme has been studied7). A ferrite-loaded untuned cavity with multiple RF power feeding has been designed and constructed8). The concept of the feeding is shown in Fig. 7. According to the cold model test the reflection power from the cavity is reduced from 75% of the forward power in the direct coupling case to 20% in the multi-feed coupling case. It is also confirmed that the cavity voltage is increased by factor 1.5 for multiple coupling case comparing to the direct coupling case8). The power model test is being carried out in cooperation with Hitachi Ltd.

7. Other studies

Space charge effect and halo formation in case of high intensity linac are investigated by analytical and simulation methods. A simulation code is developed at our laboratory9). A normal mode analysis of transmission lines for TEM mode waves is applied to a 4-rod RFQ resonator10). Results of this analytical method are in good agreement with calculations by MAFIA code. A 2.5-D RF cavity code PISCES II is also developed11).

A pulsed neutron source which consists of a proton linac and a subcritical assembly is proposed for a future project of Kyoto University Research Reactor Institute12). The linac will accelerate a 300 MeV-30 mA proton beam and the power gain of the subcritical assembly will be 20. Characteristics of an example of the proposed pulsed reactor with a proton linac are listed in Table 4.

Table 4. A proposed pulsed reactor with a proton linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion source</td>
<td>multi-cusp field type</td>
</tr>
<tr>
<td>RFQ section</td>
<td>2 MeV, 433 MHz</td>
</tr>
<tr>
<td>DTL section</td>
<td>100 MeV, 433 MHz</td>
</tr>
<tr>
<td>DAW section</td>
<td>300 MeV, 1,300 MHz</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>30 mA at peak</td>
</tr>
<tr>
<td>Pulse width</td>
<td>30 µsec</td>
</tr>
<tr>
<td>Repetition</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Neutron yield</td>
<td>10^10 /sec at peak</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Subcritical assembly</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>235U</td>
</tr>
<tr>
<td>Peak power</td>
<td>180 MW</td>
</tr>
<tr>
<td>Average power</td>
<td>600 kW</td>
</tr>
<tr>
<td>Neutrons</td>
<td>10^10 /sec at peak</td>
</tr>
</tbody>
</table>

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CONSTRUCTION OF A NEW PRE-INJECTOR SYSTEM FOR THE RILAC

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Abstract

A new pre-injector system for the RIKEN heavy-ion linac (RILAC), which is used as an injector of the RIKEN Ring Cyclotron (RRC), has been completed in order to increase beam intensities of heavy ions by one or two orders of magnitude. The system consists of an ECR ion source, a variable-frequency RFQ linac and a beam transport line between them. The performance tests of the whole system including beam acceleration test are being made successfully. It is planned to be installed on site next year.

1. Introduction

Recently we have started to do R&D's for the RI-beam factory project, which aims to increase beam energies up to 400 MeV/u for light heavy-ions and 150 MeV/u for very heavy ions using a superconducting ring cyclotron as a booster of the RIKEN Ring Cyclotron (RRC). One of the main purposes of the project is to produce radioactive-isotope beams and/or new isotopes in the wide range of nuclear masses up to uranium. In order to achieve the goal, it is indispensable to provide the RIKEN heavy-ion linac (RILAC) the injector of the RRC, with much higher-intensity of heavy ions.

To meet the above demand, we have developed a new pre-injector system for the RILAC. The RILAC consists of six resonator tanks, each being of the Widoroc type and frequency tunable. The existing pre-injector system consists of an 8 GHz NEOMAFIOS and a 450 kV Cockcroft-Walton terminal. In the new pre-injector system is used a high-field, 18 GHz ECR ion source that is expected to have significantly high performance compared to the present 8 GHz NEOMAFIOS. A variable-frequency RFQ linac is adopted as an equivalent to the existing Cockcroft-Walton terminal, which is unable to accommodate such an 18 GHz ECR ion source that requires high electric power.

In this paper we describe the characteristics of the new pre-injector system and the status of its construction.

2. Description of the New System

Figure 1 shows a planned layout of the new pre-injector system together with the beam transport line from the existing one. The existing beam transport line is slightly modified from the present for installation of the new system.

2.1 18 GHz ECR Ion Source

The ECR ion source is of a single-stage type and operates at 18 GHz. The axial mirror field has peaks of 1.4 T (mirror ratio is 3.0) and the radial hexapole field is 1.4 T at the pole surfaces of 80 mm in diameter, both of which are high enough for the double-frequency operation. The axial mirror field is produced...
with a pair of solenoids enclosed with an iron yoke that are excited by two power supplies of 800 A. The power consumption of the solenoids is 140 kW and the required electric power for the power supplies is 210 kVA. The outer dimension of the yoke is about 700 mm in diameter and 550 mm in length. The radial field is produced with 36 segments of permanent magnets made of Nd-Fe-B, each segment 224 mm in length. The permanent magnet is protected from plasma heat by a plasma-chamber that is cooled by water of 20°C. The chamber is made of two copper cylindrical tubes that are welded to each other after the surface of the inner tube is carved to make conduits for coolant water. The thickness of the chamber is 3 mm. The temperature of the chamber is expected to rise up to 26°C at the maximum. The magnet is also protected from the heat of the solenoid coils by a similar copper cylinder. RF of 18 GHz is fed by a Thomson TH 2463 klystron with a maximum output power of 1.5 kW. This RF power source is designed to operate in both cw and pulse modes. A rod of metal can be inserted axially for producing metallic ions. The plasma cathode method can be applied. The inside of the plasma chamber is evacuated with 500 and 150 l/s turbo-molecular pumps. Ions are extracted from an orifice of 10 mm in diameter with a maximum voltage of about 10 kV. The orifice is positioned at the end of the permanent magnet.

2.2 FC-RFQ Linac

The RFQ linac\(^4,5\) is required to have the same function as that of the existing 450 kV Cockcroft-Walton terminal. It is designed to accelerate ions with a range of m/q = 6-27 up to 450 keV/q in the cw mode. The operational frequency should be varied between 18 MHz to around 40 MHz, which is one of the most important problems to be solved in the design of the RFQ linac. We have adopted a "folded coaxial" RFQ (FC-RFQ) structure. This structure allows the cavity to be tunable in a wide range of frequencies and to be compact even in the low frequency region below 20 MHz. The FC-RFQ structure can also enable the intervane voltage to be flat enough to obtain high beam-transmission efficiency. The length of the vanes is 1420 mm and the inner volume of the resonator is about 1700 mm (length) \times 700 mm (width) \times 1000 mm (height). The stroke of the shorting plate for coarse tuning is 790 mm. For the details of the structure, see ref. 4. The required maximum intervane voltage is 33.6 kV. RF power is fed by an oscillator with an Eimac ACW5000E with a maximum output power of 40 kW between 16.9 MHz to 40 MHz. The total water flow for cooling is about 200 l/min of 7°C and the temperature of water is 30°C. The temperature of the vanes is expected to rise up to about 40°C at the maximum. The resonator is evacuated with two turbo-molecular pumps of 1500 l/s.

2.3 Beam Transport Line

The beam transport line\(^6\) between the ECR ion source and the FC-RFQ linac consists mainly of (from upstream) an Einzel lens, a 90° bending magnet, a beam diagnostic chamber and a solenoid magnet. In the design an ion beam is first focused with the Einzel lens onto a spot of 10 mm in diameter at the symmetric position of the extraction orifice with respect to the lens. The beam is then analysed with the 90° bending magnet having slant edges and doubly focused at a point between the bending magnet and the solenoid magnet. The dispersion and magnification in the horizontal direction at this point are 2.2 cm/° and -0.98, respectively. From the values of dispersion and magnification, mass resolution \(m/\Delta m\) is about 200. The beam is finally matched to the FC-RFQ linac with the solenoid magnet.

The Einzel lens is of three-electrode type with different diameters: the diameter of the center electrode is 100 mm and that of the end electrodes is 74 mm. A voltage of about 15 kV at the maximum is required to be applied to the lens. The bending magnet has a curvature radius of 500 mm and a gap of 80 mm. The maximum magnetic field is 0.16 T. The angle of the slant edge is 28.7° at both the entrance and the exit. The solenoid magnet consists of coils and an iron yoke enclosing them. The inner diameter, outer diameter and length of the magnet are 90 mm, 610 mm and 310 mm, respectively. The maximum magnetic field is 0.63 T. Beam diagnostic devices such as a profile monitor, a Faraday cup and a pair of slits are set in the beam diagnostic chamber located between the bending magnet and the solenoid magnet. A beam emittance monitor can also be set in this chamber. The beam transport line is evacuated with two turbo-molecular pumps of 350 l/s.

3. Fabrication and Test

Fabrication of the whole system was completed in the spring of 1995. Performance test of the characteristics of the 18 GHz ECR ion source and the FC-RFQ linac as well as beam acceleration test in the system have been made. Details of the results are reported in refs. 3 and 5.

Figure 2 shows a photograph of the 18 GHz ECR ion source. Ion beam intensities were measured for gaseous elements such as oxygen, argon and krypton with an extraction voltage of up to 15 kV (though a required maximum voltage is about 10 kV for delivering a beam to the FC-RFQ). Obtained beam intensities of \(\text{Ar}^{11+}\) and \(\text{O}^{17+}\) ions, for example, were 160 and 130 mA, respectively, with an RF power of about 600 W and an extraction voltage of 15 kV. Typical gas pressures of the plasma chamber...
Figure 4 shows a photograph of the FC-RFQ linac. The vanes have been three-dimensionally machined and assembled within an accuracy of ±50 μm, the value meeting the requirement for good beam transmission. The surface of the vanes were polished with electrochemical buffing within a flatness of less than 1 μm. The resonant frequency was measured to vary from 17.7 MHz to 39.2 MHz. The measured Q-values and shunt impedances were about 60% of the MAFIA calculations. From the shunt impedance measurement, the required maximum RF power was found to be 26 kW (cw). Typical gas pressure of the resonator was 1–3×10⁻⁷ Tor. We have encountered a serious problem on the ceramic pillars that are used to fix the high voltage part (to which the vertical vanes are attached) on the bottom plate of the resonator. A multipactoring occurred on the pillars at an interwave voltage of below 15 kV, and heating due to dielectric losses in a local region of the pillars occurred at an interwave voltage of above 35 kV. To fix this problem, ceramic pillars were redesigned and are being newly fabricated. Beam acceleration tests have been performed for Ar, Ar+, Ar11+, and O5+ ions at the frequencies of 17.7, 26.1, 34.4 and 39.2 MHz, respectively, at the interwave voltage of about 20 kV. The beam velocity after acceleration, which was measured by the TOF technique using three capacitive pickup probes, was in agreement with the designed value within 1%. The beam transmission efficiency of 85% at the maximum was obtained. Beam emittance has not yet been measured in the acceleration test.

4. Summary

A new pre-injector system for the RILAC was completed in the spring of 1995. The performance tests including beam acceleration test showed that the beam intensity from the RILAC will increase by one or two orders of magnitude as expected. The system is planned to be installed on site next year. A beam rebuncher will also be installed at that time between the FC-RFQ linac and the RILAC.

5. References

PROGRESS REPORT ON THE CONSTRUCTION OF THE HEAVY-ION LINACs FOR RADIOACTIVE NUCLEI


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Abstract

A heavy-ion linac complex for radioactive beams is now under construction at INS. The linacs are a 25.5-MHz split coaxial RFQ and a 51-MHz interdigital-II (IH) linac. Ions with a charge-to-mass ratio \( \frac{q}{A} \) greater than \( \frac{1}{30} \) are accelerated from 2 to 172 keV/u by the RFQ. The beam passes through a carbon-foil, and ions with \( \frac{q}{A} > \frac{1}{10} \) are accelerated further by the IH linac. The output energy is variable in the range of 0.17 through 1.05 MeV/u. The RFQ has already accelerated stable ions Ne\(^+\) and N\(^+\). The IH linac has undergone low-power tests. Other devices in the beam transport line between the linacs are under fabrication or tuning. The first beam acceleration through the linacs is scheduled for March, 1996.

1. Introduction

A radioactive-beam facility is now under construction at INS. The beam from an isotope separator on-line (ISOL) will be accelerated by a 25.5-MHz RFQ and a 51-MHz interdigital-II (IH) linac, and used for nuclear physics experiments.

Figure 1 shows the layout of the linac system. The RFQ accelerates ions with a charge-to-mass ratio \( \frac{q}{A} \) greater than \( \frac{1}{30} \) from 2 to 172 keV/u. The output beam is enhanced in charge state in a carbon-foil stripper (\( \frac{q}{A} \geq \frac{1}{10} \)), and then shaped in the longitudinal and transverse phase spaces by a 25.5-MHz rebuncher and 2 doublets of quadrupole magnets. The IH linac consists of 4 tanks and 3 triplets of quadrupole magnets between tanks. The tanks are excited separately by 4 rf power sources, and hence, it is possible to vary the output beam energy continuously in the range from 0.17 to 1.05 MeV/u by adjusting the rf power levels and phases.

In Fig.1, the ion source, low-energy beam transport, RFQ, and the first quadrupole doublet came into operation in March, 1995. The RFQ, whose parameters are given in Table 1, accelerated stable ions Ne\(^+\) and N\(^+\). The ion source was a 2.45-GHz ECR one located near the RFQ. The measured transmission efficiencies and emittance profiles of the output beam agreed well with PARMTEQ predictions.\(^1\) The IH tanks have undergone low-power tests: tuning of the resonant frequency, measurement of the Q-values, and evaluation of the shunt impedances. Similar low-power tests have been conducted on the rebuncher cavity, which is a folded coaxial-line resonator with 6 gaps.\(^2\) The second quadrupole doublet is now being fabricated.

The linac system will be completed in March, 1996. Then the first beam acceleration through the linacs will be conducted.

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Figure 1: Heavy-ion linac system under construction.
5% = 0.53 ms x 95 Hz). At the nominal voltage (Vvv = 109 kV), 90% of the injected ions were accelerated; 91.4% is the PARMETEQ value. Good agreements between the experimental data and simulation predictions were obtained also at higher intervane voltages; the maximum was 81 kV. At Vvv = 81 kV, the rf peak power (P_peak) and the averaged one (P_ave) were 134 kW and 6.7 kV, respectively. At such a P_ave level or lower, the RFQ has a good performance; this is our conclusion for the beam tests.

We aim at operating the RFQ at higher power levels. The issues are to keep the resonant frequency under control and to verify that the vanes are well cooled. If they are distorted by heat, the beam performance obtained at the lower powers would not be preserved. We have been trying to raise the intervane voltage to 109 kV (design value for q/A = 1/30 ions), and the duty factor to 30%. As shown in Table 2, the duty factor is still lower, but the intervane voltage has almost reached the goal.

3. Interdigital-H Linac

Table 3 lists main parameters of the IH linac. The output energy is variable in the range of 0.17 through 1.05 MeV/u. Figure 2 shows a simulation result of the energy spread as a function of the output energy. The levels and phases of the rf powers into the tanks are optimized so that the energy spread might be minimized. The input beam is a simulated C²⁺ ion that has passed all the elements before the IH linac (a 10-µg/cm² carbon-foil stripper is included). The input energy is 167 keV/u, and the full widths of the phase and energy spreads are 35° and 1 keV/u. Resultant energy spreads at the output are ±0.85% at 0.7 MeV/u, and ±0.45% at 1 MeV/u. Without the stripper the energy spreads are 3/4 of these values.

We had fabricated a cold model for each of the 4 tanks, and studied the rf characteristics of the IH cavity. The models were scaled up to the present IH tanks; the scale factors are 20/9 at Tanks 1 ~ 3, and 2 at Tank 4. Low-power tests of the tanks have been almost finished. The results are summarized in Table 4. Every tank was matched to a 50-Ω signal generator via a loop coupler. It was attached to a port placed near a ridge end. Before the tuning, Tanks 1 ~ 3 had resonant frequencies (f_initial in Table 4) higher than 51 MHz by 84, 134, and 180 kHz, respectively. We decreased the frequencies closer to 51 MHz (f_tuned) by using capacitive tuners: every tank has a C-tuner, which is a movable disk (19 cm dia) facing a ridge.

---

### Table 1

Design parameters of the RFQ.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (f)</td>
<td>25.5 MHz</td>
</tr>
<tr>
<td>Charge-to-mass ratio (q/A)</td>
<td>1/30</td>
</tr>
<tr>
<td>Kinetic energy (T_in - T_out)</td>
<td>2 ~ 172 keV/u</td>
</tr>
<tr>
<td>Normalized emittance (ε_n)</td>
<td>0.056 • cm-mrad</td>
</tr>
<tr>
<td>Vane length (L_v)</td>
<td>858.5 cm</td>
</tr>
<tr>
<td>Number of cells (N_c)</td>
<td>172</td>
</tr>
<tr>
<td>Intervane voltage (Vvv)</td>
<td>108.6 kV</td>
</tr>
<tr>
<td>Maximum surface field (E_L_max)</td>
<td>178.2 kV/cm</td>
</tr>
<tr>
<td>Mean aperture radius (r_0)</td>
<td>0.9846 cm</td>
</tr>
<tr>
<td>Minimum aperture radius (r_min)</td>
<td>0.5388 cm</td>
</tr>
<tr>
<td>Max. modulation index (m_max)</td>
<td>2.53</td>
</tr>
<tr>
<td>Final synchronous phase (ϕ_f)</td>
<td>-30°</td>
</tr>
<tr>
<td>Transmission (0 mA input)</td>
<td>91.4%</td>
</tr>
</tbody>
</table>

### Table 2

Progress in feeding high power into the RFQ.

<table>
<thead>
<tr>
<th>Date</th>
<th>Vvv (kV)</th>
<th>P_peak (kW)</th>
<th>P_ave (kW)</th>
<th>Duty (%)</th>
<th>Width rep. (%)</th>
<th>f (Hz)</th>
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</thead>
<tbody>
<tr>
<td>3/22/95</td>
<td>81</td>
<td>134</td>
<td>26.5</td>
<td>19.8</td>
<td>0.66</td>
<td>300</td>
</tr>
<tr>
<td>4/13/95</td>
<td>91</td>
<td>170</td>
<td>2.6</td>
<td>1.5</td>
<td>0.53</td>
<td>29</td>
</tr>
<tr>
<td>6/20/95</td>
<td>104</td>
<td>220</td>
<td>13.2</td>
<td>6.0</td>
<td>0.50</td>
<td>120</td>
</tr>
<tr>
<td>7/12/95</td>
<td>107</td>
<td>242</td>
<td>6.1</td>
<td>2.5</td>
<td>0.50</td>
<td>50</td>
</tr>
<tr>
<td>9/05/95</td>
<td>108</td>
<td>235</td>
<td>18.8</td>
<td>8.0</td>
<td>2.00</td>
<td>40</td>
</tr>
<tr>
<td>goal</td>
<td>109</td>
<td>242</td>
<td>72.6</td>
<td>30.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3

Main parameters of the IH linac.

<table>
<thead>
<tr>
<th>Tank</th>
<th>Vvv (kV)</th>
<th>P_peak (kW)</th>
<th>P_ave (kW)</th>
<th>Duty (%)</th>
<th>Width rep. (%)</th>
<th>f (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>294</td>
<td>475</td>
<td>1.0</td>
<td>98.0</td>
<td>9.7</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>725</td>
<td>753</td>
<td>1.2</td>
<td>98.0</td>
<td>9.7</td>
<td>51</td>
</tr>
<tr>
<td>3</td>
<td>1053</td>
<td>1034</td>
<td>1.4</td>
<td>98.0</td>
<td>9.7</td>
<td>51</td>
</tr>
<tr>
<td>4</td>
<td>134</td>
<td>132</td>
<td>1.6</td>
<td>98.0</td>
<td>9.7</td>
<td>51</td>
</tr>
</tbody>
</table>

---

Figure 2: Energy spread vs output energy.
Table 4

Summary of low-power tests of the IH tanks.

<table>
<thead>
<tr>
<th>Source</th>
<th>P (kW)</th>
<th>(\Delta V_{\text{gap}}) (%)</th>
<th>(\Delta P_{\text{out}}/P_{\text{out}}) (%)</th>
<th>(\Delta \phi) (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1 (for Tank 1)</td>
<td>12,000</td>
<td>±0.24</td>
<td>±0.1</td>
<td>±0.1</td>
</tr>
<tr>
<td>No. 2 (for Tank 2)</td>
<td>22,000</td>
<td>±0.1</td>
<td>±0.2</td>
<td>±0.1</td>
</tr>
<tr>
<td>No. 3 (for Tank 3)</td>
<td>30,000</td>
<td>±0.3</td>
<td>±0.15</td>
<td>±0.15</td>
</tr>
<tr>
<td>No. 4 (for Tank 4)</td>
<td>50,000</td>
<td>±0.4</td>
<td>±0.15</td>
<td>±0.15</td>
</tr>
</tbody>
</table>

4. Acknowledgments

We express our thanks to T. Nomura for his encouragement. The IH linac was fabricated by Sumitomo Heavy Industries, Niihama Works, and the IH power sources by IDX Corporation.

References

[2] Y. Hashimoto et al., "Cold test of a 25.5 MHz Double-Coaxial \(\lambda/4\) Resonator", this symposium.
ACCELERATION TESTS OF THE JAERI TANDEM SUPERCONDUCTING BOOSTER

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Abstract

An independently phased heavy ion linac composed of 46 superconducting quarter wave resonators has been built for the booster of the tandem accelerator at Japan Atomic Energy Research Institute, Tokai. Several kinds of heavy ions of Si to Au have been accelerated. The performances of the resonators and the results of the beam acceleration are described.

1. Introduction

An upgrade project of the JAERI tandem accelerator with a superconducting booster has been completed after a R&D of a superconducting quarter wave resonator from 1984[1], fabrications and testing of prototype units composed of two superconducting resonators from 1986 and a full scale construction of the booster from 1988[2-4]. Heavy ion beams of Si to Au have been accelerated by the tandem and the booster for the commissioning test in 1994.

For heavy ion beams up to around Au, a bombarding energy higher than nuclear reaction threshold has become available at the new target room.

2. Outline of the Tandem Booster

The diagram of the JAERI tandem booster is shown in Fig.1. The continuous beam from the tandem is injected into the booster. The booster starts off with a double drift bunching system composed of two 129.8MHz QWRs and two 259.6MHz QWRs. One of the two for each frequency is used, while the other stands by. The linac comprises ten acceleration units, each of which contains four 129.8 MHz QWRs in a cryostat and a quadrupole doublet lens outside. After the linac, there is a debunching unit composed of two 129.8MHz QWRs. The debunched beams are analyzed by a double focusing bending magnet. The beams obtained from the booster are, then, 129.8 MHz CW beams.

With respect to the beam transport system, the beam waists should be located at the middle of the two bunching units, at the entrance of the linac, in the middle of the linac, at the exit of the linac, at the object and image points of the analyzing magnet and finally the target position in a target beam line. At or near the waist points, apertures or slits, beam profile monitors and Faraday cups are placed. Beam baffle apertures of 16mm in diameter are put at the entrances of all the acceleration units to protect resonator surfaces from stray beams.

The longitudinal beam diagnostics are important to an independently phased linac. Energy and time detectors are placed before and after the linac and after the debuncher. Those are compact scattering chambers that ions scattered from an Au foil are detected by a solid state detector. Three beam bunch phase detectors, 129.8 MHz normally conducting QWRs, are used for the phase setting of the linac resonators.

3. Cryogenics

The booster is equipped with two identical refrigerators of Claude cycle with two expansion turbines. Each system has two loops, a liquid helium loop and a 80K gaseous helium for the radiation shielding in the transfer line and in the cryostats.

Fig. 1 Diagram of the JAERI tandem booster.
4. Resonator Performances

The resonator performances were measured in an off-line test cryostat. Fields of about 7 MV/m were obtained at an rf input of 4 W\[4, 5\]. For most of the resonators, the Q-decrease due to electron field emission at high fields was not so much that high maximum fields were obtained without high power pulse conditioning. This result is due to that the resonators were cleaned well in the final surface treatment.

We have found the Q-degradation with the resonators which absorbed much of hydrogen (an order of a few wppm) in the electro-polishing and were cooled slowly around 120K\[4, 5\]. This phenomenon is understood as a precipitation of a niobium-hydride weak superconductor onto the niobium surface\[6\]. The cooling rate at 120K was 10K/h when the resonators on line were cooled by the refrigerators. The rate is approximately one-fourth of that in the off-line test cryostat. The Q-values at low fields measured for the resonators in off-line and on-line are shown in Fig.3. A strong Q-degradation happened to most of the resonators from no.1 to no.16. Hydrogen absorption was not prevented enough for them. But, the following improvement was given to the resonators from no.17 in the surface treatment. The hydrogen gas coming out during electro-polishing was brought away as much as possible from the polishing solution by passing nitrogen gas bubbles. The bubbling seemed to be efficient for preventing hydrogen absorption into the niobium for the closed cavity structure.

Fields gradients obtained for the on-line resonators are shown in Fig.4. The resonators of no.1 to no.16 needed the present allowable rf power input of about 4W per resonator mentioned above to obtain their maximum field gradients. Many of them were lower than the design value of 5 MV/m. For those from no.17 to no.40, the degradation was not so severe that field gradients higher than 5 MV/m were obtained within 4 W.

The Q-degradation can be reduced by increasing the cooling rate at the precipitating temperature, around 120K. The cooling rate from 130K to 90K was increased to about 15K/h in a test that we split the 16 resonators into two groups and used the whole gas from the cold box to cool down one of two groups at a time over the temperature range. The increases are also shown in Fig. 4. An increase of about 0.5 MV/m was obtained. The acceleration voltage summed over all the resonators finally passed 30 MV.

With respect to the frequency stability, the frequency oscillation was only a few Hz when the cryogenic system was stable. A frequency deviation of about 10 Hz or more happened at the time that the liquid levels fell down from 100% or came back to 100 %, and the pressure deviated by about 0.05 kg/cm^2. The rf input coupling was set to give a band width of more than 20 Hz for stable phase lock.

5. Resonator Control with Beam Diagnostics

Each resonator is controlled in a self-excited resonant loop which is composed of a resonator with a variable rf input coupler and a signal pick-up probe, a resonator control circuit and a 120 W rf power amplifier. The rf signal and the rf power are transmitted through heavy doubly shielded coaxial cables. We use control stations made by Applied Superconductivity Inc., in each of which control circuits for 8 resonators are assembled.
For setting the buncher resonators of $\omega_1$ (29.8 MHz) QWR and a $2\omega$ (259.6 MHz) QWR, the energy and time detector located at the entrance of the linac was mainly used in the beam acceleration tests. Next to the detector, a beam bunch phase detector, a $2\omega$ normally conducting QWR, is placed. The phases of the beam bunches respectively bunched by the $\omega_1$ QWR and the $2\omega$ QWR were measured by using the phase detector and a vector volt meter. This was useful for quick phase setting.

For the phase setting of the linac resonators, three beam bunch phase detectors, $\omega_1$ normally conducting QWRs are located after the 3rd acceleration unit, after the 6th unit and after the last unit. Their optimum $\beta$s are 0.08, 0.1 and 0.11 and their sensitivities are 7, 10 and 12 mV/nA, respectively. The signals are amplified by about 40 dB and inputted to vector volt meters. Computer aided measurements were done to display a curve of beam bunch phase as a function of resonator phase in an instant.

A beam bunch phase shift due to the change of time of flight is given as

$$\Delta \phi = \omega_T T = \omega L (2 \beta \nu_0 F_G) E_{acc} L_a (l/l_0) \cos \phi$$

where L is the flight length from the resonator in operation to the phase detector, $E_G$ the incident beam energy, $\beta = \nu_0/c$ the incident beam velocity, $\gamma$ the charge state, $E_{acc}$ the field gradient, $L_a$ the acceleration length, $l/l_0$ the transit time factor and $\phi$ the synchronous phase. By measuring a curve of the phase shift as a function of resonator phase, one can find the value of the resonator phase which corresponds to $f=0$ or the synchronous phase to be set.

The measurements were so quickly done that this method was suitable to repeat 40 times of resonator phase setting. At each resonator setting, the beam energy was checked by using the energy detector located after the linac.

With respect to the debuncher, one of the two QWRs was enough. Phase and field gradient were set, after bending beams $90^\circ$, by looking at the beam profile at the image of the analyzing magnet.

6. Acceleration Test Results

We have accelerated various heavy ions of $^{28}$Si, $^{35}$Cl, $^{58}$Ni, $^{74}$Ge, $^{107}$Ag, $^{127}$I and $^{197}$Au from the tandem accelerator. The results are shown in table 1. The injection beam intensities were not the maximum.

In many cases, the total acceleration voltage was about 28 MV because a few resonators were not used because of problems in control circuits. The beams of I and Au in the last two lines were accelerated after the improvement of field gradients by the fast precooling mentioned above. For Si and Ge, which were the latest cases, field gradients were set at 3 MV/m for nearly all the resonator. The synchronous phases were set to the values calculated to give a good condition for debunching. The values were the same among all the resonators from no. 1 to no. 40. The final energies were in good agreement with calculated ones.

According to the beam optics[5,6], the ideal beam transmission efficiency is about 60%. A satisfying beam transmission was obtained in the cases of $^{58}$Ni and $^{74}$Ge but not in other cases. It seemed partly due to our skill of the beam transport, because we had to transport the beams through many small apertures using many quadrupole lenses and steering magnets. For example, in the adjustment of the 9 quadrupole doublets, the transmission could not be improved by adjusting one by one. We finally obtained a good feasibility in the case of $^{74}$Ge as a result of simultaneously varying the field parameters of all the doublets. There could be partly other possibilities such that some resonators were out of alignment.

As long as the rf load to the cryogenic systems was within the limit and the liquid levels in the Dewars were kept full, all the resonators were locked in phase and stable beams were obtained for a long time with a phase stability of about $\pm 0.5^\circ$.

<table>
<thead>
<tr>
<th>Ions</th>
<th>Energy(MeV)</th>
<th>Current(nA)</th>
<th>Total acceleration phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{28}$Si</td>
<td>180</td>
<td>327</td>
<td>80</td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td>164</td>
<td>351</td>
<td>130</td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td>164</td>
<td>446</td>
<td>80</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>190</td>
<td>628</td>
<td>80</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>190</td>
<td>658</td>
<td>170</td>
</tr>
<tr>
<td>$^{74}$Ge</td>
<td>180</td>
<td>326</td>
<td>110</td>
</tr>
<tr>
<td>$^{107}$Ag</td>
<td>231</td>
<td>798</td>
<td>45</td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>225</td>
<td>812</td>
<td>20</td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>225</td>
<td>880</td>
<td>100</td>
</tr>
<tr>
<td>$^{197}$Au</td>
<td>340</td>
<td>912</td>
<td>19</td>
</tr>
</tbody>
</table>

7. Conclusion

The superconducting booster for the JAERI tandem accelerator was tested with many species of heavy ion beams. A total acceleration voltage of 30 MV was obtained as expected, although a severe Q-degradation occurred with many resonators. The cryogenic systems worked well. The rf load was limited to about 4 W per resonator in stable operation. The measurement of beam bunch phases was successfully done by using beam bunch phase detecting resonators. The beam transmission was satisfactory in a few cases. It is promising to improve the transmission for others.

Various heavy ions from C to Au can be available with enough energy for nuclear reactions from the tandem booster from now on.

References
Abstract

In designing a vacuum system of a new asymmetrical collider for KEKB, the vacuum ducts deal with intense heat from synchrotron radiation because of high stored current. Due to the short bunch length, the requirement for the smoothness of the inner surface is tight. OFC is adopted for vacuum chambers. Acid etch or chemical polishing is applied to clean extruded surface. Using NEG strips as the main pump, pumping speed is designed as 100 l s⁻¹ m⁻¹. When the photo-desorption coefficient is 10⁻⁶ a pressure of 10⁻⁹ Torr will be realized. All chambers are baked before installation. By adopting "dry-hood" technique, in situ bake out will be omitted. Pumping slots are backed up by grid to prevent the penetration of beam induced field which causes heat up of pump elements. A gap between flanges are filled using Helicoflex as a vacuum seal. Contact force of an RF finger in a bellows is assured by a spring finger.

1. Introduction

KEKB is a project to study B meson physics as a second stage of TRISTAN. The accelerator consists of two rings with one intersection where electrons and positrons collide with different energies [1]. The vacuum system deal with high beam current to obtain high luminosity. Described in the following are general aspects applied for the most part of rings which includes the regular arc, the wiggler straight and the RF cavity sections. The design outline of KEKB vacuum system are summarized in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER</th>
<th>HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>3.5 GeV</td>
<td>8.0 GeV</td>
</tr>
<tr>
<td>Beam current</td>
<td>2.6 A</td>
<td>1.1 A</td>
</tr>
<tr>
<td>Circumference</td>
<td>3016 m</td>
<td>10446 m</td>
</tr>
<tr>
<td>Bunch length</td>
<td>4 mm</td>
<td>10.9 m</td>
</tr>
<tr>
<td>Bending radius</td>
<td>16.31 m</td>
<td>7.11×10²¹ photons s⁻¹ m⁻¹</td>
</tr>
<tr>
<td>Total Power of SR</td>
<td>2117 m² (arc)</td>
<td>3817 m² (bend)</td>
</tr>
<tr>
<td>Critical Energy of SR</td>
<td>5.84 keV</td>
<td>5.8 (bend)</td>
</tr>
<tr>
<td>Total photon flux of SR</td>
<td>7.35×10²¹ photons s⁻¹ m⁻¹</td>
<td></td>
</tr>
<tr>
<td>Local maximum of the linear power density</td>
<td>-13 (wiggler front)</td>
<td>7.11×10²¹ photons s⁻¹ m⁻¹</td>
</tr>
<tr>
<td>Duct material (thickness)</td>
<td>OFC (6)</td>
<td></td>
</tr>
<tr>
<td>Radiation dose on duct surface</td>
<td>&lt;10⁻⁵ rad year⁻¹</td>
<td></td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>120 (bend)</td>
<td>not estimated</td>
</tr>
<tr>
<td>Maximum strain</td>
<td>-0.15 (bend)</td>
<td>not estimated</td>
</tr>
<tr>
<td>Surface exposed to SR</td>
<td>wall of beam duct</td>
<td></td>
</tr>
<tr>
<td>Average linear photon density</td>
<td>3.3×10¹⁸ photons s⁻¹ cm⁻²</td>
<td></td>
</tr>
<tr>
<td>Average pressure with beam</td>
<td>~10⁻⁹ Torr</td>
<td></td>
</tr>
<tr>
<td>Average base pressure</td>
<td>~10⁻¹¹ Torr</td>
<td></td>
</tr>
<tr>
<td>Photo desorption coefficient</td>
<td>10⁻⁶ Torr</td>
<td></td>
</tr>
<tr>
<td>Static outgassing rate</td>
<td>~10⁻¹² Torr</td>
<td></td>
</tr>
<tr>
<td>Linear pumping speed</td>
<td>100(target)</td>
<td>1 s⁻¹ m⁻¹</td>
</tr>
<tr>
<td>Cross section of duct</td>
<td>circle racetrack</td>
<td></td>
</tr>
<tr>
<td>Conductance of beam duct (1m)</td>
<td>102 52.3</td>
<td></td>
</tr>
<tr>
<td>Arrange of pump</td>
<td>array of port integrated</td>
<td></td>
</tr>
<tr>
<td>Main pump</td>
<td>NEG cartridge NEG strip</td>
<td></td>
</tr>
</tbody>
</table>

2. Effect of Synchrotron radiation

In designing pumping system, we assume the desorption coefficient reaches $10^{-6}$ after about 1000 Ah operation for the LER. In recent high current rings this is an attainable value [2]. It is considered important to set a static base pressure to be one order lower than the operating pressure. Because of the high local linear power density, OFC is adopted as a material for vacuum chambers of the LER. It is known copper works as a good self-shield against γ-rays[3]. So it is used also for the HER.

In the LER, rather large strain of -0.15% is induced locally by synchrotron radiation from a dipole magnet. Applying a 0.15% strain over $10^8$ cycles does not cause cracks on a half or quarter tempered OFC[4]. However, localized heating will lead to annealing of the material which can reduce the local mechanical strength[5]. Annealed OFC can still withstand $10^4$ cycles of 0.5% deformation at 150°C[6]. But it is considered preferable to keep the local temperature below 140°C at KEKB.

2. Fabrication of copper chamber

The grade of OFC is ASM C10100 (oxygen-free electronic copper) for vacuum surface, and C10200 (oxygen-free copper) elsewhere. An oxide layer on the inner surface of an extruded pipe contains a large amount of carbon compositions, which are released as CO and CO$_2$ in photo-desorption. To avoid frequent conditioning of NEG during commissioning, it is necessary to remove this first oxide layer and to produce a new oxide layer with much less carbon. This treatment will be done by using a commercially available chemical polisher which contains H$_2$O$_2$ and H$_2$SO$_4$[7]or by applying standard acid etch with H$_2$SO$_4$, HNO$_3$, HCl, and water. Both treatment can reduce the total amount of the desorbed gas to a one order value compared to an untreated case.

Joining together Cu pieces is possible by TIG welding, EBW and Brazing. TIG welding in uncontrolled atmosphere will give a damage on vacuum surface. The use of TIG welding must be limited. The joint between Cu and stainless steel which is necessary to use stainless steel flanges is possible by various ways, direct welding along a lip structure[8], welding using third material, explosive bonding, HIP, and brazing.

3. Pumping elements

Since the space of dipole magnets fills only 5% and 31% of the standard cell in the LER and the HER, respectively, a build in sputter ion pump is not effective as a distributed pump. We adopt, instead, NEG[9] strip (St707) for distributed pumping. All pumps of LER are attached to pumping ports (see next section). A distributed pumping speed of 100 l s$^{-1}$ m$^{-1}$ is possible by installing a 200 l s$^{-1}$ pump to a port with a 200 l s$^{-1}$ conductance at every 1 m. A special cartridge arranged with short NEG strips is designed for the LER. At the HER, a beam duct is pumped through side slots by long NEG strips.

In addition to NEG, 200 l s$^{-1}$ ion pumps are installed at every 10 m in the arc. These ion pumps are of recently developed type which can keep their nominal pumping speed down to $10^{-10}$Torr[10]. Roughing pumps are attached at every 40 m. Roughing unit consists of a magnetic bearing turbo-molecular pump and a scroll pump. It is essentially oil free. The pressure of the ring must be monitored at intervals less than 20 m to find a vacuum leak which affect an average pressure over the ring. Cold cathode gauges will be equipped at the same pumping port as an ion pump.

All chambers are baked 24 hour at 150°C before installation fully equipped with vacuum components to check an outgassing rate. After bake out they are filled with dry N$_2$ and closed with flanges for storage. In the tunnel chambers are connected using "dryhood" technique like ALS[11] and will not be baked in situ.

4. Impedance-related structures

Pumping slots must be backed up by a grid so that penetration of wake fields which causes a heat-up of pumping elements may be reduced. Unfortunately no reliable estimation is available on the magnitude of the radiation that propagates through pumping slots. Consequently, the vacuum system design must be prepared for an unexpectedly high power penetration especially in the LER which has higher current. This is done by making it possible to add a further grid through a pumping port.

The connection with standard conflat flanges will leave a gap between the gasket and the flange where beam induced field can be trapped. There are 1500 flange connections in the LER arc. The contribution for broad band impedance is not negligible. The use of Helicoflex[12] with the same inner diameter as a beam duct can drastically reduce the loss factor to an acceptable level.

All bellows have an RF-shield inside to connect a duct aperture smoothly. In our
design, contact fingers are pressed by spring fingers to ensure a contact force between the contact finger and an inner tube. The detail of this bellows will reported by Ohshima[13].

Fig. 1 Typical vacuum chambers of the LER

5. Vacuum chambers

In the current design three types of beam ducts will be fabricated. The first is the "B chamber" which is used with dipole bend magnets and supplied with pumps. In B chamber the linear power density is highest.

The second is the "Q chamber" which is used for quadrupole magnets. It includes a beam position monitor and a mask, but no pumping port. Q chamber is fixed to a quadrupole magnet through the support of the beam position monitor. It is separated from other chambers with bellows of 16 cm long to avoid strong force from outside. It has a symmetrical cross section which is necessary to causes the eddy current with a good left-right symmetry during an active modulation of the excitation of quadrupole and sextupole magnets for the beam-based alignment.

The third is the straight "S chamber" which has a cooling channel, a mask and pumping element. It is used between Q chambers. Typical Q chamber and S chamber of LER are shown in Figure 1.

6. Schedule

LER chambers will be fabricated from 1995 to 1996. The fabrication of HER will start in 1996 and continue to 1997. Installation will start in the beginning of 1997. During 1997-1998 other special chambers used in the injection section and the interaction region will be constructed.

Acknowledgment

We would like to thank not only the companies noted in the text but also the following companies for their sincere collaborations and valuable information: Ishikawajima-Harima Heavy Industry, Mitsubishi Heavy Industry, Mitsubishi Electric Corporation, and NEOS.

We also thank KEKB stuff for their help on designing, especially Dr. Y. H. Chin for impedance calculation and Dr Y. Namito for radiation dose estimation.

Notes and References

[4] private communication from Hitachi Works
[5] heat cycle test was carried out by Hitachi Zosen using laser beam.
[7] the use of chemical polisher was proposed by Toshiba.
[10] the use of the new ion pump is suggested by ULVAC.
[12] Helicoflex delta of Le Carbone-Lorraine Ceflac will be used.
Abstract

We developed an experimental system investigating trapping of dust particles and installed it to an electron storage ring (TRISTAN AR) where one can reproduce a condition that microparticle trapping artificially occurs. Using this system called micro particle analyzing system (µPAS), trapping of microparticles was systematically observed for the first time in a manner that a well-defined microparticles are dropped into the electron beam. It was found that trapping of metallic microparticles does not occur but trapping of ceramic microparticles and diamond microparticles do for several ten minutes. This would be explainable based on heating and radiation cooling of microparticles which determines a lifetime of trapped microparticles in conjunction with an electron beam current.

1. Introduction

Phenomena that a beam lifetime drops suddenly have been seen in some electron storage rings[1-6] including the observation of it in TRISTAN AR[7]. It was recently reported by DESY group that a considerable problem of the sudden beam loss has been found in HERA ring and has limited the operation for the luminosity run[5, 6]. In HERA ring the problem is attributed to operation of the integrated ion pumps (at the dipole magnets) where dust particles which are generated and positively charged at the anode surfaces are ejected through the pumping slots to the beam duct so as to be trapped by the electron beam. But neither many experiments to reveal the mechanism were made nor the details of the trapping have been made clear. Moreover all the trappings can be explained by the same scheme while efforts to explain some observation theoretically were done.

The most difficult thing in observation of microparticle trapping in reality is that one could not reproduce the trapping at any time. One might see trapping by exploring operation conditions of a beam of a ring and the related equipments of the ring such as applied voltage of ion pumps for instance. This is again difficult since it is impossible to control generation of dust at all and dusts generate spontaneously under a complex condition.

Therefore we tried to establish an active observation system where microparticles are able to be given to an electron beam at any required time. This system would be able to ensure observation of trapping under a condition that information about both the microparticle such as its atomic composition and its size distribution and operation conditions of the ring is well known. In this report we mention the installation of µPAS and the first observation of microparticle trapping which was reproducible in TRISTAN AR under defined conditions.

2. Experimental

A schematic of µPAS is shown in Fig. 1. µPAS mainly consists of a microparticle launcher, a microparticle collector, a vacuum system and a monitoring system. In the launcher there are small eight holders where option of a species of microparticle can be made and dropping of the microparticles is carried out by remote computer control and is confirmed by a CCD camera. After a free fall of 250mm, microparticles are crossed over the electron beam probably as a cluster. The horizontally cross-sectional size of the cluster is restricted by a guide tube to be no more than 1mm in a diameter before the crossing. \( \sigma_x \) and \( \sigma_y \) are typically measured to be 2.2mm and 0.1mm, respectively. The crossing time was estimated to be 90\( \mu \)s. The crossing is finally controlled by adjusting COD.

Microparticles which are passing down through the beam are collected at the bottom of the vacuum system. The all flange ports of the beam duct at µPAS are equipped with many small holes (5 mm in a diameter) for shielding RF. The vacuum of µPAS is maintained by turbo molecular pumps (TMPs) and a sputter ion pump (SIP) giving a base pressure of \( 10^{-8} \) Pa. Total and partial pressures of residual gas in the system are measured by residual gas analyzers (RGAs).

The geometrical configuration of the...
monitoring system of μPAS and lead glass counters at a northwest arc section of TRISTAN AR is shown in Fig. 2. The electron bunches move forward clockwise. Four lead glass counters which are labeled Up-Out, Dn-Out, Up-In and Dn-In at the outside and the inside or the upstream and the downstream of μPAS were used in this experiment as shown in Fig. 2. Two counters of Up-Out, Dn-Out are for observation of γ-ray due to Bremsstrahlung and others of Up-In and Dn-In for monitoring beam loss. An ion source of one of RGA faces with the electron beam of the ring from its inside in order to monitor not only residual gas species but also possible evaporation of microparticles. Installation of a sapphire borescope with a CCD camera into μPAS was also made for visual observation.

Species of microparticle with information of their typical sizes are the followings: Al(0.1μm), Ti(45μm), Cu(0.1μm), Zr-V-Fe(unknown), C(diamond, 0.5μm), TiO₂(0.3μm), CuO(0.35μm), and SiC(1μm). The size distribution of microparticles for most of the materials are known. Less sized micropowders of Ti were not prepared due to its strong combustibility. Zr-V-Fe is a material of pumping elements of NEG. Its microparticles with a typical size of several ten μm were produced by grinding the material which had been used hard in vacuum and would have been strongly oxidized while the analysis was not done. Molar quantity of each species of microparticles which were introduced onto the beam was regulated to be 5 μmol except an amount of 10 μmol for diamond aiming an accuracy of 10% in the weighing. Purity of those materials except Zr-V-Fe were measured to be not more than 99.8 wt%.

3. Results and Discussions

Microparticles of CuO, TiO₂ and Zr-V-Fe were introduced into the electron beam in a series. Fig. 3 shows beam current, beam lifetime and signals of lead glass counters as a function of elapsed time when microparticles of CuO and TiO₂ were dropped. Note that time stamps of the current, the beam lifetime and the signals of the counters differ each other in the chart of a mechanical pen recorder and baselines of those records do each other as well. Therefore the introductions of CuO and TiO₂ are labeled by the symbols a and b in the figure, respectively.

The collision of CuO microparticles with the beam made the current reduced from 28 mA to 14 mA. Trapping, however, did not occur since the lifetime recovered in half a minute and the detector signals were observed only in a moment. In addition to this, trapping of the microparticles of Al, Ti and Cu was not observed either while they were repeatedly introduced into the electron beam for a couple of times and an interaction with the beam was confirmed by sharp signals from the detectors. Those microparticles would have been melted simply ( m.p. of Al, Ti, Cu and CuO are 930, 1940, 1360 and 1650 K, respectively ).

On the other hand, trapping of microparticles of TiO₂ (m.p.: 2100 K) and Zr-V-Fe (m.p.: 1600-3200K depending its oxidation) was clearly observed as shown for TiO₂ in Fig. 3. The beam current decreased from 14 mA to 6 mA at the moment of the collision with the microparticles. After a sudden drop of the lifetime, its slight recovery to 80 min was found with a remarkable Bremsstrahlung as seen in the signal of Dn-Out. Then the signal lasted roughly for 20 min with its monotonic decrease until the trapping ended. The lifetime that gradually got recovered was recorded to be 375 min by the end. The similar trend was found in the signal of Dn-In while the signal intensity was small, showing a beam loss for a long time.

The monotonic decrease of Bremsstrahlung for 20 min implies that mass of the trapped microparticles slowly decreases through its evaporation as a result of high temperature where beam heating and radiation cooling become equilibrium. A number of the
trapped microparticles is unknown. But the spikes and the steps which were seen in the monotonic decrease of Bremsstrahlung would suggest that some amount of the microparticles occasionally escapes from the trapped volume and microparticles or a cluster of microparticles sometimes get burst due to the heating. Trapping of TiO$_2$ was reproducible. Trapping of Zr-V-Fe microparticles was also observed while it lasted only for several minutes, showing smaller signals of the detectors. Fig. 4 shows trapping when microparticles of diamond (m.p.: 4000 K) were introduced into the beam. Different from the result of TiO$_2$, the beam current gradually decreased almost to null for a few minutes and the lifetime hardly recovered. Looking into the detail, the lifetime which slightly recovered to about one minute in half a minute after the sudden disruption resulted in a lifetime of 3 minutes during a few minutes. In the mean time, the signals of the counters smoothly decreased showing relatively stable thermal evaporation except a stepwise decrease which is coincident with the recovery of the lifetime.

According to a preliminary result of calculations on the microparticle in a condition, diamond microparticles have a lifetime of a few minutes though Cu microparticles melt away in a time of less than ms. This result does not contradict the observation and gives a qualitative explanation that microparticles of a material which has high melting point would get easily trapped.

Fig. 3 Beam current, beam lifetime and signals of lead glass counters as a function of elapsed time when microparticles of CuO and TiO$_2$ were dropped into the electron beam.

Fig. 4 Beam current, beam lifetime and signals of lead glass counters as a function of elapsed time when diamond microparticles were introduced into the beam. Note the different ordinates and the zoomed ordinate of the lower plot.

Acknowledgments

We wish to thank KEKB Vacuum Group in KEK for their technical assistance and their useful comments. We acknowledge with pleasure the calculation of the tapping behavior of Dr. Y. Suetsugu in KEKB Vacuum Group.

References

MEASUREMENT OF MAGNETIC FIELD CENTER OF THE QUADRUPOLES AND SEXTUPOLES FOR THE SPRING-8 STORAGE RING

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abstract

The quadrupole and sextupole magnets for the SPring-8 storage ring were made the measurement of the magnetic field center with a rotating coil one by one to define the position of the fiducial points above the upper part of yokes. The measurement accuracy was estimated to be about 10 μm. This paper describes the measurement system, method and error estimation.

1. Introduction

The SPring-8 storage ring has a circumference of 1436 m with a Chasman-Green lattice of 48 unit cells and contains 88 dipole, 480 quadrupole and 336 sextupole magnets. Their mechanical design and fabrication was started in 1991 and finished all in this spring by Hitachi, Sumitomo Heavy Industries and Mitsubishi Electric Corp. Field Measurements have been made in the SPring-8 site for all of about nine hundreds magnets. It took nine months from September 1994 to June 1995 for the measurement of the quadrupoles and sextupoles. The magnetic lengths and multipole field strengths were measured for all magnets and the position of the magnetic field center also measured for the quadrupoles and sextupoles. A long flip coil was used for the measurement of the dipoles and a rotating coil for the quadrupoles and sextupoles.

Main parameters of the storage ring magnets is listed in Table 1. They are normal ones with water cooled coils. Magnet yokes are made of laminated silicon steel of a thickness of 0.5 mm. Manufacturing accuracy was achieved within ±40 μm in bore diameter and minimum gap for the quadrupoles and ±50 μm for the sextupoles.

TABLE I
MAIN PARAMETERS FOR THE SR MAGNETS

<table>
<thead>
<tr>
<th></th>
<th>Dipole</th>
<th>Quadrupole</th>
<th>Sextupole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>88</td>
<td>480</td>
<td>336</td>
</tr>
<tr>
<td>Gap / Bore Diameter (mm)</td>
<td>64</td>
<td>85</td>
<td>92</td>
</tr>
<tr>
<td>Length (m)</td>
<td>2.8</td>
<td>0.35, 0.41, 0.51, 0.97</td>
<td>17.5, 420</td>
</tr>
<tr>
<td>B(T), B'(T/m), B''(T/m²)</td>
<td>0.679</td>
<td>1232</td>
<td>550, 300</td>
</tr>
</tbody>
</table>

All magnets have two machined fiducial points for alignment at the upper part of the yokes in front and rear. Fig. 1 shows the fiducial points for the quadrupoles. The fiducial points consist of a plane with a hole parallel to the median plane.

Fig. 1. A top view of the quadrupole magnet. Fiducial points are located on top of yokes, which consist of planes with a hole (Ø20) parallel to the median plane.
Fig. 2. (a) A side view of the rotating coil system. Four arrows indicate fiducial points. We place a CCD camera and basement (b) on each fiducial point and measure the position of the laser beam.

supported with bearings at the both sides and can be pulled out during the exchange of magnets or probes on left side in the figure. The coil is rotated at about 30 r.p.m. The output from the coil is integrated with a PDI 5025 (METROLAB) by a constant angle (ex. 2π/32 rad.). The main and multipole components of the magnetic fields can be calculated by the Fourier transformation. The multipole components can be separated into normal and skew components against the direction of the main field.

In case of quadrupoles, a deviation between a rotating axis of the probe and a magnetic field center induces a dipole component in the output signal. The ratio of the both components is proportional to the deviation as the follow equations.

\[ dx = \Phi_1 n / \Phi_2 n \times R / 2, \quad dy = \Phi_1 s / \Phi_2 n \times R / 2 \]

\( \Phi_1 \) and \( \Phi_2 \) indicate the maximum flux of dipole and quadrupole fields which goes through the coil. Suffix \( n \) and \( s \) denotes normal and skew components. \( R \) means a radius of the coils. In case that a quadrupole is measured with coil 1 of probe A, maximum flux is 0.24 Vs at maximum current level and output voltage is about ±0.75 V. The resolution of the integrator is \( 4 \times 10^{-6} \) Vs in five times amplification because a V-F converter of 500 kHz / 10 V is used for voltage integration. Consequently, the resolution of position measurement of the magnetic center corresponds to 0.2 μm. Actually measurement stability was about 2 μm due to coil vibration and others.

The rotating coil measures an average field along beam axis because measuring coils are longer than the magnets. In the measurement of the field center, only an average position is measured and the direction of magnet axis cannot be measured. However, the direction of magnet axis does not affect the beam if it is not very large.

The measurement procedure of the field center is following: First, a sample magnet is pre-aligned on the rotating coil system in about 0.1 mm. In the first measurement after the initialization process, the deviation of the field center from a rotating axis of the coil is measured. The stage where the magnet is located can be driven with motors with accuracy of several microns. Actually, the field center is made coincidence.

Fig. 3. Cross-sectional views of the rotating coil probes. Probe A is for the measurement of the main term and probe B for multipole fields.
Fig. 4. Histogram of the position of the magnet fiducial points measured with the rotating coil system. Dx and dy indicate horizontal and vertical deviations.

with the rotating axis of the coil by moving the magnet with the stage. After that, the main term and multipole field strengths are measured in some current levels. Finally, the position of the fiducial points on top of the magnet is measured. The method is as follows.

The rotating coil system has two fiducial points just above the bearings on the both sides. A laser beam goes through above the four fiducial points and its positions are measured by locating the target with CCD camera on each fiducial point by turns. The accuracy of these position measurements is about 5 micrometer meters in the farthest point from the laser source because of the fluctuation of the laser beam. This system is also used for the magnet alignment in the ring and being reported in another paper of this meeting.

In addition, the tilt of the magnet has to be measured at the same time because the position of the laser beam is located in a height of 500 mm from the median plane of the magnet as already mentioned. The tilt is measured with an electrical level instrument TALYVEL (RANK-TAYLOR-HOBSON). The TALYVEL had to be located in the same position on the fiducial plane every time because the roughness of the surface was not very good. This positioning of the TALYVEL could obtain the reproducibility of 10-15 μrad between the position measurements on the magnet alignment.

3. Result and Analysis

Each quadrupole and sextupole was made the measurement of position of the fiducial points. Fig. 4 shows the histogram of the measured position of the fiducial points. The fluctuation of the position deviations is within ±140 μm for horizontal direction and ±50 μm for vertical. This fluctuation indicates the fabrication one of the fiducial points though a measuring error of about 10 μm is included as mentioned later and it is found that the magnitude is agreement with the specification of the fabrication accuracy. The reason why the averages do not equal to zero is that some kinds of offset exists in fabrication and measurement such as position error of the fiducial point of the rotating coil, coil sag and so on.

Now, it is important to estimate the accuracy of the measurement because all magnets are aligned in the ring according to each measured position of the fiducial points. Table 2 lists the estimation of the measurement errors of the field center. The quantity of errors indicated in the table is about half of the maximum and may correspond to the standard deviation. The first, fourth and fifth error sources listed have been mentioned in a previous section. The second source means the reproducibility of the coil position in clamping on the bearings. This reproducibility was confirmed by measuring the field center with two probes for every magnet. The third means that a slight tilt of the bearing supports with the fiducial points is changed with time and the points are moved. Though the tilt of the supports was being monitored and the position of the fiducial points corrected, this order of error was remained. The sixth is the effect due to the temperature difference between the apparatus and the magnet generated by the change of the room temperature.

Total of these errors is estimated to be 9 μm in the standard deviation for both horizontal and vertical directions.

4. Conclusion

Strong quadrupole and sextupole magnets are used in an electron storage ring with low emittance beams and beam dynamics are very sensitive to their alignment. Accordingly, the alignment accuracy of 50 μm is required to the SPring-8 storage ring. This value is comparable to the dimensional accuracy of usually fabricated magnets and it is impossible to make fiducial points mechanically with more accuracy. Therefore, it is significant and essential to position the fiducial points by measuring the magnetic field center.
HIGH STABILITY, HIGH CURRENT DC-POWER SUPPLIES

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Abstract

Improvements of the power supplies and the control system of the AVF cyclotron which is used as an injector to the ring cyclotron and of the transport system to the ring cyclotron were done in order to get more high quality and more stable beam. The power supply of the main coil of the AVF cyclotron was exchanged to new one. The old DCCTs used for the power supplies of the trim coils of the AVF cyclotron were changed to new DCCTs to get more stability. The potentiometers used for the reference voltages in the other power supplies of the AVF cyclotron and the transport system were changed to the temperature controlled DAC method for numerical-value settings. This paper presents the results of the improvements.

1. Introduction

The K=140 AVF cyclotron is a three sector, 180° single-dee, variable energy machine. Any necessary isochronous field can be produced by a main coil and sixteen trim coils. The power supplies of these coils have been used for more than 20 years. The AVF cyclotron is now mainly used as an injector of the ring cyclotron. In order to obtain more high quality and more high stable beams in acceleration of ring cyclotron, the quality of the beam from the injector is essential. Accordingly, more high stability of current is required for these power supplies. Improvements of all power supplies of the injector have been made to achieve more high stability.

2. Power Supply for the Main Coil of the Injector

The maximum rating currents of the power supply is 1,430 A and the output voltage is 350 V. The old power supply of the main coil was pre-regulated by a motor generator and the DC current was regulated by series transistors. The stability was about $3 \times 10^{-5}$/8h. The stability was not so good to get high quality beam. So, the power supply of the main coil has been changed to a new one.

The new power supply is pre-regulated by a saturable reactor in stead of a motor generator and is current regulated by series transistors. A current sensor to achieve high stability is performed with a high precision shunt resistance made of germanium manganese copper alloy (ZERMAMIN) with a temperature coefficient less than 3 ppm/°C between 15°C and 40°C. The shunt resistance is cooled by temperature controlled water in ±0.1 °C. The feedback amplifier and the DAC for the current control are placed in the thermostatic oven.

The stability and ripple were examined. The current stability of $4 \times 10^{-6}$ for 8 hrs was achieved at the currents between 1300 A and 400 A. The stability was measured with a zero-flux current transformer (DCCT) put in the cubic for a current monitor. Figure 1 shows a result of the measured current stability. Figure 2 shows a photograph of the voltage ripple of the output. The results are very similar to the stability of the power supply for the main coil of the ring cyclotron.

![Fig. 1 A result of stability measurement of main coil power supply for the injector.](image-url)
3. Zero-flux Current Transformers

Zero-flux current transformers (DCCT) have been used as current sensors for trim coil power supplies of the injector. However, these DCCTs are old and are not satisfactory in accuracy, reliability and in thermal stability, the current stabilities of the power supplies were $1 \times 10^{-4}$. In order to exchange the old DCCTs used for the trim coil power supplies to more high precision ones, we have carried out performance tests of a few type of the DCCTs. Figure 3 shows a schematic block diagram for the measurements. Figure 4 shows the results of measurements of the temperature coefficients and Figure 5 shows the sensitivity (resolution) by a current change of 1 ppm for the two kinds of DCCTs made by A company and B company, respectively. The temperature coefficient of A is less than $0.04 \text{ppm/}^\circ \text{C}$ and that of B is about $0.25 \text{ppm/}^\circ \text{C}$. The DCCT made by A company has better quality in both temperature coefficient and sensitivity than one made by B company, but is easily affected by a small noise from the outside and stops to work. The DCCT made by B company is not so influenced by a noise. We have adopted the DCCTs made by B company as the current sensors of trim coil power supplies because we have to consider a counterplan for a noise.

4. Power Supplies of the Trim Coil for the Injector

A new DCCT has been included as a current sensor of the trim coil power supply. The maximum current of the power supply is 1500 A. The DCCT feedback signal is 10 V for the current of 1500 A. The feedback amplifier and the DAC are placed in an oven. We have measured the current stability of the power supply. Figure 6 shows a result of the measurement of the current stability. We have obtained the current stability of less than $1 \times 10^{-5}$. The current stability has been improved by about 10 times in comparison with the current stability of the power supply. We are going to change the old DCCTs used as current sensors in other many power supplies to the new ones of high precision.

5. Improvement of Power Supplies for the Injector

An improvement has been made to the water cooling system of the injector to ensure better beam stability, because the current stabilities of power supplies are severely dependent on the temperature of the cooling water. So, the temperature control devices of the system have been improved.
cooking water have added to the cooling system.

Fig. 5. Sensibility of DCCTs by a current change of 1ppm.

Fig. 6. Results of the current stabilities of trim coil power supplies.

The potentiometers used as the reference voltages in the all power supplies of the injector and the beam transport system have been changed to the temperature controlled DAC method for numerical value settings. Due to the DAC method, the old type control system for the injector and the beam transport system has been replaced to the computer control system and has been included in the control system of the ring cyclotron.

The beam stability for a long time has become better due to these improvements.

Acknowledgments

The authors are indebted to IDX Tokyo Densi Corporation and Kudo Denki Corporation for their kindness to provide some data and information.
DESIGN OF MAGNETS AND POWER SUPPLIES OF 3 GEV BOOSTER
FOR JAPAN HADRON PROJECT

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Abstract
Magnets and power supplies of 3 GeV Booster for Japan Hadron Project (JHP) have been designed. This paper describes design concepts and the parameters of the magnets and the power supplies.

1. Introduction
3 GeV Booster for Japan Hadron Project (JHP) is a rapid-cycling synchrotron with a repetition rate of 25 Hz. The repetition rate will be revised up to 50 Hz when an rf acceleration system is completely installed. The Booster supplies 3 GeV proton beams into 50 GeV Main Ring, a neutron facility and a meson facility. It comprises 48 bending magnets and 48 quadrupole magnets. The optics of this machine is described elsewhere in this proceedings. In addition, two bending magnets and two quadrupole magnets are needed to measure magnetic field, which is used by a current feedback system.

Magnets are classified into three groups in accordance with their functions such as bending, focusing and defocusing. Each group is excited using an independent resonant network:

- BM Network (for Bending Magnets),
- Qf Network (for Focusing Magnets Qf),
- Qd Network (for Defocusing Magnets Qd).

Each network contains a resonant capacitor and a choke transformer for feeding a dc current. Using the resonant network, magnetic field is obtained by a superposition of the dc current and the resonating ac current or sinusoidal current.

Two kinds of feedbacks are needed in this magnet system. One is a current feedback in order to maintain a stable magnetic field and the resonating ac current or sinusoidal current. The other is a phase feedback for 'tracking' which fixes phases of oscillating currents of four resonant networks.

A total power of 6 MW was estimated including power dissipation of resonant capacitors and choke transformers.

2. Magnet Design
The requirements of the 3 GeV Booster to magnets are summarized in Table 1. Here, we intend to use the same quadrupole magnet for focusing and defocusing magnets.

Table 1
Requirements of the 3 GeV Booster to magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Kinetic Energy (GeV)</td>
<td>0.2 ~ 3.0</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>25</td>
</tr>
<tr>
<td>Bending Magnet</td>
<td></td>
</tr>
</tbody>
</table>
Table 2
Parameters of the bending magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap Height (mm)</td>
<td>212</td>
</tr>
<tr>
<td>Number of Turn (turn/pole)</td>
<td>42</td>
</tr>
<tr>
<td>Maximum Current (A)</td>
<td>1916</td>
</tr>
<tr>
<td>Minimum Current (A)</td>
<td>323</td>
</tr>
<tr>
<td>dc Current (A)</td>
<td>1119.5</td>
</tr>
<tr>
<td>ac Current (A)</td>
<td>796.5</td>
</tr>
<tr>
<td>series resistance (mΩ)</td>
<td>25.6</td>
</tr>
<tr>
<td>series inductance (mH)</td>
<td>58.1</td>
</tr>
<tr>
<td>Power dissipations</td>
<td></td>
</tr>
<tr>
<td>dc loss (kW)</td>
<td>32.1</td>
</tr>
<tr>
<td>ac loss (kW)</td>
<td>12.3</td>
</tr>
</tbody>
</table>

2-2 Quadrupole Magnet

As mentioned above, we use the same quadrupole magnet for two kinds of quadrupole magnets which are required by the optics in this machine. The magnet parameters were optimized with respect to the specification of the Qf. Fig. 2 shows plan view of the quadrupole magnet. The shape of the pole is a hyperbola and a shim was optimized by an arc (A - B), supposing the homogeneity of the field gradient of \( \pm 5 \times 10^3 \). In Table 3, the parameters of the quadrupole magnet are listed.

Table 3
Parameters of the quadrupole magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore Radius (mm)</td>
<td>130</td>
</tr>
<tr>
<td>Number of Turn (turn/pole)</td>
<td>18</td>
</tr>
<tr>
<td>Maximum Current (A)</td>
<td>1914 (Qf)</td>
</tr>
<tr>
<td>Minimum Current (A)</td>
<td>323 (Qf)</td>
</tr>
<tr>
<td>dc Current (A)</td>
<td>1119 (Qf)</td>
</tr>
</tbody>
</table>

ac Current (A) 796 (Qf) 604 (Qd)
series resistance (mΩ) 9
series inductance (mH) 8.4
Power dissipations
dc loss (kW) 11.3 (Qf) 6.5 (Qd)
ac loss (kW) 4.5 (Qf) 3.0 (Qd)

3. Resonant Network

As mentioned above, magnets are grouped in accordance with their functions. Each group is excited using an independent resonant network:
- BM Network (for Bending Magnets),
- Qf Network (for Focussing Magnets Qf),
- Qd Network (for Defocussing Magnets Qd).

The resonant network comprises magnets, resonant capacitor and a choke transformer for feeding a dc current. Fig. 3 shows the BM Network. Here, Lch is inductance of the choke transformer, C is the resonant capacitor and Lm is inductance of the magnets. The number of magnets included in Lm is restricted by an allowable ac voltage. In our case, such a voltage is 10 kV. It is easily proved that Lch, C and Lm form a parallel resonant circuit. The number of such a circuits is called a mesh number. For example, BM Network is 25-mesh resonant network and Lm includes two bending magnets. The parameters of resonant networks are listed in Table 4. Here, repetition frequency was supposed to be 25 Hz.

Table 4
Parameters of the resonant networks

<table>
<thead>
<tr>
<th>BM Network</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Mesh</td>
<td>25</td>
</tr>
<tr>
<td>Number of Magnets (/mesh)</td>
<td>2</td>
</tr>
<tr>
<td>Lm (mH)</td>
<td>29.05</td>
</tr>
<tr>
<td>Lch (mH)</td>
<td>58.1</td>
</tr>
<tr>
<td>C (mF)</td>
<td>2.09</td>
</tr>
<tr>
<td>dc Current (A)</td>
<td>2239</td>
</tr>
<tr>
<td>ac Current (A)</td>
<td>1593(magnet)</td>
</tr>
</tbody>
</table>
In order to reduce an ac voltage, coils of the bending magnet are connected parallel so that the inductance \( L_m \) is reduced to one-fourth.

### 4. Power Supplies

#### 4-1 dc Power Supplies

<table>
<thead>
<tr>
<th>Name of Network</th>
<th>BM</th>
<th>Qf</th>
<th>Qd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>3210</td>
<td>565</td>
<td>325</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>1433</td>
<td>503</td>
<td>382</td>
</tr>
<tr>
<td>Current (A)</td>
<td>2239</td>
<td>1119</td>
<td>849</td>
</tr>
</tbody>
</table>

#### 4-2 Pulse Power Supplies

A schematic view of a pulse power supply is shown in Fig. 4. Parameters of the elements shown in the figure are listed in Table 6.

<table>
<thead>
<tr>
<th>Name of Network</th>
<th>BM</th>
<th>Qf</th>
<th>Qd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>1665</td>
<td>232</td>
<td>154</td>
</tr>
<tr>
<td>Vs (V)</td>
<td>909</td>
<td>1390</td>
<td>1060</td>
</tr>
</tbody>
</table>

---

Fig. 4 Schematic view of the pulse power supply.

Concluding Remarks

In order to realize the magnet and power supply system of the 3 GeV Booster, there are many problems to be solved. At first, magnet size is very huge, which makes accurate stacking of thin iron plates so difficult. Therefore, large-scale and accurate stacking method must be established. An aluminium stranded conductor of 30\( \times \)30 mm\(^2\) is used as a coil conductor. Since a stranded conductor requires a larger radius for bend than a radius of a hollow conductor, a free space between magnets may be shortened. This problem, however, is solved by using a stranded conductor with smaller size.

Concerning the power supplies, the most important problem is to establish a feedback method. Especially, there is no established method by which large-scale and independent resonant networks are operated synchronously. Now we are preparing an R & D in order to fix a feedback method by which phases between two resonant networks are adjusted.
DEVELOPMENT OF HIGH DUTY PULSE POWER SUPPLY FOR S-BAND KLYSTRON


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Abstract

As industrial equipments, we have developed the line-type pulse modulator for S-Band klystron with 700pps maximum repetition rate and 205kW average electric power loss. And then PFN charging period is about 500μS, charging peak current is 50A and average current is 16A. Especially, we describes an issue on the design and test results in this paper.

Introduction

This paper describes the outline and test results of Klystron Pulse Modulator which we have developed as S-Band rf power supply of the industrial equipments in order to operate steadily with high duty (see Table 1).

Table 1

<table>
<thead>
<tr>
<th>Parameter of power supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystron beam voltage [kV]</td>
</tr>
<tr>
<td>Klystron beam current [A]</td>
</tr>
<tr>
<td>Gun voltage [kV]</td>
</tr>
<tr>
<td>Gun current [A]</td>
</tr>
<tr>
<td>Pulse width [μS] flat top</td>
</tr>
<tr>
<td>-3dB</td>
</tr>
<tr>
<td>Pulse stability and flatness [%]</td>
</tr>
<tr>
<td>Pulse rise time [μS]</td>
</tr>
<tr>
<td>Pulse repetition [ppS]</td>
</tr>
</tbody>
</table>

Composition

Fig.1 shows the block diagram of klystron modulator and Fig.2 indicate the Klystron mount. And then Photo.4 shows the thyratron unit.

Fig.1 Block diagram of this klystron modulator

Fig.2 Klystron mount
**Design point**

1. Selection of switching device:

Thyratron is used in general for the switch of high voltage and high current. As to the thyratron as satisfying to Table 2, we have chose the big tube, CX-1720MN which has an effective result after discussion with EEV (Maker of thyratron).

<table>
<thead>
<tr>
<th>Parameter for operating switching device</th>
<th>Max. rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFN charging voltage [KV]</td>
<td>33 50</td>
</tr>
<tr>
<td>PFN peak current [A]</td>
<td>1080 5000</td>
</tr>
<tr>
<td>PFN average current [A]</td>
<td>14.4 25</td>
</tr>
<tr>
<td>Recovery time [uS]</td>
<td>25</td>
</tr>
</tbody>
</table>

2. Use of command charging system

One of specifications in thyratron, there is problem of recovery time. In order to recover thyratron, it should be kept over 25uS at condition of Anode voltage below 100V after stopping thyratron. Therefore, thyristor is used for the switch in order to turn on or turn off the charging voltage. Thyatron surely was recovered by trigger timing as Fig.3.

3. Selection of SCR thyristor for holding off of command charging system

The SCR thyristor is required to satisfy Table 3, and so there are two important issues. One is the research for the SCR break down voltage (3-1). The other is the SCR gate trigger system (3-2).

### Table 2

<table>
<thead>
<tr>
<th>Parameter for operating switching device</th>
<th>Max. rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFN charging voltage [KV]</td>
<td>33 50</td>
</tr>
<tr>
<td>PFN peak current [A]</td>
<td>1080 5000</td>
</tr>
<tr>
<td>PFN average current [A]</td>
<td>14.4 25</td>
</tr>
<tr>
<td>Recovery time [uS]</td>
<td>25</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Parameter of thyristor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFN charging voltage [KV]</td>
<td>33</td>
</tr>
<tr>
<td>PFN charging Peak current [A]</td>
<td>50</td>
</tr>
<tr>
<td>RMS current [A]</td>
<td>30</td>
</tr>
<tr>
<td>Average current [A]</td>
<td>16</td>
</tr>
</tbody>
</table>

3-1. Research for the SCR break down voltage

In case of high speed thyristor, the peak repetitious opposite voltage is about 2500V at the maximum, if required as Table 3, it is better to use in series /30pcs according to the device of dilating break down voltage, and then we use 6pcs per 1 stack, ie using 5 stack. And also using high speed thyristor (turn off time <40uS) was adopted in order to keep the precision of charging voltage.

3-2. SCR gate trigger system

It is required to put the reliable gate trigger in order to operate surely all of SCR/30pcs at the same time without failure, and then it is operate by the insulated pulse transformer which is able to endure 40kV. Fig.4 shows the configuration of the insulated pulse transformer for SCR gate trigger unit.

![Fig.3 Block diagram of trigger timing](image)

![Fig.4 Configuration of the insulated pulse transformer for SCR gate trigger unit](image)

4. Treatment for noise

With regard to noise treatment, we bind the sheet copper (width 365mm, thickness 0.1mm) to bottom of enclosure and between enclosure and klystron. Then we have succeeded to operate surely this equipment without any trouble.
Test results

Picture 1 through 3 shows the wave form at each position for this line-type pulse modulator, and then these wave form have indicated really steady operation without disturbance due to noise.

Photo.1
Up rf output power 5.5MWpeak
Down Klystron beam voltage 140kVpeak

Up 50mV/div 5uS/div
Down 20kV/div 5uS/div

Photo.2
Up de-Q R current 300Apeak
Middle de-Q current 800Apeak
down de-Q C current 800Apeak

Up/Middle/Down 200A/div 200uS/div

Conclusion

We have succeeded to develop the pulse power supply at the first achievement in the world which has gained pulse width 14uS and the pulse repetition 700pps.
Development of Long Pulse, High-Flatness Pulse Modulator for an S-band Klystron

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Abstract

Two infrared free electron lasers (FELs) of the FEL1 are operating using an S-band 80-MeV linac with a thermionic gun and a 165-MeV linac and UV-FEL facility are in the commissioning stage. Since an RF system for linac-based FELs is required of long pulse duration and high quality, improved pulse klystrons (Toshiba E3729) have been operated in 24-MW, 24-μs pulse mode for the FEL1 linac. Our klystron modulator developed by the FEL1 and NISSIN Electric Corp. has an inverter-converter charging system. The line switch is consisted of 30 light triggered thyristors (Toshiba SL1500GX22). A saturable reactor is used in series to protect 30 thyristors from overvoltage caused by a delay of thyristor's turn-on time. The flatness of modulator pulses is 0.08%P-P at 24-MW, 24-μs pulse operation. The 24-μs stable RF pulses can increase a conversion efficiency from electron beam power to FEL power for IR- and UV-FELs.

1. Introduction

The FEL1 is now operating two IR-FELs using an 80-MeV linac with a thermionic gun and is testing a 165-MeV linac and an UV-FEL facility. It is essentially necessary for linac-based FELs using pulsed rf sources to get a stable and long rf pulse from a klystron. A stable and long rf pulse sources enables to yield a stable and saturated FEL pulse source. The FELIX group has succeeded in keeping a pulsed rf source stable to accelerate a 22.5-MeV, 10-μs beam with an energy spread of 0.5% [1]. For this purpose, we have developed a 24-MW, 24-μs pulse modulator for an S-band klystron (Toshiba E3729) at three operation modes shown in Table 1. Mode 1 and Mode 2 are for FEL generation and Mode 3 is for injection to a storage ring.

2. Klystron Modulator

Figure 1 shows the circuit diagram of the klystron modulator. This modulator is consisted of the charging section using the converter-inverter, the pulse forming network (PFN) section, the main switch section using light triggered thyristors, and the mounting tank for the klystron to supply high voltage by a pulse transformer. The output voltage is measured at the secondary side of the pulse transformer by a capacitive divider. Details of these sections are as follows.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage (kV)</td>
<td>285</td>
<td>304</td>
<td>390</td>
</tr>
<tr>
<td>Output current (A)</td>
<td>280</td>
<td>305</td>
<td>477</td>
</tr>
<tr>
<td>Pulse width (μs)</td>
<td>24</td>
<td>12.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Flat-top (%)</td>
<td>0.08</td>
<td>0.08</td>
<td>1.5</td>
</tr>
<tr>
<td>Stability (%)</td>
<td>0.08</td>
<td>0.08</td>
<td>1.5</td>
</tr>
<tr>
<td>Repetition (pps)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Rise time (μs)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Fall time (μs)</td>
<td>3</td>
<td>3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

* Rise and fall time is measured from 10-90% of the output pulse.

(1) Charging Section

We use a converter-inverter charging circuit instead of IVR-De-Qing one, because De-Qing one has the following problems.

i) A charging voltage of the PFN involves about 0.2% fluctuation due to an input voltage.

ii) Pulse repetition rate is low (10pps). Therefore, the scale of charging section becomes bigger due to a large time of constant at resonant charging.

Therefore, our inverter is consisted of 5 cascades at 15kHz and we have achieved a high stability within $\pm 1 \times 10^{-4}$ of charging voltage.

(2) Pulse Forming Section

The output pulse width of the PFN are 24 μs, 12.5 μs and 0.5 μs at mode 1, 2 and 3, respectively. Each reactor of the PFN is adjustable by means of a remote control system using a motor driving plunger. The minimum adjustable amount of the PFN reactor is 0.005% and the maximum adjustable span is 45%.
Therefore, the adjustment of output waveform has been easily performed, and a 0.08% flat-top of output pulse waveform has been achieved. If the klystron has break down during a high voltage is applied, the PFN capacitors suffer from large reverse voltage. To reduce this damage, an EOL (End of line) clipper circuit is set and the reliability of the modulator is improved.

(3) Main Switch Section

We have used the light triggered thyristor (Toshiba SL1500GX22, 30series) stack as the main switch for keeping the output voltage stable. Generally speaking, a thyratron is suitable for switching of high voltage and large current. But in this case, the thyratron is not suitable because a change of its resistance become large during the conduction time, if the pressure in the tube changes. Therefore, we decided not to use the thyratron in order to achieve the 0.08% stability.

However, in order to use the light triggered thyristors, we had to solve the following problems.

i) The value of dI/dt is more ten times (~3000A/µs) than the thyrator's specification.

ii) It is necessary to trigger 30 thyristors simultaneously as a switch.

Before adopting the light triggered thyristor, we have tested dI/dt of the same device. The results was that the thyristor was broken down at about 1700A/µs. The damage occurred at the only part of near the center gate. The reason is that the light triggered thyristor could not have the conduction space by the high dI/dt.

Therefore, we have set a saturable reactor in series with the light triggered thyristors to secure the conduction space before large and high dI/dt main current follows and to keep a counter-measure to a delay of each thyristor's turn on. The use of the saturable reactor enables us its running under a hard condition of dI/dt ~3000A/µs. On the other hand, the use of the light triggered thyristors makes it is easy to insulate the gate drive circuit and to withstand to a high reverse voltage.

3. Performance

(1) Light Triggered Thyristors

Figure 2 shows the time response of the resistance of light triggered thyristors at the mode 1. After the main current reached the peak, the resistance is about 0.6-0.3 Ω/30devices, that is, 20mΩ–10mΩ/1 device.

The resistance at the whole conduction is about 0.5 mΩ (at 4kA). Therefore, the conduction space of this thyristor is about 1/40–1/20 of the whole conduction at the mode 1. Though we have already tried 4 x 10⁷ shots under this condition, there are no any troubles at all.
It is easily understood from Fig. 2 that the resistance of the light triggered thyristor decreases in micro-second order, so we can adjust the waveform so as to cancel this effect.

(2) Klystron Modulator and Klystron

Table 2 shows the characteristics of the output at three modes and Figs. 3 and 4 show the waveforms of the output voltage at the mode 1.

Table 2 Performance of Klystron Modulator and Klystron E3729

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage(kV)</td>
<td>285</td>
<td>304</td>
<td>390</td>
</tr>
<tr>
<td>Output current(A)</td>
<td>280</td>
<td>305</td>
<td>477</td>
</tr>
<tr>
<td>Pulse width(μs)</td>
<td>23.2</td>
<td>12.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Flat-top (R-P) (%)</td>
<td>0.08</td>
<td>0.08</td>
<td>0.3</td>
</tr>
<tr>
<td>Stability (%)</td>
<td>0.07</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Repetition(pps)</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Rise time(μs)</td>
<td>2.0</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Fall time(μs)</td>
<td>4.5</td>
<td>6.5</td>
<td>6.4</td>
</tr>
<tr>
<td>RF output(MW)</td>
<td>24</td>
<td>34</td>
<td>70</td>
</tr>
</tbody>
</table>

* Rise and fall time is measured from 10-90% of the output pulse.

The rise time of the output is about 2–3 μs. This shows that the light triggered thyristors can withstand for the rise of 2–3 μs because of the effect of saturable reactor. Fig. 4 shows the flatness of the modulator pulse is kept within 0.08%r–r at 24–μs pulse operation

(3) Modulator Pulse and 24–μ s rf Pulse

Figure 5 shows the waveforms of the modulator current pulse and 24–μ s rf pulse. Tiny ripples seen on the waveforms are due to white noise of the sampling oscilloscope (TDS460–Tecktronics).

4. Conclusions

We have succeeded in the development of the long pulse (24, μs), and high-flatness (0.08%) klystron modulator using the light triggered thyristor as a main switch and the remote control systems for variable reactors of the PFN. This modulator have contributed needless to say much to the FEI oscillations[2].

References

Manufacture of the 6-10 GHz Compact ECR Ion Source With a Variable Permanent Magnet Mirror

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Abstract

A new small size ECR ion source working in 6-10 GHz is manufactured and now under the first test. This source is made of permanent magnets only, and its total weight is about 40 kg. Its remarkable features are continuously variable axial mirror field, comparatively large inner diameter of the plasma chamber and radial multiport windows for an RF injection and a plasma viewing. The variable field is realized by a continuous replacement of the mutual position of two ring magnets on the beam axis. The design, manufacture, experimental setup and introductory beam test for this new source are reported shortly.

1. Introduction

Until quite recently, as for a very compact ECR ion source with permanent magnet only, there was "NANOGAN" alone in the world\(^1\). But now, such kind of sources are in manufacturing at several institutes\(^2\). Usually, typical measures of these sources are within tens of kg in total weight and roughly within \(0.2 \times 0.2 \times 0.2\) m in outer dimension.

However, these compact sources have commonly a few problems to be improved. First, the confining magnetic field is fixed in almost cases and hard to change continuously for the fine tuning of an extracted ion beam. Second, when the source size is reduced as possible as small, the inner size of the plasma chamber is also apt to shrink correspondingly. Third, in addition, both local heating by the microwave power which is not absorbed into the plasma and the reduced size of the plasma chamber give rise to a hardness of an effective cooling of the source. Considering these problems, we have developed a new compact ion source with a variable axial mirror field and with a large size ratio of the plasma chamber compared to the outer total size. Its outline will be described below.

2. Design Parameters and Structure of the Source

Table 1 shows main parameters of our new ion source. Especially remarkable points are as follows:

- The inner diameter of the plasma chamber is set to \(0.30\) m. This is the largest value in several same order compact sources in the world (Usually, its order is \(0.15\) m). In order to produce a multiply-charged ion beam as possible as high, it is desirable that the inner diameter of the plasma chamber is over several trees larger than the anode hole diameter.
- The confining magnetic field can be changed continuously by a replacement of two radially magnetized ring magnets on the beam axis (one is magnetized to inner direction and the other outer direction). As a result, the axial mirror ratio can be controlled continuously for an optimization of the extracted beam.
- A few quartz windows are mounted in the radial direction into the plasma chamber. These are used for the microwave port and also as a viewing port. Furthermore, it is also possible to inject the microwave power from such multiports simultaneously. It can be considered that the radial injection method of microwave power is not necessary inferior to an axial one\(^3\).
- The total volume of the permanent magnet parts are considerably decreased than the other compact sources. By this reason, our new source is made with very small expense. Its volume is a very important measure for compactness, lightness and economy of a source.
- Considering that if this source is used for the injection to an ion accelerator (such as linac or cyclotron), the beam hole diameter is set to \(0.2-0.4\) m, which is relatively smaller than many usual cases.
- The total weight of the source amount to about 40 kg and the plasma chamber is cooled with pure water. The photograph and sectional views of the new source are shown in Fig. 1 and Fig. 2 respectively. These design concept and technology are mainly based on a succeeding experience of development works for the 2.45GHz compact ECR ion sources in INS\(^4\).

3. Magnetic Field Configuration of the Source

The confining magnetic field distribution is shown in Fig. 3. The solid and broken line denote the simulated results by the POISSON code and circled points are measured results. The used magnetic material is a neodymium alloy with a maximum BH-product of 46MGOe(NRDAX-46). The simulated results agree with the measured one within accuracy of 3%.

As for the axial mirror field, if the ring-to-ring distance is selected properly to a given microwave frequency, the required ECR field is sufficiently realized within the axial region in the plasma chamber corresponding to 6-10GHz one. On the other side, the radial ECR field is formed always (that is, independent of the ring-to-ring distance, in the first order approximation) inside the wall of the plasma chamber within the range of 6-10GHz. Very roughly speaking, the maximum distance between two ring magnets \((\geq 0.15\) m) corresponds to the 6 GHz operation and minimum distance \((\leq 0.06\) m) to the 10GHz operation.

Therefore, to a certain given frequency, the extracted beam can be optimized by a fine adjustment of the initial position of these two ring magnets on the beam axis. Since these ring magnets are jointed by a cylindrical yoke with the dimension of \(0.190 \times 0.220 \times 190\) mm\(^3\) and sextapole magnets are surrounded also by this yoke, a leakage flux to the radial direction is extremely reduced. Further, as the extractor electrode is made of a mild steel, the axial mirror field is for-
more effectively than in case of a non-magnetic material. As in Fig.3, a very strong inverse magnetic field is formed in the gas-supporting side on the beam axis. Generally, if a microwave power is injected from this axial direction, this feature limits to the effective absorption to a plasma. But in our case, the microwave power is injected from the radial direction of the chamber, then the problem does not become seriously. A more detailed description on these field configuration is given in our other report.  

4. Experimental setup

The constructed ion source is set into the injection transport system of the INS-SF Cyclotron. A 45° bending magnet of the transport line is used as the ion analyzer. The distance from the ion source to the analyzer is 1827 mm, which is relatively longer compared to an usual setup. Then, in order to arrange the focusing condition and to realize the calculated beam envelope, an einzel lens, a collimator and a Q-triplet are installed between them. A typical example of the beam trace is given in Fig.4. The simulation was carried out by the GIOS code. In this choice, about 50 of the mass resolving power are realized. The ion source is exhausted by a 300 1/s turbo molecular pump through both a radial side port of the plasma chamber and the axial anode electrode hole. The no-loaded pressure and the working one is 2.1x10⁻⁶ Torr and 3-5x10⁻⁶ Torr at the beam-extractor side respectively. The microwave power is injected into this ECR ion source from the proper microwave system for the large ECR ion source of the SF-Cyclotron. This microwave source is a klystron amplifier and the operating frequency is fixed at 6.1 GHz. Therefore, a 10GHz operation and a variable frequency performance are not scheduled in the first beam-extraction test.

5. Summary

A new type of a very small size ECR ion source has been made using permanent magnets only.
(1) The inner diameter of the plasma chamber is set to φ60mm. This value is the largest size among those kind of compact sources in the world, at present.
(2) Its confining fields can be changed continuously by a replacement of the radially magnetized ring magnets.
(3) Since the volume ratio of magnets to a whole of the source is fairly reduced, the cost reduction for making the source is realized drastically, too.
(4) Based on the experience for manufacture of this new source, a further advanced version can be designed.

Now the beam extraction has started up. By a very introductory adjustment, about 800 μA of a total beam is extracted from an anode hole of φ5mm at 10 kV, when the input RF power is 80 W. But in order to produce the multiply-charged ion beam effectively, there are a few tasks to be done as follows: (1)production of electron source as a first stage,(2)optimization of the relative axial position of the anode to the peak magnetic field, etc. These problems will be handled hereafter.

Acknowledgements

This work was supported by the inner grant for scientific and engineering research in INS. Authors wish to thank members of the INS-Machine shop for their exclusive cooperation.
Fig. 2 Sectional views of the ion source

Fig. 3 Magnetic field configurations of the ion source

Fig. 4 Typical beam trace in the test stand
PRODUCTION OF POLARIZED NEGATIVE DEUTERIUM ION BEAM
WITH DUAL OPTICAL PUMPING

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Abstract
To obtain highly vector-spin polarized negative deuterium ion beam, a dual optically pumped polarized negative deuterium ion source has been developed at KEK. It is possible to select a pure nuclear-spin state with this scheme, and negative deuterium ion beam with 100% nuclear-spin vector polarization can be produced in principle. We have obtained about 70% of nuclear-spin vector polarized negative deuterium ion beam so far. This result may open up new possibilities for the optically pumped polarized ion source.

1. INTRODUCTION
An ordinary deuteron beam was successfully accelerated to an energy of 11.2 GeV (5.6 GeV/u) in the KEK 12 GeV proton synchrotron (KEK-PS), the limiting energy of the ring, in 1992.[1] The beam intensity of the accelerated deuterons reached more than 2 x 10^12 ppp which was almost the same as that for protons. Following this success, it has been strongly requested to accelerate polarized deuteron beam, and it will be started from this autumn. For this purpose, a polarized deuteron beam with high nuclear-spin vector polarization and large beam intensity is demanded. So we started development of polarized negative deuterium ion source with dual optical pumping.

As for polarized ion source, an optically pumped polarized ion source (OPPIS) has been used for generating nuclear-spin polarized negative hydrogen ion beam so far. The idea of this type of polarized ion source was proposed by Anderson[2] and the first operational ion source has been successfully developed at KEK.[3] Afterwards, various institutes have developed an optically pumped polarized ion source (OPPIS) for their accelerators.[4][5][6]

It has been believed that this type of polarized ion source is not useful to produce a highly nuclear-spin polarized (vector and tensor) deuteronium ion beam. In 1987, Schneider and Clegg[7] proposed a new nuclear-spin state selection scheme. In spite of this possibility of making a highly polarized deuteron beam by optical pumping, they concluded eventually in their paper that this dual optical pumping scheme might not be practical because efficient optical pumping of the thick target in the ionizer is difficult due to radiation trapping. However, we have re-examined the dual optically pumped scheme in detail and found that radiation trapping was not a serious problem and highly nuclear-spin polarized negative deuterium ion beam could be obtained with the dual optically pumped scheme.[8]

In this paper, we report the experimental results which showed that the highly nuclear-spin vector polarized negative deuterium ion beam could be produced by OPPIS with dual optical pumping.

2. DUAL-OPPIS FOR DEUTERON
The principle of a dual optically pumped polarized negative deuterium ion source is shown in Fig.1 schematically. The idea of this scheme is as follows: After picking up the polarized electrons from optically pumped alkali atoms, for example, deuteronium atoms are electron-spin polarized in the state of mj = +1/2 as shown in Fig.1.

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3. EXPERIMENTAL APPARATUS

Fig. 1 The principle of a dual optically pumped polarized negative deuterium ion source

Schematic of dual-OPPIS

Figure 2 shows a schematic diagram of a dual-optically pumped polarized negative deuterium ion source which has been developed at KEK. There are ECR ion source and neutralizer in the super conducting magnet which makes a high magnetic field of about 2.7 Tesla. A microwave is fed into ECR source from upstream of it. The solenoid has three independent coils which allows control of the magnetic field shape. A deuteron beam is extracted from ECR ion source by an electrode system which accelerates the beam to energy of approximately 6 keV. The deuteron beam enters a electron-spin polarized rubidium vapor cell, where a fraction of the deuterons picks up a polarized electron by charge transfer from rubidium and are thus neutralized, we call this cell neutralizer. The electron-spin polarization is induced by optical pumping with circularly polarized laser tuned to the rubidium D₁ transition at 795 nm. Rubidium is chosen because of its relatively high charge exchange cross section with fast deuterons, and the availability of high laser power at the wavelength.

Most of neutralized deuterium is created in the excited n=2 state. For that reason it is necessary that charge exchange occurs within a high magnetic field which preserves the electron-spin polarization of deuterium atom as the atom decays to the ground state. The ECR cavity extraction electrodes and neutralizer are both contained within the same high magnetic field which reduces the effective emittance increase of the deuteron beam as it enters the magnetic field region of the neutralizer. The magnetic field reverses direction in the region between neutralizer and negative ionizer cell, and as the neutral deuterium beam passes through this region, the nuclear-spin polarization is enhanced by means of a Sona transition. This deuterium atom picks up a polarized electron by charge transfer from rubidium in ionizer. The electron-spin polarization is induced by optical pumping. Nuclear-spin vector polarized negative deuterium ion beam is created with this scheme. In the downstream of the ionizer, there are einzel lens, Wien filter and Faraday cup for which D⁺ beam current is measured. In order to pump the rubidium atoms in neutralizer and ionizer, two broad band Ti-sapphire lasers are fed into neutralizer and ionizer from downstream of it respectively. The thickness and electron-spin polarization of rubidium in neutralizer and ionizer are measured by Faraday rotation with linearly polarized laser light tuned to the rubidium D₂ transition at 780 nm. This probe laser fed into neutralizer and ionizer from upstream of this ion source.

ECR Deuteron Source

Figure 3 shows a schematic diagram of ECR deuteron source and extraction electrode system. The ECR cavity is a stainless steel cylinder of 29 cm length and 6 cm inner diameter. It is mounted to an insulating Teflon holder to allow the application of the 6 kV potential for deuteron extraction. The Teflon holder also supports the extraction electrode system. The plasma chamber is made of stainless steel and the inside of it a quartz glass tube contains to evacuate the plasma. External grooves in the stainless steel cylinder hold a Sm-Co hexapole structure to make a good plasma confinement. Microwave is fed into a plasma chamber through a thin vacuum sealed microwave window. Microwave power is generated by a 18 GHz klystron which operates with a long pulse duration (up to 1 msec) and high repetition rate (20 Hz). A maximum power of microwave generated by this klystron is 1 kW.

Fig.2 Schematic diagram of a dual optically pumped polarized negative deuterium ion source at KEK

Extraction Electrode System

A three-electrode system consists of 0.5 mm thick niobium disks with an hexagonal array of 91 holes 0.9 mm in diameter. The first electrode is integral to ECR cavity. The outer two electrodes are supported by stainless steel holders which are attached to the Teflon insulator. The first electrode and second one are consisted in 1 mm apart, and the distance between second electrode and third one is 1.5 mm. The electrodes are operated in an accel-accel mode with the second electrode set about 1 kV below the cavity potential. The third electrode is kept at ground potential.

4. EXPERIMENTAL RESULTS

In a dual optical pumping scheme, the deuteron polarization can be estimated with an unique method, which is called as "intensity modulation method". One of three hyperfine sublevels is selected to be D⁺ ions by Pauli exclusion principle.
Beam intensity can be modulated by switching an optical pumping from on to off or changing a electron-spin polarization direction. Deuterium atoms in only one hyperfine sub-level can become negative deuterium ions by picking up polarized electrons from the optically pumped alkali atoms in the ionizer. Thus, the beam intensity of negative deuterium ions depends upon the population of deuterium atoms in each hyperfine sub-level after the Sona transition. This means that the deuteron vector polarization ($P_z$) and the electron-spin polarization of optically pumped alkali atoms in the ionizer ($P_e'$) affect the beam intensity of negative deuterium ions. These values are related each other as expressed in the following equation.

$$P_z = -2e / P_e' (1 - e).$$

Here, $e = (I_{off} - I_{on}) / I_{on}$, where $I_{off}$ and $I_{on}$ are the beam intensities of negative deuterium ions when the optical pumping of the alkali atoms in the ionizer is turned off and on, respectively. The result of the experiment is shown in Fig.4. The vertical axis in the figure presents the nuclear-spin vector polarization of negative deuterium ions. The horizontal axis shows the relative change of the beam intensity of the negative deuterium ions by switching the optical pumping of the alkali atoms in the ionizer on and off. The solid line in the figure presents the relation between $e$ and nuclear-spin vector polarization for $P_e' = 0.95$. In our experiment, the electron polarization of the alkali atoms in ionizer was 95 %. The electron-spin polarization of alkali atoms in the ionizer ($P_e'$) was measured by using a Faraday rotation method. The nuclear-spin vector polarization of D$^-$ ions can be estimated from that equation. The triangle plot in the figure shows the experimental result when the magnetic field strength of neutralizer is 1.2 $T$ and 2.7 $T$.

5. CONCLUSION

We have been developing a dual optically pumped polarized negative deuterium ion source for producing deuteron with high nuclear-spin vector polarization. With this source, negative deuterium ion beam with about 70 % nuclear-spin vector polarization was obtained in the present experiment. In order to obtain a large beam intensity, we are optimizing this source. We are now installing this source into the high voltage station for the KEK 12 GeV proton synchrotron (KEK-PS). We hope to get the polarized deuteron beam acceleration in the KEK-PS by the end of this year.

REFERENCES

DEVELOPMENT OF RIKEN 18GHZ ECRIS

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Abstract

We constructed a new ECRIS which has an operating frequency of 18 GHz. The intense beams of multi-charged ions are successfully produced. We observed that the beam intensities of highly charged and heavier ions are strongly enhanced using an afterglow mode. This ion source is connected to a new variable-frequency RFQ and used as a new injector of the RILAC(RIKEN heavy ion Linear Accelerator)-Ring cyclotron complex.

1. Introduction

Electron Cyclotron Resonance Ion Source (ECRIS) technology has developed rapidly since the original pioneering work of the Grenoble group. These ion sources are capable of producing intense beams of highly charged ions. They are used as an external ion source of cyclotrons and linacs, and also for atomic physics experiments. Recently, intense beams of medium mass heavy ions, mainly metallic ions, becomes one of the major requests in RIKEN Accelerator Research Facility. For satisfying such request, a new ECRIS is demanded as an external ion source of the RILAC-Ring cyclotron accelerator complex. According to the scaling law proposed by R. Geller, the beam intensity increases with increasing microwave frequency and magnetic field strength. Therefore, the microwave frequency of 18 GHz has been chosen for the RIKEN new ECRIS. It is connected to a new RFQ and used as a new injector as described in refs 3 and 4.

2. Description of RIKEN 18 GHz ECRIS

Figure 1 illustrates the design of RIKEN 18 GHz ECRIS. A single 18 GHz, 1.5 kW klystron supplies RF power to the source. The axial confinement of plasma is obtained by two solenoid coils which provide magnetic mirror. The source is completely enclosed by an iron yoke in order to reduce the current of solenoid coil. The maximum power consumption is 140 kW. The mirror ratio has a nominal value of 3.0, as shown in fig.1 (B_max ~1.4 T, B_min ~ 0.47 T). To optimize the radial confinement of the plasma, we used a hexapole magnet which consists of 36 segments made of Nd-Fe-B permanent magnets. The outer diameter (OD) and inner diameter (ID) are 180 and 80 mm, respectively. The field strength at the surface of magnets is about 1.4 T. To protect the hexapole magnet from demagnetization by high temperature, a water-cooled plasma-chamber (ID=74 mm, OD=80 mm) has been constructed. The water cooled hexapole housing also protect the permanent magnet from the high temperature caused by the solenoid coil.

The high vacuum of the plasma chamber is very important to produce the intense beam of highly charged ions. This may be due to the effect of recombination of the ions. To minimize such effect, the plasma chamber is evacuated with 500 and 150 l/s turbo-molecular pumps. The ultimate vacuum pressures of the plasma chamber and extraction stage are the middle of 10^-8 Torr.

In this paper, we present the description and the performance for producing multi-charged ions from gaseous elements in the 18GHz RIKEN ECRIS.
3. Performance of 18 GHz ECRIS

3.1. CW mode operation.

Figure 2 shows the beam intensities of highly charged ions produced from gaseous element. These results were obtained by using the gas mixing method. The typical gas pressures of plasma chamber and extraction stage were 1.0x10^{-6} and 9x10^{-7} Torrs, respectively. The extraction voltage was 15 kV. For example, beam intensities of Ar^{11+} and O^{7+} were 160 and 130 eA, respectively. Figure 3 shows the beam intensities of Ar^{11+} as a function of the extraction voltage. As shown in fig.3, the beam intensity is proportional to $V^{1.5}$ below 10kV, which follows the Child-Langmuir law, where $V$ is the extraction voltage. Above 10 kV, it deviates from it and increases linearly with increasing the extraction voltage.

The distance between the orifice ($\rho_1=10$ mm) and the extraction electrode ($\rho_2=13$ mm) is also one of the important parameters to optimize the performance of ECRIS. It strongly depends on the condition of plasma, shape of extraction electrode, and charge state of extracted ions. For RIKEN 18 GHz ECRIS, the best results of medium charge states of heavy ions (i.e., O^{5+}, Ar^{8+-11+}) could be obtained at the distance of about 30 mm.

Figure 4 shows the beam intensities of Ar^{11+} ions for 18 GHz ECRIS, CAPRICE (14.5 and 10 GHz) developed in Grenoble and ECRIS 4 (GANIL) as a function of RF power. At the same RF power, the beam intensity increases with increasing the frequency of microwave and magnetic field strength. In the figure the $B_{\text{max}}$ indicates the maximum field strength of the mirror magnetic field.

![Figure 2: Charge state distributions of O, Ar and Kr ions](image)

![Figure 3: The beam intensity of Ar^{11+} as a function of extraction voltage](image)

![Figure 4: Beam intensity of Ar^{11+} for various ion sources as a function of RF power](image)

3.2. Pulsed mode operation

It is well known that at the turnoff of the RF power of an ECRIS, the extracted current for highly charged heavy ions dramatically increases. As described in Ref. 10, if the central plasma shows a depressed negative potential $\Delta \phi$, the ratio between the beam currents of a steady state and the afterglow can be written as follows,

$$\frac{I_{\text{afterglow}}}{I_{\text{steady}}} = \exp(q\Delta \phi/kT), \quad (1)$$

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- 225 -
where \( q \), \( \Delta \Phi \) and \( T_i \) are the charge state of ions, depressed negative potential, and ion temperature, respectively. Figure 5 shows the typical result of \( \frac{l_{\text{afterglow}}}{l_{\text{steady}}} \) as a function of charge state in the case of Kr and O ions. In this figure, we observe the exponential dependence of this ratio as described in eq. (1).

![Figure 5. \( \frac{l_{\text{afterglow}}}{l_{\text{steady}}} \) for Kr and O ions](image)

The maximum current can be produced only if the duration of the RF pulse is long enough to achieve the maximum ionization of the considered ions. In our case the duration was fixed to 15 ms to produce the Kr, and Ar ions. Figure 6 shows the comparison between the best results of CW mode operation (open circles) and afterglow mode (closed circles) at the extraction voltage of 10 kV. The RF power was kept at the same value for both operations. It is clearly seen that the beam intensity of highly charged and heavier ions strongly enhanced by pulsed mode operation.

![Figure 6. Charge state distributions of Ar and Kr ions. Open and closed circles are the results of CW and pulsed mode operation, respectively](image)

4. Conclusion

The RIKEN 18 GHz ECRIS has been constructed and tested in CW and pulsed mode operation. The intense beam of multi-charged ions can be produced at the relatively lower micro wave power (for example, 160 \( \mu \)A of Ar\(^{11+}\), 130 \( \mu \)A of O\(^{7+}\) at 600 W). In the case of pulsed mode operation, we observed that the beam intensities of highly charged and heavier ions were strongly enhanced. In the next step, we will try to produce the highly charged ions from solid materials.

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THE NEW EXTERNAL ION SOURCES AND THE NEW AXIAL INJECTION SYSTEM AT RCNP

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abstract

A new polarized ion source and a new axial injection system have been constructed at RCNP in order to increase beam intensities and to get high quality beams. We get a proton current of 50 nA in the axial injection system. The polarization of the proton accelerated by a cyclotron is 70% or more. Beams from an ECR heavy ion source were successfully injected into AVF cyclotron through the new axial injection system at the end of September, 1994. We use a spiral inflector instead of the old mirror system to obtain good transmission of beams.

1. Introduction

At the Research Center for Nuclear Physics, Osaka University, a large fraction of the experimental program is devoted to studies of spin degrees of freedom. The original atomic beam type polarized ion source and the axial injection system were constructed in 1975, and since then extensive researches have been performed with polarized protons and deuterons accelerated by the K140 RCNP AVF cyclotron. In 1991, a ring cyclotron (K=400) was completed as a post accelerator which is designed to accelerate protons up to 400 MeV. Polarized proton beam current on the target in the scattering chamber was a few nA. In order to enhance the opportunities in spin physics research using intermediate energy beams from the ring cyclotron, the construction of a new High Intensity Polarized Ion Source (HIIIPS) and a new axial injection system using glaser lenses were proposed as a two years project in 1993. Its design is based on sources in operation at PSI and IUCF, and RIKEN, which employ cold (~30 K) atomic beam technology and electron cyclotron resonance ionizers. The source is coupled by a high-efficiency bunching system, a high-transmission injection system to the AVF cyclotron and a spiral inflector system. Both polarized ions from HIIIPS and unpolarized ions from an ECR source, NEOMAFIOS, are injected through the vertical injection system and the inflection system. Due to this injection system we can not only decrease the maintenance times, but also accelerate highly charged heavy ions from NEOMAFIOS up to higher energies than those from the internal source.

2. The new External Ion Sources

2.1 High Intensity Polarized Ion Source (HIIIPS)

The overall feature of the HIIIPS built at RCNP is shown in Fig. 1. The beam of H or D atoms is produced from H2 or D2 gas in a 13.6 MHz, 50~200 W discharge contained in a pyrex tube of 20 mm inner diameter. The discharge is cooled by water flowing between the dissociator tube and the second, surrounding pyrex tube of larger diameter, 30 mm. The Macor serves to isolate the nozzle thermally at ~30 K from the high temperature of the discharge. The nozzle is cooled by conduction to the cold head of a 9 W closed cycle helium refrigerator. Helium cooling of the nozzle part of the vessel is very effective to get a high intensity atomic beam. Cooled atoms emerge as a directed jet from a 3 mm diameter nozzle orifice into the first vacuum chamber which is evacuated by a 2800 C/sec turbomolecular pump with a magnetic suspension. With 25 std-cc/min of H2 flowing into the dissociator, the pressure in the first chamber is < 6.5 x 10^-3 Pa.

An atomic beam is formed at the entrance to the second vacuum chamber when the beam passes through a skimmer aperture placed 25 mm from the end of the nozzle. This skimmer separates the first and second chambers. With other two 2800 C/sec turbomolecular pumps on the second chamber, the pressure there is < 1.2 x 10^-4 Pa. A third vacuum chamber follows where another 2800 C/sec turbomolecular pump holds the pressure during operation < 3 x 10^-5 Pa.
The design of the ECR ionizer was essentially based on that at PSI. The microwave frequency is 2.45 GHz at present. If the magnetic field 87.5 mT deteriorates the proton polarization, we can increase the microwave frequency higher than 6 GHz.

The desired states of nuclear polarization for $^5$H and $^3$D beams are produced by three sextupole magnets with one weak field radio-frequency transition (RFT) unit between the second and the third magnet, and the second weak field and one (455 MHz for $^5$H) or two (455 MHz and 331 MHz for $^3$D) strong field units following the last sextupole. With this configuration, both the pure vector and the pure tensor states are produced for deuterons.

2.2 ECR Ion Source (NEOMAFIOS)

NEOMAFIOS is the ECR ion source of 10 GHz RF frequency for non-polarized light heavy ions. This ion source has a permanent magnet (Fe-Nd-B) instead of solenoidal coil and was built by R. Geller at Grenoble. Main parameters of NEOMAFIOS is shown in Table 1. Intensities and charge states of typical ions are shown in Table 2.

![Figure 2: Injection system of the RCNP AVF cyclotron](image)

NEOMAFIOS are injected through the common vertical injection system and the common inflection system. A schematic layout of the new injection system is shown in Fig. 2. At the exit of the source, protons and deuterons are longitudinally polarized. Protons are deflected by 96.7 degrees with a dipole magnet, and deuterons by 105 degrees, so that the beam remains longitudinally polarized after the 90 degrees deflection into the vertical beam line. For this purpose, small parts of pole pieces are added at the magnet entrance when deuterons are injected into the cyclotron.

An electrostatic deflector is used to compensate the beam trajectory shifts. In the system electrostatic lenses are used instead of electrostatic ones used in the previous system. They ensure an efficient focusing and a good vacuum through the line. A beam buncher is plussed 2.5 m upstream from the median plane of the cyclotron. It consists of two parallel mesh plates forming a single gap, and is excited by an RF voltage with a sawtooth-like waveform generated by combining RF sine waves with the first three higher harmonics.

A spiral inflector system was designed and fabricated. In the previous axial injection system, an electrostatic mirror system has been used to inflect polarized ions on the median plane of the cyclotron. A spiral inflector seems more suitable for high intensity beams than a mirror system, because there are no
grids intersecting beams. A spiral inflector can be treated as a component of a beam transport system either analytically or numerically. The shape of electrodes was designed based on the analytic solution of the Lorentz equation \(^7\). The electric radius was taken to be 24 mm, and the magnetic radius of the first cyclotron orbit 15.1 mm. For 65 MeV protons the injection energy is 15 keV. These parameters were determined by the simulation of a particle orbit in the central region of the cyclotron. Numerical integrations of the equation of motion were performed with an impulse approximation assuming a Dee voltage 70 kV. The electrode spacing is 6 mm and the electrode width is 16 mm. Results of initial testing of the new system are summarized in Table 1. In the table, the efficiency is the ratio of the beam intensity extracted from the AVF cyclotron to the beam current measured after the mass analysis magnet in the axial line. The accelerated beam current increases by a factor 3 \(\sim\) 6 by using the buncher.

4. Development of the Source

4.1 Reliability

During initial off-line testing of the source, it was noticed that the ECR ionizer worked stably for periods of more than two months. On the other hand, the atomic beam intensity from the dissociator dropped by a factor procedure, warming the copper nozzle to room temperature then cooling it under vacuum, could not recover the source. The accumulation of green spots was observed on the surface of the copper nozzle. The material of the nozzle was changed from copper to aluminum. In the beginning of the operation, the aluminum nozzle produced an atomic beam of similar intensity as the copper nozzle, and the source could be recovered by a heat cycle. It was found that the cold nozzle occluded with frozen ammonia. By reducing the \(N_2\) gas flow rate to the cold nozzle, the dissociator now runs stably for periods of longer than one month before nozzle cleaning is required. With nominal source operating conditions, a proton current of 50 \(\sim\) 100 \(\mu\)A was measured at 15 keV after the mass analysis magnet in the axial injection line. A maximum proton current of 8 \(\mu\)A was extracted from the AVF cyclotron at 65 MeV.

4.2 Polarization

When the source began to deliver beams for experiments last November, the proton polarization was much lower than expected. The beam line polarimeter measurements indicated an average polarization of \(p = 0.55\) or less. Extensive investigations have been performed to optimize source parameters in order to improve proton polarization. It was found there were two kinds of sources of unpolarized protons; one was residual hydrogen molecules and the other recombined molecules\(^1\). The former is now reduced by improved pumping of the plasma region. The latter was due to atoms from the dissociator which were not ionized in the ECR ionizer and recombined on the surface of quartz vessel containing the plasma or on electrodes. In the RCNP source, since we use permanent magnet sextupoles to focus the atomic beam, there are no ways to adjust the hardware of the atomic beam transport system, so it had to be optimized by simulations using a Monte-Carlo code. Diameters of the nozzle, the skimmer aperture, and the spacing between them were optimized to improve proton polarization. The optimum diameter of the nozzle orifice was 3 mm which is the same as that initially designed. The skimmer aperture diameter was reduced from the initially designed 6 mm to 4 mm. Additional orifices were installed at weak field RF transition units to reduce the undesired flow of molecules and atoms to the ionizer. Each orifice has a conductance of 6 \(\ell\)/sec for air at room temperature. One of two turbomolecular pumps initially installed at the dissociator was moved to the exit chamber of the ECR ionizer for improved pumping of the plasma region. These modifications improved the average polarization to \(p \sim 0.75\).

Conclusion

The RCNP atomic beam source was successfully constructed on schedule, and has delivered polarized proton for nuclear physics experiments at intermediate energies. It has operated stably for periods of longer than one month of continuous operation without maintenance. With normal source operating conditions, a proton current of 50 \(\sim\) 100 \(\mu\)A was obtained from the AVF cyclotron at 65 MeV and a polarization is about 0.75. Future development will be devoted to improve the degree of polarization, and to get polarized deuterons.

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RF Beam Chopping in a Surface-Plasma Type Negative Ion Source

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Abstract

A direct fast chopped beam extracted from a surface-plasma \( H^- \) ion source is proposed and a preliminary test has been examined. The converter bias voltage is modulated by rf pulses and the extracted \( H^- \) beam is observed. The direct fast chopped \( H^- \) beam extracted from the ion source has a good response to the modulation of the converter bias voltage as expected. The chopped \( H^- \) beam extracted by this method has been injected into the 500 MeV booster synchrotron at KEK-PS.

1 Introduction

Recently, the increase of the beam intensity is more desired at 12 GeV proton synchrotron in KEK (KEK-PS). One of the difficulties to increase the beam intensity is the beam loss at the beam injection from the linac to the booster synchrotron. In order to eliminate the beam loss at the beam injection, the fast chopped beam synchronized with the rf frequency of the booster synchrotron is required.

The fast beam choppers such as electrostatic deflection devices have been developed and successfully achieved. However the space charge neutralization is distracted, and then the beam loss and the emittance growth become severe in this device. Therefore, it would be ideal that the fast beam chopping can be achieved the \( H^- \) formation in the ion source. Some new methods are attempted to make the fast chopped beam in the ion source. For example, there are two methods to make the fast chopped beam by applying the pulsed high voltage at the collar electrode in the PIG type \( H^- \) ion source[1] and at the plasma electrode in the volume-production-type \( H^- \) ion source[2].

At KEK-PS, a surface-plasma type \( H^- \) ion source (BLAKE)[3][4][5] is used for the \( H^- \) beam formation. In this ion source, the negative ions are produced by the interaction between the positive ions in the plasma and the metal surface called converter that is shielded from plasma. The converter bias voltage is modulated by the synchronized pulses with the rf frequency of the booster synchrotron. The direct fast chopped \( H^- \) beam is produced by changing the \( H^- \) production efficiency.

In this paper, a new method of the fast beam chopping in the surface-plasma \( H^- \) ion source at KEK and preliminary results from the direct fast \( H^- \) beam chopping are presented.

2 Experimental setup

Schematic drawing of a surface-plasma type \( H^- \) ion source used in this experiment is shown in Fig. 1. Permanent magnets surrounding a plasma chamber are used to confine the plasma by cusp magnetic field. The hydrogen plasma is produced by the electron emission from a couple of LaB6 filaments. To enhance the \( H^- \) beam, the work function of the converter must be lowered. Cs vapor is introduced into the plasma chamber and
the thin layer of Cs atom is formed onto the converter surface. H\(^+\) ion is produced by the interaction between the plasma and the converter surface. The direct fast chopped H\(^+\) beam is produced by changing the efficiency of H\(^+\) formation following the frequently changed voltage of the converter bias. The extracted H\(^+\) beam is accelerated up to 750 keV by Cockcroft-Walton type pre-accelerator and up to 40 MeV by the linac. The frequency of the direct chopped H\(^+\) beam is synchronized with that of the rf cavity in the 500 MeV booster synchrotron. Therefore by injecting a chopped H\(^+\) beam into each rf bucket, the beam loss caused by the leak of the rf bucket is decreased in principle.

3 Result and discussion

3.1 Production of direct fast chopped H\(^+\) beam

The circuit diagram of the rf modulated power supply for the converter is shown in Fig. 2. The converter bias is modulated with the high voltage pulse triggered by the clock pulse of rf frequency of the booster synchrotron. The characteristic of the output voltage for the input voltage of the matching circuit as a function of the rf frequency is shown in Fig. 3. In the region of this experiment (about 2.2 MHz), the matching circuit is designed to make the unique ratio of input voltage to output voltage and not to cause any resonance. The converter is shielded from the plasma by the ion sheath. However the ion sheath is broken by applying the rf voltage beyond the ion-plasma frequency. The ion-plasma frequency, \(\omega_i\), is given by,

\[
\omega_i = \sqrt{\frac{Z^2 e^2 n_i}{c_0 m_i}},
\]

where \(n_i\) is the ion density in the plasma. In this ion source, the ion density seems to be about \(1 \times 10^{12}\) (cm\(^{-3}\)). The ion-plasma frequency is estimated about 200 MHz. The frequency of modulated voltage for the direct fast beam chopping is about 2.2 MHz which is a negligible value from the ion-plasma frequency. The H\(^+\) ion source is operated in pulse mode (200 \(\mu\)sec \(\times\) 20 Hz) and the fast chopped H\(^+\) beam produced from the ion source is accelerated up to 30 keV at the test stand. The H\(^+\) production efficiency was changed by the modulated voltage of converter bias with this circuit, and the direct fast chopped H\(^+\) beam was produced successfully.

3.2 Acceleration of the direct fast chopped H\(^+\) beam

The power supply for the rf modulation of converter bias is installed in the high voltage station of the Cockcroft-Walton type pre-accelerator. A direct fast chopped H\(^+\) beam extracted from the ion source is accelerated up to 750 keV, injected into the 40 MeV linac and then injected into the 500 MeV booster synchrotron of the KEK-PS. The wave form of the direct fast chopped H\(^+\) beam measured by the Faraday cup after the 40 MeV linac is shown in Fig. 4. About 94% of the maximum H\(^+\) beam current is suppressed by the modulation of converter bias voltage[6].

3.3 Longitudinal emittance of the direct fast chopped H\(^+\) beam in the booster synchrotron

The direct fast chopped H\(^+\) beam is accelerated at the linac and injected into the booster synchrotron. The wave form of each bunched H\(^+\)
beam is observed during the accelerating period in the booster synchrotron, and the bunch length including 90% of the bunch height is measured. The longitudinal emittance is derived from the bunch length of each bunch in the direct fast chopped H̄ beam injected into the booster synchrotron. From the phase equation of the longitudinal emittance, \( \sigma_l \), is given by,

\[
\sigma_l = \Delta E \cdot \frac{\tau}{2},
\]

where \( \Delta E \), \( \tau \) are the energy spread for the energy of the synchronous particle and the bunch length of 90% of the bunch height, respectively. The longitudinal emittance as a function of the time delay from the particle injection in each experiment is shown in Fig. 5. The particle number injected into the booster make to be almost equal in each experiment; about \( 4 \times 10^{11} \text{ppp} \). In non-chopped H̄ beam directly from the ion source, the beam intensity is decreased by the carbon mesh. The longitudinal emittance with the direct fast chopped H̄ beam is almost equal to that without chopped H̄ beam directly from the ion source. Using the direct chopped H̄ beam, the beam loss of the leak from the rf bucket could be suppressed by a good matching between rf bucket and linac beam. From this figure, the longitudinal emittance depends upon the amplitude of the rf voltage, nevertheless the particle number is equal in each experiment.

4 Summary

The direct fast chopped H̄ beam is produced from the ion source and injected into the 500 MeV booster synchrotron of the KEK-PS. And it is confirmed that the longitudinal emittance depends upon the amplitude of the rf bucket.

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References

R&D Status on the High Intensity Proton Accelerator in JAERI

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Abstract
The R&D for the high intensity and high duty factor proton linear accelerator has been carried out since 1991. A hydrogen ion source, an RFQ and an RF power source have been developed and 2 MeV proton beam test has been conducted to study the front end of the accelerator. To demonstrate the high duty operation of the DTL, a hot test model was fabricated and high power test has been carried out. In this report, present status of the R&D is described.

Introduction
A high intensity proton linear accelerator with an energy of 1.5 GeV and an average current of 10 mA has been proposed to perform the various engineering tests for the nuclear waste transmutation system and to apply for the basic researches[1,2]. In the R&D for the accelerator development, low energy accelerator components have been developed, since the beam current and the quality are mainly determined by the low energy portion. Heat removal problem of the accelerator structures is an important issue because of the high duty factor operation.

To study the front end of the accelerator, the ion source, the RFQ, and the RF source were fabricated and 2 MeV beam tests have been performed. In the beam test, acceleration current of 50 mA with a duty factor of 6 % was achieved. To demonstrate the high power and high duty factor operation of the DTL, a hot test model was fabricated and a high power test has been carried out by feeding an RF power.

Beam Test of the 2 MeV RFQ
The RFQ is a four-vane type and designed to accelerate 100 mA (peak) of protons to 2 MeV with a duty factor of 10 %[3]. The low power tuning, the high power conditioning and the first beam test were carried out at the test shop of Sumitomo Heavy Industries, Ltd. and the basic performance of the RFQ was obtained[4]. To study further properties, the beam test has been made at JAERI since November, 1994.

The layout of the RFQ beam test is illustrated in Fig. 1. A multicusp type ion source has been developed to obtain a high brightness proton beam. The ion source has been operated successfully at the designed current of 140 mA at 100 keV[5]. The proton beam from the ion source was focused by the two solenoids to match to the RFQ acceptance. The input and the output beam currents of the RFQ were measured by the Faraday cups of FC2 and FC3, respectively, and the RFQ transmission was deduced. The energy of the proton beam from the RFQ was measured by the compact magnetic energy analyzer (MEA) installed in the medium energy beam transport (MEBT). Figure 2 shows the beam energy spectra for five relative intervane voltages as well as the PARMTEQ simulated results. As the vane voltage is reduced, the energy spectrum shifts to the lower energy and many peaks are observed, which are in good agreement with the simulated results.

The maximum RFQ output current was 70 mA at the ion source extraction current of 155 mA. The ordinary RFQ operation current, however, was 50 - 60 mA at the ion source current of 125 - 135 mA to prevent an overheat to the ion source electrodes. The estimated transmission rate through the RFQ was around 70 %, although the precise proton fraction in the input beam was not clear due to the mass separation effects of the solenoids. There are several reasons to be considered for lower transmission than that of the designed value of 95 %. To reveal the reason for the lower transmission rate, re-alignment of the components, proton fraction and emittance measurements of the injected beam are being prepared.

Fig. 1 Layout of the RFQ beam test
FC: Faraday cup
PM: Beam profile monitor
MEA: Magnetic energy analyzer
At the beginning of the beam test in JAERI, the maximum duty factor was limited less than 2% due to the partial burn out of the RF contact at the RFQ. The silver plated spiral type RF contact, which is made of beryllium copper alloy, was used between the tank and the vane. To improve the heat transfer properties, it was replaced by a thicker silver plated type. In addition to the contact replacement, a copper block was installed to cover the open space between the vane and the tank to reduce the heat dissipation at the vane end region. As a result of these modifications, a duty factor of 6% at the beam current of 50 mA was achieved. The further study is in progress to achieve the designed duty factor of 10%.

**Development of the 1 MW RF Source**

The RF source was designed and manufactured for the RFQ beam test and the DTL high power test. The tetrode tube, 4CM2500KG (E1MAC), is used with three-stage amplifier configuration[6].

The dummy load tests have been made successfully. The RF power output of 1 MW was achieved at the duty factor of 0.6%, whereas the measured gain of the final stage amplifier is lower than the designed value. The power efficiency was 60% which is in good agreement with the designed value of 62%. At the high duty operation of 12%, RF power of 830 kW was generated, which satisfied the requirement for the tests in the R&D.

The low level controller of the RF system includes feedback circuits to compensate power loss and phase shift due to the beam loading. The performance of the feedback system was examined in the RFQ beam test. Waveforms of the forward and reflected power from the RF source to the RFQ, RF pickup level in the tank and accelerated beam are shown in Fig. 3. The amplitude change was remarkably small to be within 0.5% when the beam loading was 110 kW. On the other hand, the phase error was relatively large to be > 5 deg. The feedforward control system will be examined to improve the phase error.

**High Power Test of the DTL Model**

A DTL hot test model with 9 cells, which is a mockup of the low energy portion of the DTL, has been fabricated to study the RF characteristics and the cooling capabilities[7]. An electromagnetic quadrupole using a hollow conductor (5mmx5mm) was chosen for the focusing magnet, of which field is 80 T/m with 5.5 turns of 780 amperes. Two quadrupole magnets have been fabricated and installed in the test model.

The high power test was carried out with the RF power source. Figure 4 shows the schematic layout of the test. Prior to the cooling capability test, high power conditioning was made with monitoring the vacuum pressure and the RF signals from the pickup loop and the directional coupler. In the conditioning, the input RF power of 128 kW with a duty factor of 20% was fed to the model. Bremsstrahlung X-ray spectra from the gap were measured to estimate the gap voltage. The measured gap voltage was 195 kV at the RF power of 128 kW, which was in good agreement with the calculated value of 197 kV by the SUPERFISH code.

The measured RF heat dissipation power in the each drift tube and end plate was in good agreement with the SUPERFISH results. The frequency shift as a function of the
#S drift tube temperature also agrees well with the calculated values as shown in Fig. 5. These high power test results confirm the heat dissipation calculation and the cooling design of the DTL.

Fig. 4 Schematic layout of the DTL high power test

Fig. 5 Frequency shift of the DTL model tank as a function of the #8 drift tube temperature

Summary and Plan

The R&D with the design and the fabrication of the prototype accelerator structures (ion source, RFQ, DTL and RF source) have been carried out. The good performance of the components has been confirmed, while some problems are remaining. For the RFQ, it is necessary to increase the duty factor and the transmission. For the DTL, erosion and corrosion in the hollow conductor will be examined to establish a reliable operation. These further R&D will be performed in FY-1995.

To inject the beam into the storage ring for the application of the basic researches, negative ion beam is required. The development of the negative ion source has been started and the R&D is continued[8].

For construction of the high intensity accelerator facilities, beam dump is one of the important issues to stop the accelerated beam effectively and safely. To investigate a beam stopper fabrication method and its thermal performance, preliminary mock-up experiment using 2 MeV proton beam has been started[9].

The superconducting (SC) cavity is one of the feasible candidates for the high-p structures and its design work is about to be started. For the injector of the SC cavities, continuous-beam or much longer duty operation will be required. Design work on the RFQ and DTL as well as SC cavities for the CW operation are being performed.

References


DEVELOPMENT OF A VARIABLE-FREQUENCY RFQ LINAC FOR THE RILAC

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Abstract

Development of a variable-frequency RFQ linac which will be used for a new injector for the RIKEN heavy-ion linac (RILAC) is under progress. The RFQ will accelerate ions with mass-to-charge ratios of 6 to 27 at up to 450 keV per charge by varying its operational frequency from 17.7 to 39.2 MHz. The RFQ resonator has a folded-coaxial structure and the resonant frequency is changed by a movable shorting plate. After low- and high power tests of the real RFQ structure, the acceleration tests have been performed using Argon and Oxygen beams at the frequencies of 17.7, 26.1, 34.4, and 39.2 MHz. The maximum transmission efficiency obtained from the first tests was 85%.

1. Introduction

A new injector for the RIKEN heavy ion linac (RILAC)1) has been developed, which consists of an 18GHz-ECRIS and a variable-frequency RFQ linac, in order to meet the growing demand for more intensity of heavy ion beams. As for the RFQ linac, a real structure has recently been constructed based on the study of the rf characteristics using a half-scale model. In this paper we describe recent results obtained from various tests as well as the outline of the RFQ resonator.

2. RFQ resonator

The RFQ resonator is based on a folded-coaxial structure. The distinct features of this RFQ are that it can be operated in a low frequency region and the frequency range is quite large.2) Figure 1 shows a schematic layout of the RFQ resonator. Horizontal vanes are held by front and rear supports fixed on the base plate. Vertical vanes are fixed on the inner surfaces of a rectangular tube which surrounds the horizontal vanes. This tube is supported by four ceramic pillars placed on the base plate. A stem suspended from the ceiling plate is in electric contact with the rectangular tube. A shorting plate placed around the stem can be moved vertically, which varies the resonant frequency. Radio-frequency power is capacitively fed through the side wall. A capacitive tuner is set on the other side and two capacitive pick-up monitors are on the base plate.

In addition to the equipment described above, a detachable stem is installed underneath the conductor tube. This stem is, however, pulled in only when high-frequency operation is required, and is in electric contact with both the conductor tube and the base plate while it is detached below the base plate in low-frequency operations. Because at installation, the rf electric current is shared by the detachable stem and the upper stem, the power consumption is expected to be less than that when only the upper stem is used.3) The inner volume of the resonator is about 1700 mm (length) x 700 mm (width) x 1000 mm (height). The resonator is separable into upper and lower parts, as shown in Fig. 1. The horizontal vanes and the rectangular tube with the vertical vanes are rigidly fixed inside the lower part. The upper part containing the stem and the movable shorting plate can be removed as a unit. This separable structure permits accurate alignment of the vanes and easy maintenance.

The cooling pipes are placed by taking the result of the heat analysis into account. Cooling water for the horizontal vanes is supplied through the front and rear supports of the vanes. That for the vertical vanes and the rectangular tube is supplied through the inside of the upper stem. The total water flow is 155 l/min of 7 atm.
Two turbo-molecular pumps (1500 l/s) are fixed on both sides of the resonator.

The vanes have been three-dimensionally machined within the accuracy of ±50 μm. The vane parameters have been modified from the output values of the PARMTEQ program because decrease of the transmission efficiency has been observed by a numerical simulation.4)

### 3. Recent results

#### 3.1 Low power tests

The resonant frequencies, the Q-values and the shunt impedances were measured in the same manner as in our previous paper.2) Figure 2 shows the measured resonant frequency along with the values calculated by the MAFIA program. The horizontal axis represents the gap distance between the top surface of the conductor tube and the bottom surface of the shorting plate. The resonant frequency varies from 17.7 to 39.2 MHz by changing the position of the shorting plate by a stroke of 790 mm.

![Graph showing measured and calculated resonant frequencies](image)

**Figure 2.** Measured resonant frequency along with the MAFIA calculations. The closed circles and the solid curve represent the measured and the calculated values, respectively, when the detachable stem is out of the resonator. The open circles and the dashed curve represent the measured and the calculated values, respectively, when the stem is in the resonator.

Figure 3 shows the measured Q-values and shunt impedances. The corresponding MAFIA-calculation curves are shown in the figures as well. The shunt impedance $R_S$ is defined by $V^2/(2P)$, where $P$ is the rf power consumption and $V$ is the intervane voltage. As expected, above 30 MHz the measured Q-values and shunt impedances with the detachable stem installed are larger than those without the detachable stem. The MAFIA calculations overestimate the measured values by about 50%. This is considered to result from the fact that the calculation does not realistically treat the roughness of the wall surface and the imperfection of the electric contact. The power losses estimated from the shunt impedances are 6 kW at 17.7 MHz and 26 kW at 39.2 MHz for the designed intervane voltage of 33.6 kV in the cw operation.

![Graph showing measured Q-values and shunt impedances](image)

**Figure 3.** Measured Q-values and the shunt impedances along with the MAFIA calculations. The data of symbols and curves are obtained under the same conditions as in Fig. 2.

#### 3.2 High power tests

The rf power source with an Eimac 4CW5000E has a cw power of 40 kW at maximum between 16.9 MHz and 40 MHz.

As a result of the high power tests, the following results have been obtained: [1] The RFQ can be stably operated when the intervane voltage is between 20 kV and 30 kV. The vacuum stays in a range of 1 - 3 x 10^-7 Torr at a pump head. No temperature rise has been detected during the operation. [2] Emissions of blue-white glow are observed on the ceramic pillars below the intervane voltage of 15 kV. [3] Emissions of red-white light are observed above the intervane voltage of 35 kV.

The reasons of [2] and [3] described above are considered to be the multipactoring on the ceramics pillars and the heating due to the dielectric losses around the metal screws fixing the pillars to the conductor tube, respectively. Alternative structure of the pillars are under fabrication so as to avoid these drawbacks.

### 3.3 Acceleration tests

Acceleration tests have been performed using beams from an 18GHz-ECRIS. Figure 4 shows the schematic drawing of the beam line. The extracted beam
from the ion source is focused by Einzel lenses and are bent by a bending magnet. The bending magnet also has a focusing function by the slant pole edges. The beam is focused again by a solenoid lens before entering the RFQ. The diagnostic boxes contain Faraday cups, profile monitors, and slits. Three capacitive pick-up probes are used for the TOF measurement of the beam velocity.

The accelerated ions so far are Ar$^{3+}$, Ar$^{6+}$, Ar$^{11+}$, and O$^{5+}$ at the frequencies of 17.7, 26.1, 34.4, and 39.2 MHz, respectively, at the intervane voltage of about 20 kV. The maximum transmission efficiency was 85% with the beam intensity of 10 - 50 e$^{-}$A. The velocity of the output beam is in agreement with the designed value within 1%.

In these tests the emittance of the input beam was not measured. The measurement is in preparation. Acceleration tests with full-intensity beams from the ECRIS are also to be performed.

4. Summary

A variable-frequency RFQ which will be used for a new injector of the RIKEN heavy ion linac (RILAC) has been constructed. Acceleration tests have been performed using beams from the 18GHz-ECRIS after low- and high power tests of the resonator. The maximum transmission efficiency obtained from the first tests was 85%.

Alternative shapes of the ceramic pillars are under fabrication so as to avoid the drawbacks observed in the high power tests. Measurements of the beam emittance and the acceleration tests with full-intensity beams from the ECRIS are in preparation.

5. Acknowledgment

The authors are grateful to Dr. N. Tokuda and Dr. S. Arai at INS for the usage of vane-cutting program as well as for the fruitful information about the vane design. The resonator was fabricated by Sumitomo Heavy Industries, Nihama Work, and the rf power source by Denki Kogyo.

6. References

High Power Test of a Damped Cavity for High-Brilliant Synchrotron Radiation Source


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Abstract

The high power model of the damped-cavity which is being developed at ISSP and Photon Factory (PF) was fabricated. The high power conditioning of the cavity was carried out. The input power of 150 kW was obtained without any severe problems.

I. INTRODUCTION

We have developed the damped-structure RF cavity for two low emittance electron/position storage rings. One is a third-generation VUV and SX synchrotron radiation source which is a future project of the University of Tokyo. The storage ring has a beam energy of 2.0 GeV, a circumference of about 400 m, an emittance of less than 5 nm-rad [1,2]. The other is a high brilliance configuration of the PF storage ring [3]. In these storage rings, coupled-bunch instability due to higher-order modes (HOM's) in RF cavity is a serious problem when stable and high beam current is required. The damped cavity, we have studied, has large beam duct, a part of which is made of a SiC microwave absorber. The HOM's propagating out from the cavity through the beam duct are expected to be damped by the SiC part.

We fabricated two cold models of the cavity and measured their RF characteristics in low power level. As the SiC absorber, we chose CERASIC-B (made by Toshiba Ceramics Co. Ltd.) which was fabricated by sintering in an argon atmosphere under normal pressure. The low power measurement showed the SiC beam ducts strongly reduce the Q-values of HOM's in the cavity [4, 5, 6]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency</td>
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</tr>
<tr>
<td>Shunt impedance</td>
<td>7.68 MΩ</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td>44000</td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>Maximum wall loss</td>
<td>140 kW</td>
</tr>
</tbody>
</table>

Table 1: Parameters of the cavity.

The design parameters of the damped-cavity are summarized in Table 1. The nominal operating voltage of the cavity system is 1.5 MV for both the PF ring and the VUV-SX ring. The number of the cavity to be installed in the storage rings is four for the PF ring and three for the VUV-SX ring. For the VUV-SX ring, the nominal gap voltage per cavity is 0.5 MV, requiring the power of about 33 kW to be dissipated in the cavity. The design of 140 kW wall loss has large safety margin and operational flexibility.

The R&D of the damped-cavity is now focusing on a high power test of the cavity. The specification of the high power model and recent status of its high power conditioning are presented here.

II. HIGH POWER MODEL

The high power model cavity was manufactured at Keihin Product Operations of Toshiba Corporation [7]. Figure 1 shows the cross sectional view of the high power model.
The main part of the cavity is made of class I-OFHC copper which was treated with Hot Isostatic Press (HIP). The layout of water cooling channel is also shown in Fig. 1. The water flow of 200 l/min is available with a pressure drop of 4 kgf/cm².

The cavity has two beam ports and four side ports for an input coupler, a tuning plunger and two blank-flanges. U-tight seal gaskets are adopted as RF contacts between the port flanges and the attached equipments.

A thermal structure calculation with two dimensional mesh was carried out [7]. The analysis assumed a water flow of 140 l/min and inlet water temperature of 20 °C. The edge of nose cone gave the highest power density in the cavity. For 160kW total power dissipation, peak power density around the nose cone was calculated to be 30 W/cm². Then, the temperature of the inner wall of the cavity was 50 - 60 °C and the edge of the nose cone was about 70 °C. The frequency shift caused by the thermal deformation was expected to be -250 kHz for the fundamental mode.

Figure 2 shows the input coupler of the cavity. The coupler was newly designed basing on the coupler which is used for the 508 MHz APS cavity of the TRISTAN ring. We changed the shape of the end of coaxial line and optimized the positions of the short plates of rectangular waveguide and coaxial line in order to obtain low-loss of 500 MHz microwave [8].

Figure 3: The newly designed input coupler.

Figure 3: The fixed tuner block.

The tuning plunger of the cavity is the same type as used in the PF cavity. The blank-flange, also called fixed tuner, is a flange with cylindrical block to pad the port of the cavity. Figure 3 shows the fixed tuner block. The center of the block was hollowed out and a viewing port was attached there. The cavity has two blank-flanges (horizontal and vertical). The blocks of the blank-flanges are projecting 10 mm from inner surface of the cavity.

III. HIGH POWER CONDITIONING

The high power test of the cavity has been carried out at the high power test bench of the Photon Factory. SiC
beam-duct was not attached to the cavity in this test. Before the high power test, the cavity was prebaked at 150 °C for 24 hours at Keihin Product Operations of Toshiba Corporation.

In the high power test, a 300 l/sec turbo molecular pump was attached to the cavity and an ionization gauge was placed between the beam port and the turbo pump. The vacuum pressure before input RF power was 5x10⁻⁴ Torr.

The high power conditioning started with an input power of a few hundreds watt and the power level was slowly increased by keeping the vacuum pressure below 5x10⁻⁴ Torr. The reflected RF power signal was used as an interlock trigger. The tuning plunger was controlled for compensating a thermal detuning of the cavity.

After 20 hours conditioning, the input power was reached to 60 kW. The vacuum pressure was 5x10⁻⁴ Torr without RF power. In order to try higher power conditioning under the lower vacuum pressure, the cavity was baked at 150 °C for 24 hours. After the baking, the pressure was dropped to 3x10⁻⁶ Torr, and then pulse conditioning at 100 kW with 10% duty was carried out for 12 hours. After that, cw conditioning was restarted.

The cavity has three viewing ports to observe discharge phenomena around input coupler, tuning plunger and nose cone. Small glowing points and occasional arcing grew with increasing input power. However, as the high power conditioning progressed, the number of these glowing points decreased at the same level of input power.

IV. ACKNOWLEDGMENTS

We would like to thank to all staff members of SRL accelerator group and of Light Source Division of the Photon Factory for their support and useful discussions.

V. REFERENCES

Study on Tuning-Free Network for RF Accelerating Cavity

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abstract

Applying a bridged-T type all-pass network to a resonator described as a parallel circuit, the output voltage of the resonator shows a band-pass feature over a certain frequency range, while the input impedance is always constant against frequency. This feature is considered to realize the ferrite-loaded tuning-free RF accelerating cavity. It has several merits such as a simple cavity structure without bias windings, an easy operation without feedback control of the bias current, applying new ferrite with favorable RF characteristics and so on.

1. Introduction

A ferrite-loaded RF cavity for an RF system of a synchrotron produces, in general, the accelerating voltage at its resonance frequency, which is synchronized with the revolution frequency by bias field. On the other hand, applying a bridged-T type all-pass network to a cavity regarded as a parallel resonance circuit, accelerating voltage shows a band-pass feature without bias field.

The accelerating cavity as above can be energized by a commercial transistor RF power amplifier because the input impedance of the network with a terminating resistor is always equal to one of the resistor, i.e. always constant against frequency.

A rough estimation of behaviors of the all-pass cavity circuit has performed, based on RF characteristics of new ferrite material under development. It shows that an RF accelerating voltage of 630 V over the frequency range from 1 MHz to 8 MHz can be achieved in a 60 cm long cavity by a 1 kW RF power amplifier. This type of accelerating cavity is applicable to a proton-synchrotron for radio therapy and a cooler-synchrotron in multi-GeV region.

2. A bridged-T type all-pass network

As shown in fig.1, a bridged-T type circuit consists of three impedances, \( Z_1, Z_2 \) and \( Z_3 \), and is terminated in a resistor \( R \). In this circuit, the all-pass conditions that the input impedance is always constant value \( R \) are,

\[
Z_2 = \frac{R^2}{2Z_1}, \quad Z_3 = 4Z_1 \quad (1)
\]

In general, a lumped constant circuit of an accelerating cavity is shown as a parallel resonance circuit with a self-inductance, a capacitance and a resistance caused by RF power loss of ferrite. However, an equivalent circuit of a cavity is approximately equal to a parallel circuit that \( Z_1 \) consists of \( L_1 \) and \( C_1 \) as shown in fig.2, because the RF power loss of new ferrite is far less than the former one, as discussed in the next section, and also because the terminating resistor exists.

From the all-pass conditions of eq.(1), \( Z_2 \) should be a series circuit of \( L_2 \) and \( C_2 \), \( Z_3 \) should be a parallel circuit of \( L_3 \) and \( C_3 \). They should satisfy the following conditions respectively in any resonance frequency;

\[
C_2 = \frac{2L_1}{R^2}, \quad L_2 = \frac{C_1R^2}{2}, \quad C_3 = \frac{C_1}{4}, \quad L_3 = 4L_1 \quad (2)
\]

When these conditions are satisfied, the ratio of the input voltage \( V \) to the input current \( I \) is constant as \( R \) against frequency, that is, an all-pass feature appears. As for the voltage \( V_R \) between both ends of the terminating resistor, \( \left| \frac{V_R}{V} \right| = 1 \) is satisfied.
at all frequencies. Then the voltage $V_1$ that appears between ends of the parallel resonant circuit of $L_1$ and $C_1$ has band-pass characteristics, as shown in fig. 3. 

$|V_1/V_0| = 1$ is satisfied at frequencies $\omega_1$ and $\omega_2$, and $V_1$ exceeds the input voltage between them, which satisfy

$$\omega_2 > \omega_1$$

where $\omega_0$ is a resonance frequency. The purpose of this study is to apply the band-pass characteristics like fig. 3 to an accelerating cavity.

Let $N$ be the ratio $\omega_2/\omega_1$, then $N$ is given as the expression with the terminating resistor $R$ and the characteristic impedance of the resonant circuit.

$$N = \frac{\omega_2}{\omega_1} = \left(1 + \frac{1}{R^2 C_1} + \frac{1}{R} \sqrt{\frac{L_1}{C_1}} \right)^2$$

From eq.(4), a wider frequency range can be realized by increasing a characteristic impedance or decreasing a terminating resistor $R$.

3. Development of new ferrite

Since there is no bias field on ferrite of a cavity in this circuit, new type ferrite material can be applied. NiZn has been used for the cavity because of quick response to the bias field. However, it is not necessary in this circuit and the ferrite containing Co can be used. Accordingly RF power loss can be reduced.

Now, such material of the ferrite, which RF power loss has minimum value around 1 MHz, has been developed, supposed that this cavity is used over the frequency range 1-8 MHz. From the preliminary data until now, the frequency dependence for $\mu Q_f$ product of the ferrite recently developed is shown in fig. 4. From this data, it is shown that $\mu Q_f$ product of developing ferrite is up to several decade times as large as conventional ones, and finally, RF power loss is strongly reduced. In fig. 4, $\mu Q_f$ product is largest around 8 MHz, but the ferrite material for a lower frequency is being developed.

An equivalent lumped circuit of an accelerating cavity is approximately equal to a parallel circuit of a self inductance and a capacitance because the RF power loss of the new ferrite is much smaller and terminating resistor exists in this circuit. It is also a merit that the accelerating cavity can be used for large amplitude. Thus Q-loss effect caused by the excitation of the exchange spin wave associated with the bias field is much less, because the ferrite without bias field is always used in the initial state.

An inner diameter of a ferrite ring cannot be very small because of the bias windings in a conventional cavity[1]. However the inner diameter of the ferrite is a little larger than the outer diameter of the flange of the vacuum duct in a new cavity, because the bias windings are not necessary. Thus the occupation of the ferrite is higher, and the self-inductance turns to be larger. From this point, a length of an accelerating cavity can be shortened. And a high characteristic impedance cavity is realized, if a capacitance of an accelerating gap can be made small.

4. Design and estimation of performance for accelerating cavity

Assuming a diameter of a beam duct is 200mm, its conflat flange cannot be smaller than ICF253. Thus ferrite toroidal core with inner diameter 255 mm is used, and the space between the vacuum duct and the flange is used for the installation space of the baking heater and for insulation. The outer diameter of the commercially available ferrite is 500 mm and its thickness is 25 mm. Since RF power loss of the new ferrite is small, a cooling system for the ferrite RF power loss becomes simpler. The structure of the system is that 1 mm thickness copper plates, whose edges are silver brazed with the copper cooling pipes, are inserted between the 25 mm thickness ferrite alternately.

The relative permeability of the ferrite is determined to be 200 because it is necessary for the ferrite that its permeability is not much changed in an available frequency range below Snoon's limit. Using 20 ferrite cores, the self-inductance is 13.5 $\mu$H, and the resonance frequency is 3 MHz, if a capacitance of an
accelerating gap is 200 pF. And the terminating resistor is 200 Ω, because a characteristic impedance is 250 Ω. From the rough estimation as above, 630 V of an accelerating voltage is achieved, in case a 60 cm accelerating cavity is energized by a 1 kW RF power amplifier.

Figure 5: Frequency dependence of |V1/V| including RF power loss of ferrite.

Fig.5. shows an analysis result for the output voltage of the cavity including the ferrite RF power loss and the frequency dependence of the ferrite complex permeability. From fig.5, the available frequency range, where V1 exceeds V, does not change so much.

5. Measurement of the performance in an equivalent lumped circuit

Figure 6: An equivalent lumped circuit model.

Figure 7: The equivalent lumped circuit model.

The authors fabricated a simple model of an equivalent lumped circuit, regarding an accelerating cavity as a parallel resonant circuit, and measured the performance. The model is shown in fig.6, and the figure of its equivalent lumped circuit is shown in fig.7. The size of the model is 25 cm x 20 cm x 25 cm. The main body is made of a copper plate, capacitances are ceramic condensers, the inductor of 56.8 μH in fig.7 is ferrite loaded coil, and other inductors are plastic loaded coil. The voltage V1 in fig.7 is shown in fig.8. It is obvious that the same characteristics as fig.3 and fig.5 appears in fig.8.

Figure 8: Frequency dependence of the output voltage |V1/V| of the model.

6. Discussion

In the next stage, the authors will construct a real cavity with a bridged-T type circuit, and will investigate whether the all-pass characteristics are achieved. With developing the ferrite, design of a real cavity is proceeding.

Since the frequency range can be tuned arbitrarily from eq.(4), this cavity can be applied in various synchrotrons. Furthermore, this cavity is also applicable to a rapid cycle synchrotron due to no bias windings.

For a high energy synchrotron, a larger amplitude circuit must be developed.

If an accelerating frequency range is higher than a resonance frequency of a cavity, the influence of the beam loading is avoided. However the case that an accelerating frequency range includes a resonance frequency is under investigation now. And in the bridged-T type circuit, when the cavity is excited by the beam energy, the current taken by the beam is considered to have a band-pass characteristic as the input current. It also must be investigated in the next step.

Acknowledgements

The authors wish to thank Mr. S.Watabe and K.Takamura of TDK for their developing new ferrite.

Reference

Conceptual Design of Compact HIF Driver by RF Linac with High Acceleration Rate


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Abstract

The Interdigital-H (IH) type linac is well known for its high shunt impedance at low and medium particle velocity. Therefore the IH type structure is possible high acceleration rate by same power. The IH linac cavity is able to generate 10 MV/m (effective acceleration voltage) with focusing particle by super conducting solenoid. We designed the compact HIF driver by the IH linac with high acceleration rate. The IH linacs can accelerate particles with a charge to mass ratio (q/A) greater than 1/250 from 0.3 MeV/amu up to 50 MeV/amu. The total effective length of the IH linac cavities is about 1250 m.

1. Introduction

Until now for the electric power plant of 1 GW, Heavy Ion Inertial Fusion (HIF) driver system was needed to the length of several km, even if it were RF linacs[1-3] or Induction linacs. In the case of Induction linac, we could not make the acceleration rate up because of the voltage limit of ferrite. And in the case of RF linac because of beam focus and wall loss of Alvarez type cavity, we could not make acceleration rate over about 2 MV/m. So that driver system of HIF is necessary the length of several km.

The LBL and LLNL group[4] in USA presented the plan of compact HIF driver in 1991. It was the type of Induction linac, the aim was to be compact of driver by combination of Induction linac and circular ring.

On the other hand, the progress of RF linac was shown in 1980's and 1990's. Especially the study of the IH linac was remarkable. In the IH type structure, it was proved that the shunt impedance was high in low and medium energy region, comparing to other linac structure. So it was possible to keep the acceleration rate to 10 MV/m in energy region of about 50 MeV/amu by using high shunt impedance. From consequence of it we chose the IH type to main linac of HIF driver. We found that the length would be 1-2 km. As we designed the conceptual design of compact driver for HIF, the following is the report.

2. High Shunt Impedance of IH Linac

2.1 IH type Linear Accelerator

In 1956, an interdigital H (IH) type linear accelerator was first proposed by J.P.Blewett[5]. As one of the various candidates for an injector of BNL proton synchrotron, AGS. In the survey of the BNL injector, Blewett indicated that the shunt impedance of the IH type structure is high at low and medium particle velocity. At higher

![Fig.1 Effective Shunt Impedance of IH and other type.](image)
energies, however, its shunt impedance falls rapidly. The further development of this structure has been abandoned in USA for a long time. The RF characteristics of an IH resonator, instead, have been extensively studied by Russian[6,7] and French [8,9]. According to their experimental results, the IH structure has the substantial advantages of small transverse dimensions and high shunt impedance especially at low velocity region (\( \beta \ll 0.1 \)).

The small tank diameter gives relatively low Q-values of the resonator, and therefore, the RF excitation is very easy to handle. A simple mechanical structure of linac cavity is also one of the most attractive points of the IH resonator. This accelerating structure, therefore, is suitable for heavy ion accelerator.

The high shunt impedance has been realized in a post accelerator of the large Tandem Van de Graaff accelerator in Munich[10-13]. The beam energy boosters for tandem accelerators have a relatively small energy gain in comparison with incident beam energy.

Table 1 Measured Effective Shunt Impedance and Cavity Parameters of IH Structure

<table>
<thead>
<tr>
<th>Institute</th>
<th>( Z_{eff} ) (MHz)</th>
<th>( f ) (MHz)</th>
<th>( D ) (m)</th>
<th>( C_{B} ) (MeV)</th>
<th>( T )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>INS[3a-5] (1983)</td>
<td>496</td>
<td>65</td>
<td>103</td>
<td>1.8</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>TIT/TUM (1990)</td>
<td>1.92</td>
<td>1.03</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>CSM (1982)</td>
<td>1.01</td>
<td>0.96</td>
<td>0.93</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>TIT-1 (1980)</td>
<td>1.41</td>
<td>1.03</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>TIT-2 (1982)</td>
<td>1.51</td>
<td>1.03</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>NII-1 (1980)</td>
<td>1.64</td>
<td>1.03</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>TUM-1 (1982)</td>
<td>1.79</td>
<td>1.03</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>TUM-2 (1982)</td>
<td>1.93</td>
<td>1.03</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
</tr>
</tbody>
</table>

An IH structure having large energy gain as main accelerator was studied in INS university of Tokyo[14] and RLNR Tokyo Institute of Technology[15-19]. Figure 1 shows comparison of effective shunt impedance of the IH structure and of other acceleration structures. Table 1 shows linac parameters and measured effective shunt impedance of IH structure until now.

2.2 Effective Shunt Impedance of IH Structure

In order to obtain a rough estimation of a shunt impedance for the IH structure linac, let's consider the simplest case where the acceleration structure is approximated by a double ridged circular wave guide resonator. As suggested by J. Pottier[20] and other groups[10,21], the shunt impedance of the ridge wave guide is estimated as:

\[
Z_s = C' \cdot \alpha \cdot \beta^{-2} \cdot D^3 \cdot f^{3.5}
\]

Where the symbols are Zs: shunt impedance, \( f \): operation frequency, \( D \): diameter of cavity, \( \beta \): synchronous particle velocity divided by light velocity c and \( \alpha \): correction factor due to the surface roughness.

The effective shunt impedance is given as follows,

\[
Z_{eff} = C' \cdot \alpha \cdot T^2 \cdot \beta^{-2} \cdot D^3 \cdot f^{3.5}
\]

\[
= C \cdot \beta^{-2} \cdot D^3 \cdot f^{3.5}
\]

where \( T \): transit time factor, \( C(\beta) \): coefficient of effective shunt impedance for IH structure linac. \( C(\beta) \) is displayed

\[
C = Z_{eff} \cdot \beta^{-2} \cdot D^3 \cdot f^{3.5}
\]

Figure 2 shows comparison of coefficient of effective shunt impedance (C) and particle velocity. The empirical coefficients are near the straight line as log-log plots as shown in Fig.2. If diameter of resonator cavity is estimated, the effective shunt impedance is expected various energy region by using the empirical line.

3. Conceptual Design of Compact Driver by IH type Linac with High Acceleration Rate

First we examine main parameters using the empirical coefficient shown in Fig.2. We can keep cavity diameter large even if
operation frequency is high, in condition of the drift tube without installing focusing elements. Therefore the shunt impedance of cavity is kept over 100 MΩ/m until 50 MeVamu. Even if we control the voltage between drift tubes into below of twice of Kilpatrick limit, we can enough keep acceleration rate 10 MV/m. From this rate, the peak wall loss is 1.2 MW/m at normal temperature, and 120 kW/m at liquid N2 temperature. So we can operate this linac system safely.

For the sake of it we can keep the acceleration rate 10 MV/m and construct the RF linac system of HIF driver in the length of 1 to 2 km. The main parameters of HIF driver linacs are shown in Table 2. As shown in Table 2, the effective length of the IH linac cavities is 1245 m and the total length of the RF linacs containing RFQ linacs is 1405 m. Considering the funneling and jointing sections, it is sufficient to be with 2 km. If acceleration rate is high at supper conducting RFQ linac cavity, the length will be shorter.

Table 2 Main Parameters of RF linacs for HIF

<table>
<thead>
<tr>
<th>Name</th>
<th>RFQ-1</th>
<th>RFQ-2</th>
<th>RFQ-3</th>
<th>RFQ-4</th>
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<tbody>
<tr>
<td>Energy (MeV)</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>


We did not mention about beam focusing in the above chapters. As the characteristic of the IH, the diameter of cavity gets small. The solenoid lens and quadrupole lens of supper conducting will be possible to set in outside of the cavity. It is efficiently expected to be focus. When it is constructed, because of the progress of super-conducting technology, stronger magnetic-field is possible to generate. We are planning to start the correct Particle analysis.

It is necessary to cool the cavity it self as the cooling shield of the super conducting system that is set outside of acceleration cavity. So it is possible that the wall loss of cavity decrease until 1/10. In the case of HIBLIC[2], HIF driver is operated in 10 Hz, and it will be driven 100 Hz. Ad in the case of 100 Hz operation, the 100 fusion reactors are possible to make electric power of 10 GW.

We must carry out a farther examination of these problems.

References

LONGITUDINAL EMITTANCE MEASUREMENT FOR 433 MHz PROTON LINAC

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Abstract

We are developing a new device to measure the longitudinal emittance of the proton beam accelerated by the Alvarez linac. For the longitudinal emittance measurement, the simultaneous measurement of the phase and energy is required. The protons scattered by a gold target placed on the beam line are deflected by an RF electric field and detected by a position sensitive detector (PSD). We can reconstruct the phase and energy of the protons on the target by the position and energy information from the PSD.

1. Introduction

The information of the longitudinal emittance may be useful for the understanding of the operation condition of the linear accelerator. But it has not yet been measured for the high frequency proton linac. There are two difficulties in this measurement. At first, the simultaneous measurement of the phase and kinetic energy of the beam requires very careful treatment. Secondly, the phase measurement requires a high time resolution.

The longitudinal emittance measurements for the $H^-$ beam using the laser neutralization technique were studied at Los Alamos laboratory. They neutralize the $H^-$ beam by the short pulsed laser for the time slice of the beam, and separate them by the dipole magnet. Then the energy distributions of the neutralized beam are measured. But this technique cannot be used for the proton linac.

The measurements of the phase distribution for the proton beam were studied by some laboratories. They developed such devices as detect the secondary electrons emitted from the biased thin wire target and deflected by an RF electric field. Only a part of the beam in the short time region sliced by this RF shutter are detected with the Faraday cup. The time distribution of the secondary electrons obtained from this monitor is well considered to have the same longitudinal structure as that of the original beam. This device has a good phase resolution, but cannot measure the kinetic energy of the proton beam.

We have been developing the new longitudinal emittance monitor which detects the phase and energy of the proton simultaneously since autumn in 1994. A focusing system using permanent magnets has been studied in order to decrease the RF voltage of the deflector and increase the phase resolution. The mechanical design of this new measurement system and the fabricated devices are described.

2. Measurement System

The longitudinal emittance monitor mainly consists of five parts: Au target, RF deflector, permanent-magnetic quadrupole-lenses (PMQ), position sensitive detector (PSD), and the circuit system. The schematic view of the monitor is shown in Fig. 1.

3. Simulation of the system

Simulations of this measurement have been performed to determine the parameters of the system. The optimization factors are the RF voltage, the deflection angle and the position resolution on the PSD. The calculated positions on the PSD as a function of the original position in the bunch applying the decided device parameters are shown in Fig. 2.
The initial longitudinal distribution of the proton beam is assumed to be uniform in a rectangular phase space. The phase spread is ± 90 degree and the energy spread is ± 100 keV. The position X on the PSD depends on the longitudinal position Z0 and the kinetic energy. Because the deflection voltage is sinusoidal, the X is not proportional to the Z0. The spread range on the PSD is about 12.6 mm.

The position data which shows the initial phase value have errors, because of the energy spread and the finite size of the target and slit. This spread limits the phase measurement resolution. We estimated the error less than 4.5 degree assuming the energy resolution of the PSD as 40 keV.

Fig. 2
The simulated positions of the protons on the PSD for the rectangular longitudinal phase space distribution. Z0 means the longitudinal position at the target and X is the position on the PSD.

4. Target

The target is located at the 20 cm downstream from the Alvarez linac. The narrow Au strip target is evaporated on the thin carbon foil whose thickness is 20 μg/cm². The deposited area is 0.7 mm x 3.0 mm and the Au thickness is 0.1 μm. The target should be set on the straight line passing centers of the PMQs. The alignment error should be less than 0.1 mm to obtain enough measurement accuracy. The angle between the accelerated beam direction and the normal line to the target plane is 20 degree. In this way, the area of the Au viewed from the PSD are reduced to nearly 0.2 mm x 3.0 mm, and the scattering cross section becomes large. The mean energy loss in the target is 9.8 keV that is not small enough but compensated value with the yield.

The proton beam is scattered by the Au on the target and is also scattered by the carbon film. The protons scattered by the contamination material in the target can be separated by the kinetic energy of the scattered protons, because the kinetic energy of the proton scattered by Au is 6.93 MeV, and one by carbon is 5.91 MeV.

5. Cavity

The RF cavity produces the electric field which deflects the proton scattered by the target. The deflection cavity is shown in the photo 1, and the specifications of the cavity are shown in Table 1. The inner conductor is tapered in order to increase the shunt impedance. The resonant frequency is tuned by a 534 mm plug tuner with 30 mm moving range. The folders of the PMQs are fixed before and after the voltage gap. The unloaded Q and the shunt impedance are evaluated as 12680 and 4.69 MΩ, respectively by the 3-D field calculation with the MAFIA code. The measured resonant frequency of the fabricated cavity was 420 MHz which is lower than design value. Then the electrode gap was enlarged from 4.0 mm to 4.65 mm for tuning. The Q value was measured to be 7010 after the resonant frequency was tuned to 433.0 MHz. The design value of the electric field is 116 keV/cm. The high electric field is desirable for the better resolution of the phase measurement. But the high electric field needs a high power source. We estimate the necessary power as 1.1 kW by the measured Q value and the calculated Z/Q. We tried the high power test and more than 1.1 kW peak power could be supplied.

Table 1
Specifications of the RF cavity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency [MHz]</td>
<td>433.0</td>
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<tr>
<td>unloaded Q</td>
<td>7010</td>
</tr>
<tr>
<td>electrode gap [mm]</td>
<td>4.65</td>
</tr>
<tr>
<td>electrode length [mm]</td>
<td>30.0</td>
</tr>
<tr>
<td>electrode height [mm]</td>
<td>14.0</td>
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<tr>
<td>outer conductor diameter [mm]</td>
<td>200</td>
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<tr>
<td>inner conductor maximum diameter [mm]</td>
<td>100</td>
</tr>
<tr>
<td>inner conductor minimum diameter [mm]</td>
<td>14</td>
</tr>
<tr>
<td>outer conductor height [mm]</td>
<td>210</td>
</tr>
<tr>
<td>inner conductor height [mm]</td>
<td>106</td>
</tr>
<tr>
<td>outer conductor material</td>
<td>Aluminum with Cu-plated</td>
</tr>
<tr>
<td>inner conductor material</td>
<td>Copper</td>
</tr>
<tr>
<td>shorting plate material</td>
<td>Copper</td>
</tr>
<tr>
<td>design gap voltage [keV]</td>
<td>54.0</td>
</tr>
<tr>
<td>necessary peak power [W]</td>
<td>1100</td>
</tr>
</tbody>
</table>
6. PMQ

The permanent magnetic quadruples (PMQ) are set to the holders in the RF cavity. The PMQ is assembled from the eight trapezoidal magnet pieces made of Nd-Fe-B (NEOMAX-41H). The PMQs installed in the holder is shown in photo 2. The specifications of the PMQs are given in Table 2. The PMQ1 and PMQ3 defocus the protons, and the PMQ2 focus them horizontally. The PMQ3 enhances the deflection angle. The 0.1 mm x 3.0 mm slit is located on the front cover of the PMQ1. The slit is made of the four pieces of 0.2 mm tantalum plates.

![Photo 2](image)

Photo 2 The PMQ folders. Right one has PMQ1 and PMQ2, and left one has PMQ3. The folders are made of copper-plated stainless. The tantalum slit is attached on the PMQ1.

<table>
<thead>
<tr>
<th>PMQ-No.</th>
<th>Bore diameter [mm]</th>
<th>Numbers of the Segments</th>
<th>Height of the segment [mm]</th>
<th>Lower base of the segment [mm]</th>
<th>Upper base of the segment [mm]</th>
<th>Field gradient [kG/cm]</th>
<th>Length [mm]</th>
<th>Material</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>8</td>
<td>9.18</td>
<td>11.75</td>
<td>-19.5</td>
<td>-14.9</td>
<td>43.0</td>
<td>Nd-Fe-B</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>-</td>
<td>9.18</td>
<td>4.14</td>
<td>4.94</td>
<td>+19.4</td>
<td>43.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>-</td>
<td>8.18</td>
<td>4.14</td>
<td>4.94</td>
<td>-14.8</td>
<td>45.0</td>
<td></td>
</tr>
</tbody>
</table>

7. PSD and circuit system

The PSD (IPP 1508-500) is a Si charged particle detector with PN junction, whose front surface is P-type semiconductor and back side is N-type semiconductor. There are two contacts on the surface side edges, and the resistance between them is about 10 kΩ. The bias voltage is +80 V to the backside N-type semiconductor. The one connector on the P-type side is grounded, and another connector is the output of the signal proportional to the charge. The connector for the N-type side is the output of the signal proportional to the energy. Therefore the position is given by the ratio of the two signals. The area of the PSD is 8x15 mm², and the position resolution is 0.15 mm. This detector is set at the 75 mm from the exit of the PMQ3. For decreasing the X-ray from the Alvarez linac, we set the Pb shield around the detector. Two magnets are also used for sweeping out the electron cloud coming from the deflection cavity.

The circuit diagram for the signals from the PSD is shown in Fig. 3. The two signals from the PSD are amplified and A/D converted to 13 bits. The timing of the event in the 60 μs of the RF macro pulse is also measured. We can know the time dependence of the longitudinal emittance in the RF macro pulse. The outputs of the three A/D converters go to personal computer and the raw data are memorized. The data taking program is KODAQ 6) which is a flexible data acquisition system based on NEC PC-9801 distributed by Institute for Nuclear Study (INS), Univ. of Tokyo. The histograms of the three ADC-outputs and two-dimensional scattered plots for the ADC-outputs of the position and energy signals can be seen on the graphic display by using this program.

![Fig. 3](image)

Fig. 3 The circuit diagram for the data taking system.

8. Acknowledgments

The authors would like to express their acknowledgment to Dr. Sugai of INS for manufacturing the excellent Au target. The authors would also like to express their acknowledgment to Mr. Omata of INS for helping them to use the convenient data taking program “KODAQ”.

References

Calibration of Beam Position Monitor for the SPring-8 Synchrotron

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Abstract

Beam position monitors (BPMs) for SPring-8 synchrotron were already designed and manufactured. 80-BPMs were successfully calibrated for the beam position measurement. In this paper, we introduce the structure of BPMs, the electronics of signal detection system and the calibration system, and the results of calibration are reported.

1. Introduction

Beam position monitors, which are placed in the SPring-8 booster synchrotron, are designed to measure a closed orbit distortion (COD). The BPMs are located at the upstream position of 80-quadrupole magnets. Each BPM consists of four button-type electrodes which are mounted on the wall of the vacuum chamber. The diameter of all the electrodes are 18 mm. Output signals from the electrodes of 20-BPMs are selected by PIN-diode switches, and the amplitudes of these signals are measured by the same detection system. Four detection systems are used at the same time for 80-BPMs, and the measurement time of this system is less than 30 ms.

The BPMs are calibrated by using an antenna to simulate an electron beam. The antenna is mounted on the X-Y table which is driven by the pulse motors. The 508.58 MHz signal, which frequency is the same one as the acceleration RF in the synchrotron, is supplied from the tracking generator to the antenna. The output signals from the electrodes are measured by the spectrum analyzer. The normalized values about horizontal and vertical positions are obtained by the output signals.

2. Structure of BPM pickup

The BPM pickup consists of four button-type pickup electrodes which are attached to the SMA-type coaxial feedthroughs welded on a 80x30 mm² or 100X30 mm² racetrack-type vacuum chamber. About the electrode, the diameter is 18 mm and the capacitance with a feedthrough is about 6.8 pF.

We use three types of BPM pickups. The type 1 BPM pickups are placed at 78 positions. The horizontal distance between the center of the vacuum chamber and the electrodes is 14 mm. Figure 1 shows a cross-sectional view of the type 1 BPM pickup. The type 2 pickup has a 100x30 mm² racetrack-type vacuum chamber, and the position of A and D electrodes are x=24 mm from the center of the vacuum chamber to measure the beam positions on both the reference orbit and the bump orbit for the beam extraction.

The type 3 pickup has also a 100x30 mm² vacuum chamber, and the position of the electrodes are as same as the type 1. The type 2 and the type 3 pickups are located on the straight-section where the beam extraction systems are placed.

3. The Electronics of BPM

The block diagram of BPM electronics for COD measurement is shown in Fig. 2. The output signals from the BPM pickups are transmitted through the 3 dB attenuators and the coaxial cables to the electrode-selector which consists of fast PIN-diode switches and a 600-MHz low-pass filter (LPF). The switching time of the PIN-diode is less than 0.01 ms, and the duration of an one-electrode selection is 0.35 ms. The output signals from the electrode-selectors are transmitted through low-loss, high-frequency cables (WF-H50-4) to the BPM-selector.

Heterodyne circuit is used at the detection system. The 508.58 MHz signal, which frequency is the same one as the acceleration RF in the synchrotron, is transformed to a signal of 70 MHz intermediate frequency by mixing with a 438.58 MHz signal from the
local oscillator. The 70 MHz signal is converted to DC level as position signal by the synchronous detector and the 3.5 MHz LPF.

The output signals from the 80-BPM pickups are detected by four detection circuits. It is expected that the total measurement time of 80-BPMs is less than 30 ms. To measure a single-bunch beam position, the output signals from a BPM pickup are observed simultaneously by digital sampling oscilloscope (SONY Tektronix CSA803A, sampling head SD-26). Five electrode-selectors have functions to change over from COD mode to single-bunch mode.

4. Calibration System

The schematic diagram of the BPM calibration system is shown in Fig. 3. To simulate an electron beam, semi-rigid coaxial cable (UT-85) is used for an antenna and is mounted on the X-Y table which is driven to x, y and s directions by the pulse motors. The coaxial cable is inserted in the stainless steel sleeve which has 3 mm inside diameter and 5 mm outside diameter. The length of the inner conductor out of the sheath is 50 mm.

The optical sensors are used to set the antenna at the initial position before every measurement. The 508.58 MHz signal is amplified and is supplied to the antenna from the tracking generator output of the spectrum analyzer (HP 8560E). The output signals from the electrodes: $V_A, V_B, V_C$ and $V_D$ are switched by electrode-selector and are measured by the same spectrum analyzer. The X-Y table and electrode-selector are controlled by HP model 362 through the motor controller and I/O box. The offset distances between the initial position of the antenna and the center of the BPM pickups have been measured previously, and they are compensated on the software.

To simulate a distribution of electromagnetic field in the beam duct, two dummy ducts are attached both ends of the BPM pickup. To avoid a noise signal by the leaked electromagnetic wave, electromagnetic shield rubbers are stuck on the inside of dummy duct's outer sides and on the base of the antenna. At the longitudinal position more than 60 mm from the end of sleeve, electric field distribution is nearly constant. Therefore, the X-Y table is driven to s-direction that the position comes on the center of the electrodes.
5. Result of Calibration

The normalized values calculated with the output signals from electrodes:

\[ H = \frac{(V_A - V_B + V_C - V_D)}{(V_A + V_B + V_C + V_D)} \]
\[ V = \frac{(V_A + V_B - V_C - V_D)}{(V_A + V_B + V_C + V_D)} \]

are obtained at a position \((x, y)\) of the antenna. Fig. 4 shows an example of a result of measurement between \((H, V)\) and \((x, y)\) of type 1 BPM. The calibrated area of type 1 and type 3 BPM pickup is \(x = \pm 15\) mm and \(y = \pm 8\) mm, and type 2 is from \(x = -15\) mm to \(x = +25\) mm and \(y = \pm 8\) mm.

Fig. 4. An example of a result of measurement between \((H, V)\) and \((x, y)\) of type 1 BPM

The relationship between \((x, y)\) and \((H, V)\) are expressed as sextic polynomials that obtained by least square method. Figure 5 shows an example of a calibrated relationship between \((x, y)\) and \((H, V)\) of type 1 BPM.

Fig. 5. An example of a calibrated relationship between \((x, y)\) and \((H, V)\) of type 1 BPM

The precision of the X-Y table is about 0.005 mm and the accuracy of installation of BPM pickup on the calibration system is within 0.05 mm. The accuracy of the optical sensors to set the antenna at the initial position is within 0.05 mm. Thus the accuracy of the calibration is about 0.1 mm. To estimate the accuracy of this calibration system, we calibrated ten times about a same BPM pickup. The deviation of the electric center, which is the position of \(H = V = 0\), is within 0.04 mm.

6. Conclusion

80-BPMs were successfully calibrated and the accuracy of calibration was about 0.1 mm. The BPM pickups are already welded to the beam ducts.
The Effect of the Aberration on the Emittance Growth Revealed in Design Study of LEBT using Magnetic Lenses for the JHP RFQ

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Abstract

The growth of effective emittances in a low energy beam transport (LEBT) is one of the most important problems to be solved for the high-energy, high-intensity proton linacs, in the high-energy part of which the beam loss should be extremely reduced. Although a variety of LEBTs using electrostatic lenses were examined at Superconducting Super Collider Laboratory (SSCL), large effective emittance growth due to lens aberrations was observed in almost of them. Therefore, we performed design studies on LEBTs with magnetic lenses in order to inject a proton beam into a 432-MHz radio frequency quadrupole linac developed for the Japanese Hadron Project (JHP). The smallest effective emittance growth (no growth in RMS emittance and small growth of less than 15% in 100% emittance) was obtained in the LEBT with two short, strong solenoid magnets (SMs). The LEBT with two triplet quadrupole magnets gave rise to the larger effective emittance growth than that with two SMs, even in the case that the beam optics was simulated in the ideal quadrupole field without higher-order components under the linear space charge force.

Introduction

A 432-MHz, radio-frequency quadrupole (RFQ) linac was developed as a pre-injector for the high-intensity proton linac of the Japanese Hadron Project (JHP) [1]. A variety of low-energy beam transports (LEBTs) for RFQs with resonant frequencies around 400 MHz have been studied extensively at Superconducting Super Collider Laboratory (SSCL) and Los Alamos National Laboratory (LANL) [2,3,4]. LEBTs with electrostatic lenses were studied at SSCL, while those with magnetic lenses at LANL. However, the results of their developments are not satisfactory for our purpose, since the measured “effective emittances” at the exit of their LEBTs were around twice as high as that measured just after the ion sources.

It is perhaps necessary to present the definition of “effective emittance” and the reason why we introduce this. How to eliminate the loss of the high-intensity, high-energy beam is one of the most important issues for the design of the high-energy, high-intensity proton linacs, since the beam loss gives rise to the radioactivity, eventually making the maintenance impossible. From this point of view the mathematically defined emittance or even the root-mean-square (rms) emittance is not an appropriate measure of the beam quality. In order to represent the quality of a LEBT we use the phase-space area surrounding the positions and gradients of all the particles with the designed TWISS parameters of the RFQ linac. We here refer to thus defined emittance as an effective emittance. Of course the parameters of the LEBT are here adjusted to obtain the lowest effective emittance.

Critically inspecting the experimental results at SSCL we concluded that the effective emittance grew in the LEBT with electrostatic lenses mostly through their lens aberrations. Since it is difficult to reduce the aberration of electrostatic lens, we had to give up the use of the electrostatic lenses. On the other hand, although the effective emittance in the LEBT with magnetic lenses at LANL was also increased (the reason is not clear from their papers), there is a hope of the improvement in this case, since one may find the way to improve the aberration of the magnetic lenses.

Table 1

<table>
<thead>
<tr>
<th>Design beam parameters in the LEBT</th>
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</thead>
<tbody>
<tr>
<td>Proton or H⁺ beam energy</td>
</tr>
<tr>
<td>Beam intensity</td>
</tr>
<tr>
<td>Particle distribution in transverse emittance</td>
</tr>
<tr>
<td>TWISS parameters at the entrance</td>
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<tr>
<td></td>
</tr>
<tr>
<td>TWISS parameters at the exit</td>
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Table 2

<table>
<thead>
<tr>
<th>Parameters of magnets determined by using TRACE</th>
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<tbody>
<tr>
<td>BT-SM1</td>
</tr>
<tr>
<td>BT-SM2</td>
</tr>
<tr>
<td>BT-TQM</td>
</tr>
<tr>
<td>Magnet length L (cm)</td>
</tr>
<tr>
<td>Magnet bore radius ( r_{b} ) (cm)</td>
</tr>
<tr>
<td>Field strength of 1st magnet</td>
</tr>
<tr>
<td>Field strength of 2nd magnet</td>
</tr>
<tr>
<td>Field strength of 2nd magnet</td>
</tr>
<tr>
<td>Total length (cm)</td>
</tr>
<tr>
<td>Max. beam radius ( r_{b} ) (cm)</td>
</tr>
<tr>
<td>ratio of radii ( r_{b}/r_{100} )</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic view of the LEBT
the gate valve, beam diagnostics and vacuum pumping, (3) a distance of 35 mm between the second magnet and the entrance of the RFQ vane was already occupied by the end plate of the RFQ, (4) the field strength should be smaller than the value obtainable without significant saturation in iron yoke of SM or TQM.

The BT-SM1 was designed in such a way that the maximum beam radius \( r_{\text{min}} \) was minimized by using almost the strongest magnetic field obtainable with normal-conducting solenoid magnet. The BT-SM2 was studied in order to find out the reason for the emittance growth observed at LANL. The total length of BT-SM2 and the dimensions of the SMs in BT-SM2 are similar to those used in the LEBT developed at LANL. As seen from Table 2, the significant differences between BT-SM1 and BT-SM2 are in \( r_{\text{min}} \) (1.2 cm in BT-SM1 and 1.7 cm in BT-SM2) and in the ratio of \( r_{\text{min}} \) with the bore radius \( r_{\text{bore}} \). The 0.48 in BT-SM1 and 0.34 in BT-SM2. In the later section, we will investigate which parameter of \( r_{\text{min}} \) or \( r_{\text{min}}/r_{\text{bore}} \) has more effect on the lens aberrations.

In general, quadrupole magnets are considered to have smaller aberrations than SMs. This is the reason for studying the BT-TQM. Since the convergence angle of the beam injected into the RFQ is very large (about 80 mrad), the shorter quadrupole magnets is preferable in order to reduce the beam radius. On the other hand, the thin quadrupole magnet has large higher-order components due to the fringing field. In order to compromise these two conflicting requirements we set the two additional restrictions upon TQM: (1) the minimum pole length of the quadrupole magnet is equal to the bore diameter, (2) the minimum space between the two quadrupole magnets is equal to the bore radius.

**Beam Optics Simulation in LEBTs**

As described in the previous section, we expected that the lens aberrations play an important role in the growth of the effective emittance. In order to study the effect of the lens aberrations, we have to simulate the trajectories of particles in the realistic field, for example the solenoid magnetic field calculated with POISSON. However, it takes very long time to optimize the LEBT design by using the simulation program such as BEAMPATH [9]. Therefore, we developed the program, referred to as SHU in order to simulate the effect of the lens aberrations more easily. With SHU, we trace the trajectories of particles, the positions of which in the \( x-x' \) phase space are shown in Fig. 2 (no emittance in the \( y-y' \) phase space : \( y-y'=0 \) for every particle), undergoing the realistic magnetic field. In SHU, the particles also undergo the linear space charge force estimated only from the intensity and diameter of the beam (the axially symmetric beam with the uniform particle distribution in the real space is assumed).

In order to justify the validity of the calculation using SHU, the simulated results will be compared with those using BEAMPATH. The emittance profiles calculated with SHU at the exits of BT-SM1, BT-SM2 and BT-TQM are shown in Fig. 3a), 3b) and 3c), respectively. In these figures, the design emittance profiles injected into the RFQ and the areas of the 100% emittances are also shown with dotted lines. The 100% emittance surrounding the simulated emittance profile has the same TWISS parameters as those designed. The magnetic field distributions calculated with POISSON were used in the simulations for BT-SM1 and BT-SM2. Since the current version of BEAMPATH supports the simulation only for the ideal quadrupole field (not for the arbitrary 3-dimensional field), the ideal quadrupole magnetic fields were used in the simulations for BT-TQM in order to make possible the comparison with the BEAMPATH results. The calculated emittance profiles were matched with the design profile by slightly tuning the field strength. The beam envelopes, calculated at the same time with Figs. 3, are shown in Fig. 4. In this figure, we also show the beam envelopes when the beam intensities are 0 mA. In order to compare the simulation results using SHU with those using BEAMPATH, we performed the simulations in BT-SM1, BT-SM2 and BT-TQM under the same conditions as before. In these simulations, we traced the trajectories of 10000 particles. The simulated emittance profiles at the exits of BT-SM1, BT-SM2 and BT-TQM are shown in Fig. 5a), 5b) and 5c), respectively. In these figures, the design emittance profiles injected into the RFQ and the 100% emittance profiles are also shown with dotted lines. As can be seen from Figs. 3 and Figs. 5, the simulation results using SHU are in good agreement with those using BEAMPATH. In this sense the use of SHU is justified in order to study the lens aberration effects. The calculated RMS and 100% normalized emittances of each LEBT are summarized in Table 3. The results of the present simulation studies are summarized as follows;

1. Almost no growth of the effective emittance was observed in
any LEBT, when the beam intensity was 0 mA.
(2) It can be seen from Table 3 that the effect of the lens aberration was revealed on the growth of the effective emittance for the 40-Ma beam, while almost no effect on the RMS emittance.
(3) The growth in BT-SM1 with two short, strong SMs was the smallest among the three LEBTs.
(4) The largest growth of the effective emittance was observed in BT-TQM in contrast to the naive prediction from its ideal quadrupole magnetic fields.
The sources of these emittance growths are discussed in the next section.

Sources of Aberrations

(1) Source of Aberration in TQM
In order to find the source of the aberration occurring in BT-TQM, we simulated the trajectories of the particles extracted from a point source with the ideal focusing quadrupole field. In this simulation, the beam intensity was 0 mA and the particles with initial divergences of up to ±300 mrad were traced. Since the focal length of the quadrupole magnet is 7 cm, the particles were traced until 14 cm, where the particles will be focused again at one point if there is no aberration. The simulated emittance is shown in Fig. 6. It can be seen that the linear oscillation in the ideal quadrupole field is satisfied only for the particle with initial divergence angle of around ±120 mrad. In the BT-TQM, the simulated maximum value of the divergence angles for the beam intensities of 0 mA and 40 mA are 140 mrad and 270 mrad, respectively. The latter value is significantly higher than 120 mrad. This is the reason for the remarkable filamentation in the simulated emittance at the exit of BT-TQM.

In order to study the effect of the fringing field in BT-TQM we used the SHU together with the realistic quadrupole magnetic field calculated with MAFIA. The simulated emittance at the exit is shown in Fig. 7. The extremely large filamentation was generated due to the fringing field. The filamentation shown in this figure is very similar to that observed in the LEBT with several electrostatic quadrupoles developed at SSL. It is thus concluded that any short quadrupole lens has large aberration due to the fringing field, when it is necessary to inject the beam with large convergence angle into the RFQ with a resonant frequency of around 400 MHz.

(2) Source of Aberration in SM
The divergence angle of the particles exceeded ±120 mrad, the aberration described above should also occur in the SM. Fortunately, this is not the case for SM, since there is no defocusing force in the field of SM and the divergence angle is not so enlarged as above.

In order to reveal the source of the aberration observed in BT-SM1, we simulated the beam optics in BT-SM1 with the first-order magnetic field distribution (Br=−r2/(dBz/dz)) by using SHU. The simulated emittance at the exit is shown in Fig. 8. Almost no filamentation can be seen in this emittance profile. Therefore, the effect of the aberration seen in Fig. 3a) and 5a) arises from the higher-order components of the field which are generated by the edge of the iron yoke and the fringing field. It is noted that this kind of geometrical aberrations in BT-SM1 is significantly smaller than that due to the fringing field in the realistic TQMs. The aberration in BT-SM2 also arises from the higher-order components of the field. It is seen that filamentation...
Abstract

It was pointed out recently that there exists an appreciable beam position dependence in the wall-current monitor widely used in electron accelerators. Detailed study of this dependence is performed on a test bench varying the pulse width and the frequency of the input signal simulating the beam. The results of experiments show that when the pulse width becomes shorter more appreciable becomes the dependence, and it approaches to that of calculated from the method of images. A unified analysis is under way.

Introduction

A wall-current monitor is one of the monitors which are widely used in particle accelerators. It is used to measure the beam current and its waveform, and most suited for short pulse electron beams of a few nanoseconds. However, it was pointed out recently that there is a significant beam position dependence [1] - [3]. A detailed study was then made to make clear the characteristics and performance of this monitor. One of the results of this study is that the output signal is not proportional to the input signal in magnitude, but precisely proportional in area. These results are reported elsewhere [4].

This paper describes a study about the beam position dependence of this detector; a detailed experiment is made to clarify the property of this dependence.

Experimental method

The operational principle of this monitor is well known; across the register set along the beam duct a voltage difference is produced by a wall-current flow through it, and the current flow is caused by the beam. A schematic drawing of the monitor cross-section is shown in Fig.1, the monitor has four output ports to make clear the current distribution around the register.

The layout of the experimental apparatus is shown in Fig 2. The beam duct has an insulator in its middle, around which the monitor is installed. The beam is simulated by a current passing through a wire set in the center of the beam duct. The current is supplied by a voltage pulse from a pulse generator (HP 8131A).

To measure the dependence of the monitor signal on the beam position, the beam duct is varied with a stepping motor instead of varying the wire position. It is varied by a step of 1 mm up to 5 mm in the horizontal plane as shown in Fig.1. Each signal from the four output ports is measured with an oscilloscope (TDA 6481A).

Two kinds of experiment are performed in studying the beam position dependence of the monitor. One is the experiment in which the width is varied of the input signal, the other is that the frequency is varied for the sinusoidal waveform used as an input signal. Although the beam duct is not a sinusoidal waveform, the frequency dependence of the cause to produce the position dependence may probably be shown more directly by using the sinusoidal input.

Two kinds of experiment are performed in studying the beam position dependence of the monitor. One is the experiment in which the width is varied of the input signal, the other is that the frequency is varied for the sinusoidal waveform used as an input signal. Although the beam duct is not a sinusoidal waveform, the frequency dependence of the cause to produce the position dependence may probably be shown more directly by using the sinusoidal input.

The attenuation of the signal in the cable and the voltage gain of the oscilloscope depend on the pulse width or the frequency of the signal, and both are measured and corrected for each measurement.
Results and discussions

Typical output waveforms are shown in Fig.3. The pulse width is 1 nsec, and the beam position is ±5 mm. The channel number of each signal from the top to the bottom is 1 to 4, respectively, and corresponds to the output port indicated in Fig.1. An appreciable reflection of the signal is observed, however, its influence may be mostly avoided in reading the magnitude by selecting an appropriate time point.

A result of the measurements is shown in Fig.4, in which the output signals from four channels are plotted as a function of the beam position. The pulse width is 1 nsec in all measurements. As is shown in the figure, four curves give different behaviours which are characteristic for the output positions relative to the beam position deviation from the center.

Figure 5 shows a summary of the measurements for channel 1, where the output vs. the beam position is shown and the parameter is the pulse width varied from 750 ps to 50 ns.

When the pulse width is 50 nsec long, the output scarcely depends on the beam position. However, when the width becomes shorter, more appreciable becomes the dependence, and when it comes near or less than a few nanoseconds, the outputs seem to approach gradually to a solid curve shown in the Fig.5. This curve is obtained by the method of images, and given by [5]

\[
i = \frac{r^2 - \delta^2}{r^2 + \delta^2 - 2r \delta \cos(\theta - \phi)}
\]  

(1)

![Fig.3 Waveforms of the monitor outputs from ch.1 to 4 for 1 ns input](image)

![Fig.4 Output voltage vs. beam position for ch.1 to 4](image)

![Fig.5 Output voltage vs. beam position; the parameter is the pulse width](image)
where the quantities used are those given in Fig. 6. In the calculation the value of \( r \) is required, and is assumed to be 35.25 mm which is about the average value of the solid register.

The results for channel 3 of the monitor output is very similar to the channel 1 described above. As shown in Fig. 1, the channel 2 and 3 are much less sensitive to the beam position displacement as is also expected from Eq.(1).

Figure 7 represents the output waveforms for the channel 1 to 4 when the sinusoidal input is supplied. The frequency is 300 MHz and the beam position is 5 mm. The results of the measurements for channel 1 are shown in Fig. 8, where the frequency of the input is varied. The parameter is the frequency varied from 10 MHz to 300 MHz, and at 10 MHz the output does not seem to depend on the beam position. However, the frequency becomes higher, more appreciably depends on the output on the beam position. This is very similar to the previous experiment where the pulse width is varied. The solid curve is the one calculated by Eq.(1). At 300 MHz the experimental data show more appreciable beam position dependence than the calculated. Detailed examination of these data is under way. The reason to cause such beam position dependence is suggested to be due to the existence of an impedance along the beam duct in azimuthal direction [1], [2], and this impedance is shown most likely to be an inductance [3]. However, unified quantitative analysis of this monitor is required on various characteristics, and now in progress.

References

Abstract

The KEK 12GeV proton synchrotron is scheduled to serve an intense beam for a neutrino oscillation experiment. This experiment is foreseeing about two times higher proton intensity than the current one, and accelerator machine studies are going on to improve the current proton intensity. The most important machine study is the investigation of an emittance blow up mechanism during the injection/acceleration period. An observation of a fast transverse emittance blow up is one of the key issue in this machine study and a flying wire monitor is now developing at KEK-PS.

1. Introduction

A transverse beam profile provides so many information related to the blow up mechanism, such as orbit miss matching, strength of resonances, space charge effect etc. The beam profile varies turn by turn during the acceleration. The slow profile change is caused from, for instance, weak resonance and adiabatic damping etc. It can be detectable by employing a residual gas ion monitor1), which collects the ions produced from the ionization of the residual gas by circulating proton. However, this type of monitor has ambiguity due to the space charge and the finite ion drift time to the electrode. A flying wire profile monitor is one of the candidate to check each other and to observe the fast profile change during the acceleration2)-5).

The KEK-PS flying wire monitor is designed to observe the vertical beam profile by rotating a thin Aluminum wire (25μm) into the beam bunch by a speed of 20m/sec. Then the crossing time duration is about 3msec and make it possible to observe the fast profile variation during the injection/acceleration period. A single photo-multiplier mounted beside the rotator detects the secondary particles produced by the proton/wire interaction. Figure 1 shows a mechanical device.
Flying Wire monitor is installed just behind a lattice defocus magnet as shown in Fig.2. It consists of the low inertia U-shape fork, the high precision potentiometer and the high power DC servo motor. The U-shape fork has a gap of 66mm with an aluminum wire of 25μm diameter stretched. The fork spacing and length are determined to cover whole beam size at the location where the wire is installed. The fork is placed aiming to observe the vertical beam profile and it crosses the circulating beam from up to down with the maximum velocity of 20m/sec using a DC servo motor. An angle of rotating fork is detected by the potentiometer which is connecting to DC servo motor by pulley. The fork velocity is automatically controlled by comparing the motor driving signal and the rotational angle signal.

Collision between the proton beam and the wire material produces secondary particles, number of which is proportional to the proton density in the beam bunch.

3. Data acquisition

Figure 3 shows a block diagram of the signal flow. The photo-multiplier signal and the potentiometer signal are digitized simultaneously by a Wave Form Digitizes(WFD). The photo-multiplier signals is a pulse train each of which has a length of about 100nsec and varied according to the acceleration RF frequency from 6.0MHz to 7.8MHz. Therefore the sampling rate should be at least 200Msample/sec to obtain 20samples for 100nsec. Total memory of 0.6Mbyte is necessary to cover all the times where the wire crosses the whole beam cross section. Since the harmonic number of the KEK-PS main ring is nine, a tagging signal is necessary in addition to two signals mentioned above in order to identify each bunch. The WFD stores three signals in 1Mbyte/channel memory, and transmits them to a high speed Work Station (WS) through a 16 bit parallel i/O which can transmit them by 4Mbyte/sec.

![Function Generator](trigger) through a 16 bit parallel i/O which can transmit them by 4Mbyte/sec.

Fig.4 Tagging signal and photo-multiplier signal when three bunches were injected.

![Fig.5 Potentiometer signal](trigger)

The data from the WFD is analyzed by a high speed WS. Photo-multiplier signal express the integration of number of secondary particles. The peak of photo-multiplier signal is proportional to the number of secondary particles produced when a bunch hits the wire. The analysis program of the WS looks for the peak value of the each bunch signal and plot it on the Y-axis as a function of the wire rotation angle on the X-axis. Since the bunch identification by the tagging signal is carried out, the beam profile of each bunch can be also deduced. The tagging signal and the photo-multiplier signal are shown in Fig.4, and potentiometer signal shown in Fig.5.
4. Heating of the wire and the emittance blow up

Beside the high energy secondary particle shower detected by the photo-multiplier, the beam/wire interaction also causes a multiple scattering of the circulating proton and the proton loses its energy at the same time. The temperature rise of the wire material, $\Delta T$, is assumed to be caused by every loss of the proton without consideration of the energy transfer to the secondary particle etc.

$$\Delta T = \frac{dE/dX \cdot d}{m \cdot C_v}$$  \hspace{1cm} (1)

where $dE/dX$, $m$, $d$ and $C_v$ are the minimum ionization loss, mass, thickness and specific heat of the wire, respectively.

Temperature rise is estimated by using eq.(1) and that of all wire materials is much less than the melting point as shown in Table 1.

<table>
<thead>
<tr>
<th>$d$ $[\mu m]$</th>
<th>$\Delta T$ $[K]$</th>
<th>melting point $[K]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>10</td>
<td>433.924</td>
</tr>
<tr>
<td>Al</td>
<td>25</td>
<td>35.028</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>29.435</td>
</tr>
</tbody>
</table>

The emittance blow up, $\Delta \varepsilon$, is described as

$$\Delta \varepsilon = \frac{3\sqrt{\frac{\beta_y}{\pi}} \cdot d \cdot \theta^2 \cdot n^{2/3}}{2}$$  \hspace{1cm} (2)

where $\beta_y$ is the vertical beta function, $d$ is thickness of the wire, $\theta$ is the rms value of multiple scattering angle and $n$ is the number of revolution, respectively. $\theta$ is estimated by

$$\theta = \frac{20[MeV/c]}{P \cdot \beta} \sqrt{\frac{d}{L_R}} \left[1 + \log_{10} \left(\frac{d}{L_R} \right) \right]$$  \hspace{1cm} (3)

where $P$, $\beta$ and $Z_{inc}$ are the momentum (in MeV/c), Lorentz factor and a charge number of the incident particle, $d$ and $L_R$ are the thickness and the radiation length of scattering medium, respectively. Typical circulating beam emittance, $\varepsilon$, is 45mm-mrad. Dependence of the emittance blow up on the wire materials is estimated as shown in Table 2. It is obvious that W(tungsten) causes about 10% blow up, then we don’t use it.

<table>
<thead>
<tr>
<th>$d$ $[\mu m]$</th>
<th>$\Delta \varepsilon$ $[mm-mrad]$</th>
<th>$\Delta \varepsilon$ $[mm-mrad]$</th>
<th>$\Delta \varepsilon/\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>10</td>
<td>4.2464</td>
<td>0.13117</td>
</tr>
<tr>
<td>Al</td>
<td>25</td>
<td>0.27922</td>
<td>0.0086182</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>0.25911</td>
<td>0.0079973</td>
</tr>
</tbody>
</table>

By the taking account of the temperature rise and the emittance blow up, we decided to use aluminum wire which is more easy to stretch on the fork than a carbon wire.

5. Conclusion

Design of the fast wire scanner at the KEK-PS main ring was described. This flying wire has just installed on early September. A feasibility study and the software development are now going on. The result of the study will be presented at the Symposium.

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3D Visualization of Fast Light Emission Phenomena by Dynamic CT

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Abstract

3D visualization of Cherenkov radiation in water generated by an electron beam from the 28 MeV linac of University of Tokyo was performed. We introduced the light emission computed tomography theory. We adopted the fan beam projection using a rotating mirror, a collimator, an optical fiber and a photo-multiplier. Cherenkov radiation passing through the collimator enter a photo-multiplier via an optical fiber. The optical fiber should be shielded against X rays. At the first stage, we succeeded in reconstructing the image of distribution of Cherenkov radiation in water, with the nanosecond time resolution.

1. Introduction

Recently, Computed Tomography (CT) is progressing remarkably in the field of the diagnostic technology and medical treatment technology. Dynamic light emission CT is the way of 3D visualization of a luminous body using the algorithm of CT. For now, it had obtained the distribution of the emission that was emitted from a fluorescent tube or a discharge tube, with the millisecond time resolution. The purpose of this research is to enhance the time resolution of this CT and to get the dynamic image of distribution of light emission phenomena in nano- and picosecond time domains. At the first stage, we measured Cherenkov radiation in water generated by an electron beam from the linac of University of Tokyo, and reconstructed the image of distribution of the emission by the light emission CT theory.

2. Theory of CT

In order to obtain the CT image of a body, we need to get projection data in all directions. Assuming that \( f(x,y) \) is the distribution of light emission from the body, the projection data in the \( \theta \) direction, \( p(r, \theta) \), in the \( r-s \) coordinate which rotate \( \theta \) angle from the \( x-y \) coordinate are given as follows (see Fig.1),

\[
p(r, \theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \delta(x \cos \theta + y \sin \theta - r) \, dx \, dy
\]

where \( r = x \cos \theta + y \sin \theta, s = -x \sin \theta + y \cos \theta \).

This equation is called the Radon transformation. Applying this transformation to the angle range \( 0 \leq \theta < 2\pi \), the projection data are made. This projection method is called the parallel beam projection (solid lines), while there is another method, the so-called fan beam projection (broken lines). To reconstruct the image from projection data, we backproject the projection data in all directions. Actually we perform Radon inverse transformation discretely. There are three methods for the backprojection such as the 2D-Fourier transform method, the filtered back projection method and the convolution method. Here, we use the convolution method since we can choose an appropriate filter function to get a clear image. The projection data are multiplied by filter function \( h(r) \) and we carry out the convolution to get corrected projection data. We can reconstruct the image of \( f(x, y) \) by backprojecting this corrected data (1).

\[
f(x, y) = \int_{0}^{r_{\text{max}}} \int_{r_{\text{max}}}^{r_{\text{max}}} p(r, \theta) h(x \cos \theta + y \sin \theta - r) \, dr \, d\theta
\]

\[
= \sum_{n} \sum_{m} p(n \Delta r, m \Delta \theta) h(n \Delta r)
\]
We use the Shepp and Logan filter function as follows,

\[ h(n\Delta r) = \frac{2}{\pi^2} (\Delta r)^2 (1 - 4n^2) \]

3. Experimental setup

The experimental setup is shown in Fig.2. The energy of an electron beam is 28MeV, macro pulse width is 2.5ns, electric charge is 3.2nC/pulse. The electron beam passed through a glass tube. The glass tube is filled with water and the water is shielded by Ti windows at the both ends. When the electron beam passes through it, we take Cherenkov radiation in water from the side of the glass tube through a collimator. The light signal passes through the collimator, an optical fiber, a photo multiplier with multi channel plate (MCP-PMP), and is measured and processed at a transient digitizer. The diameter and the length of the glass tube are 650mm and 175mm, respectively. The inner diameter of the collimator is 0.1mm and the outer diameter and the length of the fiber is 0.600mm, and 10m respectively. We applied -2kV to the photo multiplier. The xyz coordinate is defined as shown in Fig.2. The measurement plane is vertical to the z axis, and we carried out the fan beam projection by using the rotating mirror. Then, we move the optical equipment along the z axis, to obtain the data for 3D reconstruction. The mirror area is a 18mm square, and the mirror is fixed and centered at the axis of the rotation stage to reflect the light into the collimator. By using this mirror, we could avoid that the optical fiber faces directly, the water tube where X rays are generated, so as to reduce the light noise generated by X ray irradiation in the optical fiber. By taking account of axisymmetry of the water tube, we didn't scan the collimator in the azimuthal direction and scanned the mirror only in the range of ±24°, the step angle is 3°, and the measurement plane is changed by 10mm step from the point of z=19mm to z=119mm. We measured the light noise data by cutting the visible light at the entrance of the collimator by a paper beforehand and subtracted them from all measure data.

Because of axisymmetry of the configuration, we measured only the least necessary data, and assigned them to 31 fan beam projection data in the mirror angle range of ±15° at 72 azimuthal angles around the water tube. Under this assumption, we calculated the reconstruction image. We show the reconstruction image of the distribution of Cherenkov radiation in water as shown in Fig.3. It is the view in the x-y cross section at z=29mm After we reconstructed in the x-y image at each z position, we integrated them with respect to the x coordinate and time, the y-z image as shown in Fig.4. For comparison, we show the picture of Cherenkov radiation taken by a CCD camera as shown in Fig.5. It looks that strongly radiated area in the reconstruction is more widely distributed than in the photograph. It can be attributed to lack of spatial resolution in the x-y plane due to the large radius of the the optical fiber.

![Fig.2: Experiment setup](image)

![Fig.3: x-y cross sectional image (z=29mm)](image)

![Fig.4: Image of reconstruction integrated data along x axis and about time.](image)

![Fig.5: Picture of Cherenkov radiation in water](image)
Next, we show the time variation of Cherenkov radiation in the y-z plane at x=0 as shown in Fig.6(a)–(c). Fig.7 shows the time variation of maximum projection data at z=19mm. It is clear that the electrons lose their energy near the entrance of the electron beam and the resultant emission area is localized there.

In this experiment, we manually positioned the mirror and other optical equipments and it is thought that there are rather position errors. But now we are manufacturing a automatic measurement system as shown in Fig.8. The system has a column made of Pb to cover the body to shield the optical fiber against X rays, and the column has a small window for light extraction into the collimator. It rotates keeping the window to face the mirror. By using this system, we can get fan beam projection data with high spatial resolution quickly. Now, because we use the photomultiplier as the detector of light, the time resolution is limited to nanosecond, but we will introduce a streak camera to enhance the time resolution to picosecond soon.

A 28 MeV electron beam generated by the linac passed through the glass tube filled with water. Then we took the Cherenkov radiation in water by the collimator with the rotating mirror, the optical fiber and the photomultiplier. Using the measured data, we calculated the reconstructed image of each section which is vertical to the beam line by the light emission CT theory. Finally, then we succeeded in getting the 3D image of the radiation distribution with the nanosecond time resolution. We used the convolution method for numerical reconstruction where the Shepp and Logan filter function is used. Hereafter we attempt to enhance both spatial and time resolutions by introducing the 3D automatic measurement system and the streak camera.

Reference

Abstract

Non-destructive profile monitors (NDPM), based on micro-channel plate (MCP), have been developed and installed in both the synchrotron ring and high-energy beam transport (HEBT) line at HIMAC. Beam test using these monitors have been carried out since April of 1995 to investigate a change of vertical beam size in synchrotron and a possibility of observing beam with high energy by one pass. In this paper the measurement system is mainly reported, and the preliminary results are also briefly presented.

1. INTRODUCTION

NDPMs at HIMAC have been studied and installed for following purposes. (1) To investigate a change of vertical beam size of circulation beam during acceleration and extraction at synchrotron, because the measured vertical emittance of the extracted beam is not consistent with the calculated value based on the adiabatic dumping. (2) To monitor the beam profile non-destructively at HEBT during irradiation treatment of tumor. Therefore, two NDPMs have been designed, and installed to the synchrotron ring and HEBT, respectively.

The paper reports the design considerations of the NDPM and the preliminary testing results.

2. DESIGN CONSIDERATION

The NDPM consists of an accelerating electrode of ions or electrons created by a beam, a cascade-MCP with 32ch multi-anode strips and a read out circuit.

2.1 Estimation of output signal level

The expected signal amplitude obtained from a monitor was roughly estimated using the well-known Bethe-Bloch formula. The number of ion-pairs, that can be produced along the unit length of a 290MeV/n carbon beam, is first estimated. In this case, 5.7pairs/cm/Torr is obtained for the beam rotation frequency of 1.5MHz in the average vacuum pressure of 1x10^-9Torr in the ring. Taking these values into account, since the gain of a cascade-MCP and the beam intensity are assumed to be 10^7 and 10^7pps, respectively, the estimated output current per channel is 44nA. In NDPM at HEBT, the output current is estimated at 2.9pA/ch under the conditions of 1x10^-7Torr of the vacuum pressure and 10^7 of MCP's gain.

The estimation suggests that measurement in HEBT needs cascade-MCP to obtain large gain, and possibly worse vacuum condition, in the ring, lower gain is enough for assumed intensity. Nevertheless, cascade-MCP was adopted also for the ring to cover the request for weaker beam.

2.2 Structure of NDPM

Fig. 1 shows a photograph of the NDPM at HIMAC. The NDPM has 7 electrodes, which are arranged to realize a uniform electric-field to accelerate ions or electrons created by a beam. The field was calculated by using the code Poisson as shown in fig. 2. The maximum voltage is ±25kV. The effective area that beam can pass through is 180x75mm^2 for measuring a vertical profile in synchrotron, and 100x100mm^2 for a horizontal beam profile in HEBT. The electrode at the opposite end of the field cage to MCP is made of mesh, in order to use UV-rays for gain calibration of each anode. In both cases, the size of MCP is 55x8mm^2 (Hamamatsu Photonics F4772-01), and the interval between neighboring anode-electrodes is 1.7mm. The output of the MCP was...
operated at 0.5kV negative to the anode strips which are at the grand level.

In the case of ring, the electric field of the NDPM may distort a closed orbit by about 8mm during the injection. In order to correct this disturbance, an additional electrode is installed at just downstream of the NDPM. This correction electrode has a similar structure to the monitor, and is fed high voltage with the inverse polarity by same power supply as the NDPM. In the case of HEBT, however, the correction electrode is not used because an orbit distortion is negligible due to one pass high energy beam.

In order to keep high vacuum in the ring, the NDPM was baked at 200°C for 24hr before installation to the ring, and the resistor of 20MΩ to divide the high voltage to each electrode are equipped outside of the vacuum chamber to remove out-gas sources.

2.3 Read-out circuit and control system

Fig. 3 shows a schematic block diagram for the read-out circuit and control system. In the case of ring, the charge from the anode strip is converted to a voltage with the conversion ratio of 1V/nA, then it is digitized after a 32ch analog-multiplexer. The digitized signal is thirdly stored in a memory. The signal acquisition is repeated in this way for 1.4s at the minimum interval of 10ms. The stored data is transferred to the control computer in the central control room, and finally displayed on a CRT. The local control system is connected to the control computer through GPIB. The operation of the NDPM is normally carried out at the central control room. In the case of HEBT, generated current signal in the NDPM is integrated in the existing read out circuit with exchanging a capacitor from 1000pF to 500pF, which is used for multi-wire proportional counter type monitor[4]

3. PRELIMINARY TEST

3.1 Calibration

UV-rays were irradiated to investigate uniformity in the gain characteristics of MCP. Results of both before beam test and after 300hr beam exposition are shown in fig. 4. As can be seen in fig. 4(a), the uniformity of gain was within ±5% at NDPM in the ring before beam test. In the case of ring, however, since the created electron intensity is somewhat high due to high revolution frequency, the gain seems to become small gradually. It is thus necessary to compensate the gain deterioration. At present, the fluctuation of the gain in each channel is measured by using UV-rays, and it is compensated in the level of software, resulting in a flat response on a CRT. In HEBT, since the created electron intensity is usually small due to one pass beam, such gain deterioration has not been observed yet.
3.2 Profile measurement

As shown in Fig. 5, the beam profiles can be observed in both cases of ring and HEBT under the conditions summarized on Table 1. In the case of ring, signal levels were decreased as increasing a beam energy, because of reduction of energy loss.

When a correction electrode was not used in the ring, a decrease by 20~30% in the beam intensity was seen due to the kick by the accelerating electric field of the NDPM. Such a decrease was compensated by using the correction field. In HEBT, when the supplied voltage to the accelerating electrode is higher than 20kV, an increase in the noise can be found. As long as the vacuum pressure is better than 10^{-7} Torr, this noise remain very small, however the beam profile was not satisfactorily observed.

<table>
<thead>
<tr>
<th>Testing conditions</th>
<th>synchrotron</th>
<th>HEBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam</td>
<td>C^{6+}</td>
<td>Ne^{8+}</td>
</tr>
<tr>
<td>vacuum</td>
<td>1x10^{-4}Torr</td>
<td>3x10^{-5}Torr</td>
</tr>
<tr>
<td>energy</td>
<td>6~350 MeV/u</td>
<td>400 MeV/u</td>
</tr>
<tr>
<td>intensity</td>
<td>5x10^{8}pps</td>
<td>1x10^{9}pps</td>
</tr>
<tr>
<td>MCP gain</td>
<td>5x10^{-6}</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>field voltage</td>
<td>~17kV</td>
<td>~20kV</td>
</tr>
</tbody>
</table>

4. SUMMARY

The NDPMs at HIMAC have been designed and tested. As a preliminary result, they measured the expected beam profile in both the cases of ring and HEBT. Both in the ring and HEBT, the measured output was consistent with the estimation. In HEBT, however, the beam profile was not satisfactorily observed when the vacuum is better than 10^{-7} Torr and the beam intensity lower than 10^{9}pps.

5. ACKNOWLEDGEMENTS

The authors would like to express their thanks to the crew of Accelerator Engineering Corporation for skilful operation of the HIMAC, and to Dr. K. Kawachi, Dr. S. Yamada and the other members of the Division of Acc. Phys. and Eng. at NIRS for their warm supports.

6. REFERENCES

NUMERICAL CALCULATION OF THE ELECTROMAGNETIC COUPLING STRENGTH BETWEEN THE ELECTRODES OF A BEAM-POSITION MONITOR

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Abstract

The PF 2.5-GeV linac is now being upgraded for the KEKB project. A stripline-type beam-position monitor is under development in order to easily handle the beam orbits of primary high-current electron beams for producing a sufficient number of positrons. The spatial dimensions of the mechanical monitor components were decided during its design. In the monitor design, it is particularly important to determine the opening angle of the electrode, because larger electromagnetic couplings between the electrodes generate a larger nonlinearity concerning pick-up signals. The opening angle of the electrode was decided based on a numerical calculation which considered the charge-simulation method. This report summarizes the method and results of the numerical calculation in detail.

1. Introduction

The linac is required to stably accelerate primary high-current electron beams in order to produce a sufficient number of positrons in the KEKB project[1]. The beam-position monitor (BPM) is important in order to easily handle orbits of high-current electron beams so as to suppress any beam break-up generated by a large transverse wake field. A stripline-type BPM was designed in order to perform this function. In its design, it is required to determine the mechanical spatial dimensions of the BPM components, that is, the bore radius, the stripline length, the opening angle of the electrode etc.. The opening angle of the electrode is generally designed from the point of view of the signal-to-noise ratio of the pick-up signals and the electromagnetic coupling strength between the electrodes. That is, although a large opening angle is desirable from the former point of view, it generates a larger electromagnetic coupling between the electrodes through equivalent capacitors, which are only determined by the geometrical configuration of the conductor system. The capacitive couplings between the electrodes are directly related to the geometrical configuration of the conductor system. The charge-simulation method rearranges the charge (Q) as a finite number of imaginary charges, \( q_i \), on the conductor surface. The configuration of the imaginary charges is chosen so as to give an electrostatic potential (V) on the

2. Brief overview of the charge-simulation method

A numerical analysis based on the charge-simulation method is briefly discussed here using a simple example. Two conductor rods and a ground-potential plane are arranged by some geometrical configuration (Fig. 1). The electrostatic potentials and charges on rods #1 and #2 are given as (\( V_1, Q_1 \)) and (\( V_2, Q_2 \)), respectively. Rod #1, #2 and the ground-potential plane are mutually electrically coupled through equivalent capacitors (\( C_{ij} \)).

![Fig. 1. Schematic drawing of a simple three-conductor system comprising two conductor rods and a ground-potential plane.](image)

These parameters can be related by the following formula:

\[
Q_i = C_{i\theta} V_i + C_{i\alpha} (V_i - V_j), \quad (2-1)
\]

\[
Q_j = C_{j\theta} V_j + C_{j\alpha} (V_j - V_i), \quad (2-2)
\]

\[
C_{ij} = C_{i\alpha} \quad (i \neq j, \theta).
\]

Here, \( C_{\alpha} \) and \( C_{ij} \) (\( j \neq 0 \)) are called the self-capacitance and the partial capacitance, respectively. The coupling strength between the rods is given by the ratio of the partial capacitance to the self-capacitance (\( C_{ij}/C_{\alpha} \)). This ratio is determined only by the geometrical configuration of the conductor system. The charge-simulation method rearranges the charge (\( Q \)) as a finite number of imaginary charges, \( q_i \) (\( Q = \Sigma q_i \)), on the conductor surface. The configuration of the imaginary charges is chosen so as to give an electrostatic potential (V) on the
3. Application to the beam-position monitor

The capacitive couplings of the stripline-type BPM are shown in Fig. 2.

Fig. 2. Cross-sectional view of the stripline-type BPM. The equivalent capacitive couplings are also shown inside the pipe.

It is a conventional stripline-type BPM with $\pi/2$ rotational symmetry. The interval between the electrode and the inner surface of the pipe is chosen in order to make a 50Ω transmission line. The opening angle ($\Delta \phi$) of the electrode should be determined in terms of both the signal-to-noise ratio of the pick-up signals and the coupling strength between the electrodes.

The electric field generated by relativistic beams inside the pipe can be treated as a two-dimensional electrostatic field because the field is almost boosted in the transverse direction to the beam axis. Thus, only the electrostatic field is treated in the analysis.

Fig. 3. Segmentation of the beam pipe and electrode surface.

First of all, the surface of the pipe and each electrode are segmented as shown in Fig. 3. The black circles indicate the outline points on the pipe and electrode surfaces, the cross points being imaginary charges. The outline points on both the inner (radius $c=28.5\text{mm}$) and outer (radius $d=32.5\text{mm}$) surface of the pipe are configured in equal ($n$) parts in the azimuthal direction. The electrode surface (inner radius, $a=20\text{mm}$; outer radius, $b=21.5\text{mm}$) is segmented in the azimuthal direction so as to have an azimuthal angle which is equal to the segmentation of the pipe, and is segmented in equal $m$ parts in the radial direction. The coordinates ($x_i$, $y_i$) of the outline points are given as:

$$
\begin{align*}
x_i &= r \cos(2\pi i / n), \\
y_i &= r \sin(2\pi i / n), \quad (1 \leq i \leq n).
\end{align*}
$$

The coordinates ($X_i$, $Y_i$) of the induced charges are given as:

$$
\begin{align*}
X_i &= (r \pm \delta) \cos(2\pi i / n), \\
Y_i &= (r \pm \delta) \sin(2\pi i / n), \quad (1 \leq i \leq n).
\end{align*}
$$

where $r$ indicates the pipe and electrode radius ($r=a+(b-a)/m$), and $\delta$ is the interval between the outline point and the imaginary charge to the radial direction, which must be inside the outline point. The parameter $\delta$ is generally given by the following formula:

$$
\delta = \varepsilon \times f, \quad (3 - 5)
$$

where $\varepsilon$ is twice the interval length between the adjoining outline points and $f$ is a free parameter to be tuned (to be generally chosen within 0.2–1.5). The electrostatic potential ($V_i$) on each outline point can be calculated by superposing the potentials generated by all of the imaginary charges, as follows:

$$
V_i = \sum \nu_i, \quad (3 - 6)
$$

$$
= \sum_{i=1}^{n} P_i q_i, \quad (3 - 7)
$$

$$
P_i = \frac{1}{4\pi \varepsilon_0} \ln \left[ \frac{(x_i - X_i)^2 + (y_i - Y_i)^2}{(x_i - X_i')^2 + (y_i - Y_i')^2} \right] \quad (3 - 8)
$$

where $\nu_i$ is the potential generated by one imaginary charge ($q_i$) and $P_ii$ is the potential coefficient approximated for a line charge with infinite length. The coupling strength ($CS$) between electrodes #1 and #2 is calculated using:

$$
CS = \frac{C_{ii}}{C_{in}}, \quad (3 - 9)
$$

$$
= \frac{\sum q_i}{\sum Q_i}, \quad (3 - 10)
$$
Here, the summations of the imaginary charge ($q_x$ and $Q_i$) are on electrode #1 and on all of the electrodes, respectively.

4. Check of the numerical calculation

The parameter $f$ was tuned so as to produce good symmetrical and constant electrostatic potentials on the electrode surfaces. Figure 4 shows the result of a calculation in terms of the electrostatic equipotential field lines on the use of the parameter $f=1$, which gives the best result. The segmentation numbers (n and m) were also tuned by checking the convergence of the total induced charges on both the electrode ($Q_i$) and pipe surfaces ($\sum Q_i$). A segmentation number of n=120 (to be fixed on the segmentation number m=3) was obtained by a convergence calculation, the accuracy of which was deduced to be ~2% from the convergence. The parameters used in the calculation are summarized in the following table.

Table 1. Several parameters used in the check calculation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe potential $V_0$ (Volt)</td>
<td>0</td>
</tr>
<tr>
<td>Electrode potential $V_x-V_0$ (Volt)</td>
<td>1</td>
</tr>
<tr>
<td>Azimuthal segmentation n</td>
<td>60-140</td>
</tr>
<tr>
<td>Radial segmentation m</td>
<td>3</td>
</tr>
<tr>
<td>Free parameter $f$</td>
<td>0.2-1.5</td>
</tr>
<tr>
<td>The opening angle of the electrode (deg)</td>
<td>60</td>
</tr>
</tbody>
</table>

Fig. 4. Calculated electrostatic potential field lines (solid lines) inside the BPM pipe. The black points indicate the outline points of the pipe and the electrode surface.

4. Results of the numerical calculation

The coupling strength between the electrodes was obtained by using equation (3-10), in which the parameters derived in the section 3 were used. Figure 5 shows the variation (solid line) of the coupling strength as a function of the opening angle of the electrode. The coupling strength is about 11% at the opening angle 60° which generated a 2.3% nonlinearity of the pick-up signals induced by the beams. The induced charges through the couplings are approximately estimated only by taking account of the nearest-neighbor electrode using equation (2-1), as follows:

$$\Delta Q_i / Q_i = \frac{C_{ii}(V_i-V_x)}{C_{ii}V_i}, \quad (4-3)$$

$$= CS \frac{(V_x-V_i)}{V_i}, \quad (4-4)$$

where $\Delta Q_i$ is the charge induced by electrode #2. The pick-up voltage ($V_x$) is determined by the well-known wall-current formula:

$$V_x \propto \frac{a^2 - \lambda^2}{a^2 + \lambda^2 - 2a\lambda \cos(\phi_i - \phi)} \quad (4-5)$$

where $\lambda$ and $\phi$ are the displacement and azimuthal angle of the beam, and $\phi_i$ is the azimuthal angle of the electrode. Figure 5 shows the variations (dot lines) of the nonlinearity ($\Delta Q_i/Q_i$) as a function of the opening angle of the electrode.

Fig. 5. Variations of the coupling strength (solid line) and nonlinearity (dot lines) as a function of the opening angle of the electrode.

5. Conclusions

The opening angle of the stripline-type BPM was analyzed on the basis of the charge simulation method. The coupling strength between the electrodes was ~11% at the opening angle 60° which generated a 2.3% nonlinearity of the pick-up signals induced by the beams.

References


A BEAM SPILL CONTROL SYSTEM AT HIMAC


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Abstract

A beam spill control system has been designed and installed in order to improve a spill structure of extracted beams from synchrotron at HIMAC. The system concept is to optimize a current setting pattern for correction quadrupole magnets (QDS), by utilizing an iterative control based on information of a spill structure from the beam ripple monitor.

1. Introduction

A high accuracy for the dose distribution is required in heavy ion therapy because of its sharp localization and high RBE (relative biological effectiveness). It is thus necessary to obtain a uniform dose with sharp boundary in the lateral direction, and to control precisely the total dose per patient. An irradiation system at HIMAC adopts a beam wobbling method along with a scatterer to obtain such uniformity within ±2% [1]. However, when a frequency of ripple in the extracted beam spill is close to the driving frequency of wobbling magnets (57Hz), the dose uniformity can be lost due to a beat phenomenon.

In a resonant slow extraction at HIMAC, a main ripple of beam spill is caused by a current ripple generated in the power supply of main focusing quadrupole magnets (QF), which is 100Hz. It is monitored with a thin scintillator at extraction beam line. A signal of harmonics synchronizing with the PLL (phase locked loop) was fed forward to the active filter of QF power supply, which was effective to reduce ripple [2]. This observation suggests a possibility of ripple reduction by quadrupole components. A beam spill control system has, therefore, been developed in order to reduce a beam ripple and to secure uniformity by shaping a spill envelope. A set of QDS, originally installed for tune-shifter, is utilized in the system. This paper reports a design consideration and preliminary experimental results concerning the beam spill control system.

2. Design Consideration

2.1. Framework

As mentioned above, basic component of ripple reduction is harmonics of power supply driving frequency. Superpositioned harmonics forms starting point of QDS output current pattern. However, there must be other sources of ripple and also fluctuation in AC line, for example, affect actual ripple output. An adjustment is necessitated for current setting to reflect these effects. It means that our system should have a function of feed forward setting and feed back from ripple signal. Iterative control of current pattern by beam signal would provide long term operability against various fluctuation conditions.

2.2. Optimization Algorithm

The important aspect of the system is an algorithm to optimize a current pattern for QDS automatically by utilizing the iterative control [3] based on information of a spill structure from the beam ripple monitor.

Assumptions on the algorithm is summarized as follows: (1) transfer function concerning the parameters of digital filter and a power supply are known; (2) the extracted beam spill is reproduced at each operation cycle of synchrotron while the beam intensity is fluctuating; (3) gain of the iterative control can be optimized in order to make the control system stable.

The optimization for the current pattern is carried out separately at low (for shaping a spill envelope) and high (for correcting a beam ripple) frequency regimes, as shown in fig.1. At a low frequency regime, an error between the spill signal after the low-pass filter and a current pattern is fed back to QDS after averaging. At high frequency regime, the spill signal after the band-pass filter with phase compensation is fed forward to QDS. Each filter is employed a FIR (finite impulse response) digital filter because of considering stable. The optimization is completed when a root mean square of the error between the spill signal and the pattern becomes smaller than a specified value. Parameters of filters at both frequency regimes as well as the feed-back and feed-forward gain are designed to be adjustable.

2.3. Structure of hardware

A beam spill controller and QDS magnet power supply have been developed to realize the system algorithm. The system structure is shown in fig.2.
Fig. 1 Each algorithm enclosed by broken lines indicates the low and high frequency regimes.

QDS power supply is designed to have bipolar outputs, so that QF current pattern can be the same with or without the beam spill controller system. QDS power supply is operated according to the current pattern that is produced based on the beam waveform.

In the control device of QDS system, VME computers are used to carry out the real-time control. VME computers consist of processors, memories and I/O's in the unit, which use a digital signal processor (DSP). CPU is MVME147S, which is used for the operating and file management, DSP is DSP8031 for filtering and other pattern control function, memory is HIMV210, A/D converter is DSP8112, D/A converter is DSP8124 and clock generator is DSP8240 for making sampling clock of 6kHz. The system realizes fast I/O handling by using a "mtt Link" bus independently. The system has been designed to be maintained by E.W.S., including file management [4]. The sampling cycle of beam waveform is 1200Hz. That of the current pattern to QDS power supply is 6kHz, which was chosen to reduce

Fig. 2. Schematic diagram of spill control system and HSWG.
the peak voltage due to discrete signal.

In addition, QDS magnets and power supply are used to determine the total dose for treatment. They can directly move a horizontal line from the resonance. When the "beam stop" signal comes from the irradiation system, forcing in QDS power supply without software handling directly realizes stopping of a beam extraction faster than few ms.

3. Experimental result and discussions

3-1. HSWG with feed forward

The experiment was carried out first by using only the "Harmonics Superposition Waveform Generator" called "Ripplebasher" [5] for the feed forward to QDS power supply. It is shown in the part enclosed by broken lines in fig. 2.

Fig.3 shows beam spills and their FFT analysis in the operation with and without HSWG, under the condition of $3 \times 10^8$ ppb C$^+$ beam with an energy of 350 MeV/u. The amplitude and phase of HSWG were adjusted to reduce the frequency component of 100Hz at the beam ripple, respectively. The effect for ripple reduction was -14dB at 100Hz.

3-2. Computing system with VME

Encouraged by the experimental result of HSWG, the beam spill control system was tested where HSWG was removed from the system. The upper and lower limit of the band-pass filter were set to 150Hz and 100Hz. The dimensions of FIR filter are 81. The relation between the gain of the beam control system and the 100Hz component at the beam spill is shown in fig.4.

An effect in correcting the beam ripple of 100Hz has been undoubtedly recognized. However, it has not yet been satisfactory. Possible explanations are as follows: (1) the parameters of the band-pass filter seem to be inappropriate; (2) time delay due to the power supply and the load must be taken account; (3) the sampling cycle of the beam waveform seems to be too low. Next experiments will be carried out to shape the spill envelope at the low frequency.

![Fig.4. Relation between the beam ripple of 100Hz and F/F gain (high frequency regime). Points at gain 0 (●) represent the ripple before the correction, while the others (○) show correction effect the system.](image)

Acknowledgment

The authors would like to thank the crew of Acc. Eng. Corp. and to Dr. K. Kawachi and the members of the Division of Accelerator Physics and Engineering at NIRS for helpful discussions.

References.

PB10

A DESIGN OF THE BEAM PROFILE MONITOR FOR THE HIGH BRILLIANCE LATTICE OF THE PHOTON FACTORY

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Abstract
A beam profile monitor by means of an imaging the visible part of synchrotron radiation beam was designed for the high brilliance lattice of the Photon Factory. The design consists extraction mirror for SR beam, adaptive optical system, and focusing system. A Fourier optical analysis of the system has been done. A preliminary result of the monitor will be described.

1. Introduction
The beam profile monitor based on an imaging of the synchrotron radiation will give a visible beam profile, which greatly improves the efficiency of the commissioning of the new high brilliance configuration of the Photon Factory. By digitizing the image data, transverse beam size can be obtained, and with the knowledge of the lattice parameters, various beam parameters such as beam emittance and horizontal-vertical coupling can be deduced. The dependence of the beam size measured with this device on the beam current gives some information on the collective effects. Furthermore, by using a streak camera or photon counting system, the longitudinal profile of the beam bunch can be observed. In this paper presents the design of the optical beam profile measurement system for high brilliant configuration of the Photon Factory. A preliminary result of the system is also described.

2. Extraction of the visible synchrotron light and correction of the thermal deformation of the extraction mirror by use of corrective mirror

Since the focusing system will be placed in the atmospheric environment, which is separated from the accelerator, the visible synchrotron light must be extracted from the ring through a vacuum-tight optical quality window. The window system consist of two optical grass

windows those place in series. The windows are made of BK7 and SF11, those having a surface quality of λ/10 (λ=500nm now). The first window separates ultra-high vacuum of the ring and next high vacuum room of 10⁻⁶Pa. The second widow separates high vacuum room and atmospheric environment.

The extraction mirror must withstand the maximum angular power of the synchrotron lights given in Table 1.

<table>
<thead>
<tr>
<th>Parameters of the bending magnet and angular power of the SR light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend radius</td>
</tr>
<tr>
<td>Dipole field</td>
</tr>
<tr>
<td>Angular power of SR</td>
</tr>
<tr>
<td>Beam size (90° lattice)</td>
</tr>
</tbody>
</table>

An optimum design of a water-cooled Be mirror has been designed and constructed. The outline of the Be-mirror is shown in Fig.2. Nevertheless, a thermal deformation of the optical flatness of the mirror can exceed the tolerance of the diffraction-limited optics such as Rayleigh’s criterion (about wave front error < λ/8).

![Fig.1 The schematic design diagram of the corrective system](image-url)
There may also be the mirror deformation caused by the mechanics of mounting and cooling water. To correct such errors corrective optical system is designed\(^2\). It is basically a feedback system based on an active (corrective) mirror that makes the point response function of the two-mirror system as correct as possible. A schematic diagram of the corrective system is shown in Fig.1. Because of the wave front of the SR light is spherical, the point response between two mirror must be modified by distance of tow mirrors.

Fig.2 Design of the Be-mirror

3. Focusing system

The optical image of the beam is produce by a diffraction limited focusing system placed in the experimental room under the accelerator tunnel. The focusing system consists a ED doublet lens having a diameter of 80mm and focusing length of 1000mm which optimized to the wave length of 550nm. The theoretical remaining longitudinal aberration and modulation transfer function (MTF) on axis are shown in Figures 2 and 3. The designed wave front error is about less than \( \lambda/100 \). So the geometrical aberration by this lens is negligible small and image will be diffraction limited near by on axis. Transverse magnitude is designed to 0.141.

Fig.2 The expected longitudinal aberration of the lens

4. Fourier optical analysis of the focusing system

4-1 Transverse diffraction effects

The finite aperture of the entrance pupil of the focusing system produce a diffraction. With the Fresnel approximation of the diffraction theory and the paraxial lens transfer function, the point spread function (PSF) of the system is a Fourier transform of the generalized pupil function of the system\(^1\).

A wave front error of the lens or mirrors are treated by means of wave front aberration in these approximation, but now they will be negligible small after the corrective system. An amplitude transmittance of the generalized pupil function is modified by a vertical angular intensity distribution of the SR. To create a simple generalized pupil function, an apodization\(^2\) for the entrance pupil of the system is required. The apodization filter must have an anti-amplitude transmittance which corresponds to the vertical intensity distribution of the SR light. This aperture filter will create a flat intensity distribution on the entrance pupil, and the pupil will give a increase of the higher components of spatial frequency. Results of calculation of a PSF with the apodization for the system is shown in Fig.4. The optical parameters of the focusing system are given in Table 2.

Fig.3 The calculated MTF of the lens

Fig.4 The PSF of the focusing system. The side length of the 3-dimensional plots is 119\(\mu\)m.
Table 2
Optical parameters of the focusing system.
All the unit is in mm

<table>
<thead>
<tr>
<th>Surface number</th>
<th>Radius of surface</th>
<th>thickness</th>
<th>glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>source point</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>573.36</td>
<td>8.00</td>
<td>FPL52</td>
</tr>
<tr>
<td>2</td>
<td>-222.3936</td>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-226.5498</td>
<td>5.00</td>
<td>ZSL7</td>
</tr>
<tr>
<td>4</td>
<td>-1212.2</td>
<td>-126.00</td>
<td></td>
</tr>
</tbody>
</table>

The rms widths of the central peak of the PSF are 5.9 \( \mu \)m in vertical and 12.8 \( \mu \)m in horizontal. The image of the beam is given a convolution of the PSF and the geometrical image. Very small vertical beam size as in table 1 must analyzed by lest square fitting method for the observed image by use of PSF. The PSF of the real system must be measured for this analysis.

4-2 Longitudinal diffraction and the field depth

The field depth of the diffraction limited focusing system is dominated by the longitudinal diffraction along the optical axis\(^1\). Figure 5 shows the calculated longitudinal diffraction pattern on axis of the focusing system. From this figure, the field depth around image plane to be 500 \( \mu \)m. Effect of the longitudinal aberration as discussed in section 3 is small enough for this lens. The system appears to be diffraction limited also in the longitudinal axis. The curvature effect in the horizontal beam size of the beam trajectory by this field depth will to be.

![Fig.5 Longitudinal diffraction pattern of the focusing system.](image)

The surface quality of the Be-mirror before mounting to the holder was \( \lambda/4 \). After the mirror was mounted to the mirror holder and applying two times of 150deg backing, the mirror surface was bent permanently as like as a parabola in vertical (no distortion in horizontal). The extraction mirror was installed in the BL-27 in the Photon Factory. Maximum difference between center and edge was about 5 \( \mu \)m. The corrective mirror system for the correction of the extract mirror and the focusing system are now under construction.

A preliminary measurement of a beam profile without corrective system has been done. The normal doublet lens MELLES GRIOT LAC366 is used for focusing system. A result of observed beam image is shown in Fig.6.

![Fig.6 A beam image of the Photon Factory beam current is 2mA.](image)

5. Performance of the Be mirror and preliminary experiment at present Photon Factory

references
Development of a Two-Tap FIR Filter for Bunch-by-Bunch Feedback Systems

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Abstract

Simple digital filter system for bunch-by-bunch feedback systems have been developed. A two-tap FIR filter made of pure hardware system realizes the functions of the phase shift by 90°, the suppression of the static (DC) component and the digital delay of up to a hundred of turns. The difficulties in circuit board, such as the tuning of the time skews or the problem of the long-time reliability, have been solved by the development of custom GaAs LSI s which demultiplex and multiplex the fast digital data coming from ADC. The board has the size of 366.71×460 mm and is controlled through a VME interface. An application of the filter board, the transient memory recorder with 40 Mbytes of memory, enables us to analyze the oscillation modes of a multibunch beam with enough time span.

I. Introduction

For a storage ring which accumulate many bunches with high beam current, such as KEKB or PEP-II, it is very likely that it occurs many strong coupled bunch instabilities both in transverse and longitudinal planes. The methods to analyze and suppress these instabilities have the key to achieve the designed quality of the accelerators.

As the reduction of the sources of impedance, the strongest one comes from the higher order modes in the RF cavities, is essential to suppress the instabilities, some kind of special cavities to make impedance of higher order modes very low will be employed. However, even with these cavities, impedance of some dangerous modes may remain high. Because of the many bunches with small bunch spacing, the frequency view of the instabilities will be complicated and spread over wide frequency range. To cure those unexpected instabilities, we are now developing beam feedback systems with the bunch-by-bunch scheme.

In the bunch-by-bunch feedback system, we detect the individual bunch oscillations separately, shift the phase of the signal by 90°, then kick the beam to damp the oscillation. In this paper we describe the digital filter system developed for KEKB rings which realize the functions of phase shift of any desired value, DC suppression and adjustable digital time delay. Related parameters of the KEKB accelerators are listed in Table I and are used without further explanations.

II. Selection of the filter

As the longitudinal front-end detects the position of a bunch in our case, it is necessary to shift the phase of the signal by 90° with the filter. The static (DC) component of a position signal, which will be a function of the relative position from the head of a bunch train, has no meaning and should be rejected from the feedback signal because it spends expensive feedback power in vainly. As the speed of a signal in a circuit or in a cable is far slower than that of a beam, feedback signals must wait the bunch re-arrival at the kicker after about one revolution of the bunch.

The great progress in the digital circuit technology, such as the speedy evolution of the digital signal processor (DSP), enables us to design complicated digital filter with considerable speed. It is completely programmable and has amazing flexibility. We can change the code dynamically even in the operation period without spoiling the function of the filter. Nevertheless, the present processor is not capable to handle the signal from the ADC alone. Demultiplexing and parallel processing with many DSPs is necessary. Moreover, in many cases we should employ the down sampling technique to reduce the number of the DSPs.

Another approach, which we will employ for KEKB rings, is to make the simplest digital filter with the fast hardware logic circuits without down sampling technique. F. Pedersen of CERN has proposed the hardware two-tap FIR scheme for the filter. As shown in Fig. 1, it has only two taps (-1) and (+1) at -270° and -90° of the oscillation. The frequency response has peaks at f s, 3f s, and has zeros at 0, 2f s, ... The passband around f s is wide. We expect no filtering effect for noise component but for the DC. It is not a problem because we have measured the S/N of the detected signal from the ring and found very low noise components. The phase shift and

![Figure 1. Tap positions for the 2-Tap FIR filter.](image-url)
the time delay are tunable with the selection of the tap positions with keeping the time between the two taps.

The difficulties of the filter lie on the complication of the high-frequency digital circuits. It accesses memories three times (one write and two reads) within one data period, in our case, 2 ns. This access speed is completely unreachable without demultiplexing the digital data in many parallel lines. Demultiplexing part is a fairly complicated circuit which needs very skilled treatments on the design and tuning of the time skew of many lines and the selection of the chips with same characteristics. The difficulty in the final multiplexing process is also a severe problem. The reliability of the board will be fairly doubtful. Making this filter with the combination of existing products seems to be impossible.

The difficulties have been solved by the development of custom LSIs to demultiplex and multiplex fast digital data. The small chips contain high speed circuits which would occupy large area with skilled treatments on the board. The maintenance-free chips enable us to use dense memories of CMOS technology and ensures high reliability for the board.

III. Custom LSIs

The circuit design and fabrication of the custom LSIs for the fast data demultiplexer (FDMUX) and the fast data multiplexer (FMUX) was made by Oki Electric Industry Co. Ltd. Table II shows the main specifications of the LSIs.

<table>
<thead>
<tr>
<th>FDMUX</th>
<th>FMUX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>0.5μm GaAs DCFL</td>
</tr>
<tr>
<td>Function</td>
<td>1:16 x 4bit 16:1 x 4bit</td>
</tr>
<tr>
<td>Integration</td>
<td>~1.5k gates ~1.7k gates</td>
</tr>
<tr>
<td>Max. Clock freq.</td>
<td>&gt; 700MHz</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>3.3V and 2.0V</td>
</tr>
<tr>
<td>I/O</td>
<td>PECL and Lv-TTL</td>
</tr>
<tr>
<td>Power consump.</td>
<td>2.5W 1.7W</td>
</tr>
<tr>
<td>Packaging</td>
<td>136pins ceramic QFP</td>
</tr>
</tbody>
</table>

Table II
Main specifications for FDMUX and FMUX.

A. FDMUX

FDMUX demultiplexes 4 bits pseudo-ECL (PECL) signal up to 700 MHz to 16 channels x 4 bits of Lv-TTL signal. Here, PECL means the signal level of shifted by +2 V from the ordinary ECL level and the Lv-TTL means the reduced high level (3.3 V) TTL signal. By combining the two FDMUXs, we can create a 1:16 demultiplexer of 6 bits easily using the built-in synchronizer. The timing signal is also used to synchronize the FDMUX and the FMUX. All 16 channels 8 bits data are output simultaneously. It also offers two kinds of basic timing signals of Lv-TTL for the use of the downstream circuits. These basic timing signals will be useful and enough for many applications.

B. FMUX

FMUX multiplexes 16 channels x 4 bits of Lv-TTL signal to 4 bits PECL signal. Same as FDMUX, we can use 16:1 multiplexer with 8bits. It offers basic timing signals of Lv-TTL and PECL levels.

Figure 2 shows the bottom view of the FDMUX (GHDK4211) and FMUX (GHDK4212) chip.

Figure 2. Bottom view of FDMUX (GHDK4211) and FMUX (GHDK4212)

IV. Design of the filter board

Figure 3 shows the block diagram of the filter board. The size of the motherboard is 366.71 mm x 460 mm, where prior size corresponds to the triple height board of the VME bus. On the motherboard, there are FDMUXs, FMUXs, a DAC, field programmable gate array (FPGA) chips for the address control. There are 16 slots of connectors on the board for the memory/subtractor daughter board. An ADC is also mounted on another daughter board.

A. ADC and DAC

We have a few candidates for the ADC which works under system clock of 508 MHz and has an enough analog bandwidth. We adopted a MAX101 of MAXIM, which works 500 MSPS with an 8 bit accuracy and have 1.1 GHz of analog bandwidth. It has a 1:2 demultiplexer in the chip so there are 2 channels of outputs.

We have more candidates of DAC for our purpose. We have chosen a TQ6122-M of TriQuint which works up to 1 GHz with an 8 bit accuracy and have a 2:1 multiplexer in the chip.

Because of the demultiplexer in MAX101, we will use 4 FDMUXs and 4 FMUXs on the board. The output of the ADC are therefore demultiplexed with 32 channels. The system clock (255 MHz) for upper 16 channels (A) and lower 16 channels (B) are supplied from the ADC. Each 16 channel works simultaneously.

B. Memory and ALU daughter board

Each channel handles 160 bunches for the case of KEKB rings. We use two sets of ring memories (A and B) per each channel to reduce the memory access from three (one write and two read) to two (one write and one read). Data from FDMUX is written in both memories in the same timing with different memory address. Because the time period of the data output from FDMUXs are about 64 ns, the use of CMOS SRAM with access speed (WE) of 12 ns ensures us enough time margin. As it is necessary to
accumulate at least 100 turns of revolutions per a bunch, total memories needed amounts to $5120 \times 100 \times 2$ bytes.

We use a FPGA with the function of an subtractor. It also contains a bit-shift mechanism that shifts the output of the subtractor from 0 to 3 bit upward. It enables us to change the gain of the filter up to 20 dB dynamically.

C. Address controller and interface

We must control three addresses pointers for memory access. One is the write address (WAB) that works $508.8 \text{ MHz}/32 = 16 \text{ MHz}$. Other two addresses are used to point the 90° (RA) and 270° (RB) previous data for the bunch to feedback. We can set the address shifts of (RB-RA) and (WAB-RA) through a VME interface. Needless to say, the value must be multiples of 160 for the correct feedback. The difference between WAB and RA should be selected to tune the time delay of the feedback signal so as to have a maximum gain. We can change the time delay with the 2 ns step.

This board is now under fabrication and will be completed by the end of September, 1995 and will be tested under the operation at TRISTAN-AR.

V. Application to beam-dynamics studies

The mother board is capable to the application of a transient memory recorder by replacing the memory/subtractor daughter board with a dense memory board and by replacing the address control FPGAs. In our design, the maximum memory we can mount on the board will be about 40 MB. For the KEKB rings, it will accumulate 8192 turns of bunch positions for all 5120 bunches. Combining the memory board and the feedback system enables us to measure the growth of the instability very clearly. This memory board will be completed by the end of 1995.

VI. Summary

For the circular accelerators that accumulate many bunches with fairly high beam current, the bunch-by-bunch feedback system will play a great role in the suppression and in the analysis of the instabilities. On the development of the bunch-by-bunch feedback system, however, there lie many difficulties concerning to the bandwidth of the system. In KEKB rings, the use of the custom LSIs for demultiplexing and multiplexing the digital data enables us to develop the pure hardware two-tap FIR filter system without downsampling technique, on one board of triple-height of VME. We expect that the board has good reliability because of the packaged high frequency circuits in the LSIs. The feasibility of the board will be tested with the feedback experiment at TRISTAN-AR in these years.

References

Abstract

Feasibility of the prototype digital filter for the longitudinal bunch feedback system for KEKB rings has been examined in TRISTAN-AR. Detected longitudinal positions for individual bunches were digitized and recorded on memories. The hardwired FIR filter with 2 tap was used to shift the phase over 90° and to suppress the unnecessary DC component. The feedback signal was supplied to beam in the form of the phase modulation of accelerating cavities. The feedback system worked with the loop gain up to 30 dB. Detuning the RF cavities to excite single bunch Robinson instability with the feedback working, the instability was completely suppressed even under the growth time of 0.3 ms.

I. Introduction

In a storage ring which accumulates many bunches with high beam current, such as KEKB rings, strong coupled-bunch instabilities with many modes will occur both in transverse and longitudinal planes. To cure the instabilities, we are now developing bunch-by-bunch feedback systems for KEKB accelerators\(^1\). In the longitudinal plane, a digital filter of two-tap FIR scheme will be used to shift the phase of the detected position signal over 90° and to suppress the unnecessary static (DC) component. Prior to the fabrication of the filter complex with full function, which will work for 5120 bunches with 508 MHz of system clock, we have examined the feasibility of the two-tap FIR scheme with a quick-prototype board. Using the RF cavities as the kicker, the longitudinal feedback loop was closed for single bunch beam in TRISTAN-AR at 2.5 GeV. Feedback parameters such as the loop gain or the damping time was measured successfully. Related parameters for TRISTAN-AR at the feedback experiment are listed in Table I.

II. Experimental Setup

A block diagram of the longitudinal feedback system prototype at TRISTAN-AR is shown in Fig. 1. The system consists of the position detection part, phase shifter filter part and kicker part.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>377.26 m</td>
</tr>
<tr>
<td>Beam current</td>
<td>1 ~ 4 mA</td>
</tr>
<tr>
<td>RF frequency</td>
<td>508.5808 MHz</td>
</tr>
<tr>
<td>RF voltage</td>
<td>1 ~ 1.5 MV</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>640</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>0.025 ~ 0.032</td>
</tr>
</tbody>
</table>

Table I. Main parameters for TRISTAN-AR with the prototype longitudinal feedback
The linear bunch current dependence of the output, that means the current dependence of the loop gain, is not so severe problem because the growth rates of the instabilities will also depend on the bunch current and will be slower than the linear dependence in many cases.

B. Two-tap FIR filter prototype board

In our feedback system, the signal process (phase shift by 90° and elimination of static (DC) offset) is performed with a 2-tap FIR filter realized by a simple hardware system. As the algorithm of the 2-tap FIR filter has been described elsewhere\(^1\), we will give only a short explanation on the filter. The response of the FIR filter has the form of the linear combination of the data which have been obtained as a time series, \(x(1), x(2), \ldots\). The 2-tap filter has only two terms the coefficients of which are 1 and \(-1\) so the output has the form of

\[y(n) = x(n_1) - x(n_2),\]

and has the favorite frequency of \(1/2(n_1 - n_2)\). By suitably selecting the tap positions, \(n_1\) and \(n_2\), that means by selecting the address-shift of the memory, we can tune the center frequency and the group delay of the filter.

The quick-prototype board we have made does not use digital demultiplexing technique. Therefore it works only below the bunch frequency of 6.4 MHz. This board consists of a 125 MHz ADC (AD9002) in the front-end and a 40 MHz DAC (SONY CXD1171) in the back-end circuit, full-adders (SN74HC283) and two sets of memories (1Mx6832U1IP-15) in the digital filter. The size of the memory is 4 k bytes in total. The board is packaged in a 1-span CAMAC module. The tap positioning of the filter is set through the CAMAC command very easily. Figure 2 shows the modulation input for the beam and the output of the filter. An example of the frequency response is shown in Fig. 3.

![Figure 2. Synchrotron oscillation modulation signal for the beam (upper trace) and the output of the filter (lower trace). The clock of the filter was \(8 \times f_{\text{rev}}\), though there was only one bunch.](image)

C. Feedback kicker

Because the longitudinal kicker is still on the design stage, we used the accelerating cavities as a longitudinal kicker. In AR, there are two RF stations, EAST and WEST, each of which has 4 APS cavities of 9 cell structure. Our kicker was 4 cavities of the WEST station. We modulated the phase of the accelerating RF signal at the low level circuit. The feedback filter and the phase shifter at WEST station was connected with a coaxial cable of length of about 140 m. As the passband of the cavity is fairly narrow, we can only use single-bunch beam for the feedback experiment.

III. Result and discussion

At first, the longitudinal oscillation was excited artificially with the phase modulation of the EAST cavities. Under the condition, we tuned the tap positions of the filter to maximize the loop gain of the feedback. The tap position was chosen to be \(n_1 = 30, n_2 = 182\), where the clock frequency of the filter was \(8 \times f_{\text{rev}}\). The difference of \((182-30)/8=19\) agreed with the synchrotron tune of \(1/2f_s\), \(\sim 20\) clearly. With increasing the analog gain, it began to excite an oscillation with some other frequencies than the synchrotron frequency which virtually limited the gain of the loop. The maximum gain of the feedback was about 20 dB. Note that this gain does not show the maximum gain of the feedback loop for instabilities because the energy of the excitation was supplied continuously under the condition.

Next, the longitudinal oscillation was excited by intentionally shifting the resonant frequency of the cavities to arise the single-bunch Robinson instability. By tuning the resonant frequency shift, we controlled the growth rate of the instability. With setting the tuning angle of the accelerating cavities to be \(+10°\), we could excite constant longitudinal oscillation without losing the beam. Figure 4 shows the beam spectrum before and after the closing feedback loop at the detuning angle of the RF cavities of \(+10°\).

![Figure 3. An example of the frequency response of the filter.](image)
We measured the oscillation also by a turn-by-turn position detection system. The front-end circuit of the measurement system was equivalent to that of the feedback system but completely independent of the feedback loop. By this system we observed the change in the oscillation around at the very moment of the feedback on/off. Examples of the observed data are shown in Fig. 5. We have caught the growth of the oscillation with the maximum growth time of about 300 turns or 0.36 ms.

When we change the RF voltage, the shift in the synchrotron frequency occurs that loses the gain of the feedback system. Our filter worked well with the RF voltage 1 MV and 1.5 MV by selecting suitable tap positions for each operation. This shows the good flexibility of the feedback system under various conditions.

IV. Summary
We have examined the feasibility of the bunch-by-bunch feedback scheme with the two-tap FIR filter quick-prototype in TRISTAN-AR. The frequency performance was measured in a bench and expected characteristics were obtained by the quick-prototype board.

The experiment of the longitudinal feedback has also been performed. The kicker for the system was not an actual one but the accelerating cavities. The oscillation was safely damped by the feedback system and the damping time of, roughly, 0.1 ms was obtained. Based on the experiment, we have confirmed that the 2-tap FIR filter system is powerful enough for the signal processing of the longitudinal bunch feedback system.

We are now installing a longitudinal kicker with the bandwidth of 125 MHz with the expected shunt impedance of about 1.1 kΩ at TRISTAN-AR. With the power amplifiers that can supply up to 0.5 kW to the kickers, we expect the maximum feedback voltage of about 900 V/turn. This value corresponds to the damping time of about 7 ms at the saturating amplitude of ΔE/E=0.1%.

References
Recent Improvement of Ripple Performance in HIMAC Synchrotron Power Supply

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ABSTRACT

Ripples in the HIMAC synchrotron power supply and the admittance of the load were measured and confirmed to be small as 3 ppm for the Quadrupole Power Supply right after the commissioning. Further improvement was focused on the 50 Hz and 100 Hz ripples which were major component deteriorating the spill. By re-tuning the power supply, we could reduce the ripple to a level of 0.3 ppm. The study of the relation of the ripple and the beam spill revealed that the fluctuation of the beam spill is affected by the ripple in Bending magnet power supply in addition to that of the Quadrupole. After finding this fact, the beam spill became more uniform in routine operation by re-adjusting the Sextupole and Quadrupole strength. Encouraged by this performance, the Bending magnet power supply is upgraded by adding the active filter and the new DCCT. With this improvement the ripple became at a level of 0.2 ppm and the beam spill was improved.

I. INTRODUCTION

In a synchrotron the current of the magnet string has a trapezoidal form. Because of the resonant beam extraction, the ripple content should be a few ppm or less at the flat top. The basic ripple frequency $f_b = 1200$ Hz of the power supply is given by the frequency of the power source($f_0 = 50$ Hz) multiplied by the number of thyristors(24). The Fourier analysis of the ripple voltage also gives multiples of $f_b$. Another ripple with the frequency of $2nf_b$, is caused by imperfections of the transformers and by variations in the triggering of the thyristors. Furthermore oscillatory spike voltages are induced across each thyristor. The spikes are modulated by low frequencies and can also contribute ripple at frequencies as low as 100 Hz. Other problem associated with them is the production of noise spikes in equipment located in the neighborhood. In spite of various efforts, the reduction of spikes and ripples has been unsatisfactory for the requirement of the tolerance of the third order resonant extraction. To fulfill the requirement for beam extraction, in most of the accelerator in operation, additional mean such as spill feedback controller must be applied.

In the HIMAC synchrotron power supply, a new approach is taken.

II. HIMAC approach

We started from the proposition that the load of the synchrotron power supply is a cascaded string of the magnet inductance, its resistance and the capacitance between the excitation coil and the iron yoke. Typical magnitude of the capacitance of a Quadrupole magnet of a standard size is estimated to be a few nF. The iron yokes are assumed at a ground potential. At the HIMAC the yokes are connected by the earth line. The schematic diagram is depicted in Fig.1. This model circuit is a six terminal circuit that has parallel and series resonance. Due to

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1 Hyogo Prefectural Government
2 Hitachi Ltd.
3 AEC, Accelerator Engineering Corporation
4 Dokkyo University, School of Medicine
5 RCNP, Osaka University
The ripple component of 50 Hz and 100 Hz were the main component seen in the output of the power supply. The fluctuating component of the beam spill appeared to be 100 Hz. 100 Hz is caused by the imbalance of the phases of the AC power line. But 50 Hz can not be generated by the imbalance. These frequencies can not be damped by the low pass filter as the cut off frequency of both mode is chosen to be 75 Hz. Lowering the cut off frequency helps in reducing the ripple but slowing the response of the trapezoid pattern and deteriorating the tracking accuracy between the Quadrupole and the Bending magnet. We decided to strengthen the active filter of the Quadrupole by adding the bandpass filter of 50 Hz and 100 Hz for the individual fine tuning of the phase control. The bandpass filter worked fine as expected and the ripple was reduced. Through the careful study of the 50 Hz source, we found that the 50 Hz is originated from the DCCT. Although the relative amplitude of the DCCT was small as 50 ppm, it has been a performance limiting factor to go below ppm level. With bandpass filter the relative ripple content became at a level of 0.3 ppm for the time. The main frequency of the beam spill changed from 100 Hz to 50 Hz. We found that the 100 Hz was a superposition of the 50 Hz ripple of two different sources whose phases are shifted, namely from the power supply of the Focusing Quadrupole and that of the Bending magnet. The remained 50 Hz originated from Bending magnet power supply. The change of tune of the beam is speculated to come indirectly through Sextupole magnet that compensate the chromaticity. This was verified that by reducing the Sextupole strength, the better quality of the beam spill is obtained. With the evidence that the present beam spill is affected by Bending magnet, we decided to reduce the ripple current in the Bending magnet by adding the active filter of the similar type of the Quadrupole power supply. The inductance of the Bending magnet load is six times larger than that of the Quadrupole and supplying larger power is required. Typical reduction of 25 dB at 100 Hz was achieved after an elaborate adjustment of the cut off frequency of the high pass filter that is incorporated in the active filter circuit. Typical example of the frequency spectrum at 600 MeV/u with and without active filter are shown in Fig.2, where 50 Hz is reduced by 28 dB and 100 Hz is 32 dB. The small 50 Hz ripple is also due to the installation of the Holec DCCT. Its linearity and the stability are checked and implemented into the ACR feedback circuit.

![Fig.2 Ripple voltage spectrum of the Bending magnet at 600 MeV/u without (upper graph) and with (lower graph) active filter.](image)

IV. ACKNOWLEDGMENTS

We gratefully acknowledge the support of the members of the division of accelerator physics and engineering and AEC. The author thanks the enlightening discussion with Prof. Y. Irie of KEK.

V. REFERENCES

[1] M. Kumada, to be published in NIM.
a presence of the capacitance to the ground, the incoming current $I$ to the load and the outgoing current $J$ from the load are not identical as contrast to the ordinary model of without the capacitance to the ground. The difference current $I-J$ flows back to the neutral point of the thyristor bank. The potential at the neutral point develops and is known as a common mode voltage. In the case of the grounded neutral as in the HIMAC this potential is small. In order to estimate the magnitude of the ripple current we need to know the resonance frequencies and the admittance. If the spike frequency or the ripple frequency overlap the resonance of the magnet string, the ripple current is enhanced. To avoid the overlap, the knowledge on frequency characteristic of the load is required. No previous analysis was done in the past. Computer simulation is time consuming. By applying eigenvalue technique, we found that six terminal circuit can be reduced to two set of orthogonal four terminal circuit. We found as a special case decomposition into the normal mode and the common mode is possible. The normal mode voltage and current is defined as $U+V$ and $I+J$ and the common mode voltage and current is defined as $U-V$ and $I-J$ respectively. With the mode separation, the normal and the common mode admittance $Y_{ac}$ of the magnet string, which we model as a ladder circuit, can be written down simply as,

$$Y_n = Y_{no} \coth(N\xi_n)$$  \hspace{1cm} (1)$$

$$Y_c = Y_{co} \tanh(N\xi_c)$$  \hspace{1cm} (2)$$

where $Y_{no}$ and $Y_{co}$ is the characteristic admittance of the ladder circuit, $\xi_n$ and $\xi_c$ and the are expressed by

$$\xi_n = \cosh^{-1}(1 + Z_{nc} Y_{nc})$$  \hspace{1cm} (3)$$

$Z_{nc}$ is the mode impedance of the magnet and $Y_{nc}$ is the mode admittance expressed by the capacitance to the ground. Above equations are simple yet very powerful to fully describe the magnet string of resonant feature. The analytic solution in time domain is possible by Inverse Laplace transformation. The admittance of the HIMAC magnet string was measured and the validity of the present model was verified. The current ripple is estimated using the admittance from the voltage ripple of the power supply. At the HIMAC the resonance can be suppressed by the bridge resistor parallel to the magnet. This resistor also helps to bypass the ripple and spike current of the magnet.

With a finding of the presence of two orthogonal mode in the load, the model of the mode separation is extended to the power supply side. Direct consequence of the preceding argument is the addition of the common mode low pass filter. Without this filter, the common mode ripple voltage is directly applied to the magnet string. Furthermore the common mode current in the HIMAC Bending magnet string is considerably reduced as the magnetic field because of the separate connections of the upper and the lower coils due to the nature of the parallel direction of the current.

In this way, in the HIMAC, most of the ripple voltage of the normal and common mode is suppressed. The relative ripple current of the Quadrupole with active filter was 3 ppm and that of the Bending magnet without active filter was around 5 ppm right after the initial operation. It appeared that the beam spill did not reflect the small ripple content the study was continued.

III. Improvement at the 50Hz and 100 Hz ripples

$$Y_e = Y_{co} \tanh(N\xi_e)$$  \hspace{1cm} (2)$$
CONTROL SYSTEM FOR RCNP CYCLOTRON


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Abstract

The control system of the AVF-cyclotron is upgraded in the summer, 1995. As the result we can operate the beam from the ion source to the target by using the unified control system. At the same time we upgrade the power supplies of AVF-cyclotron.

1. Introduction

The control system of the AVF-cyclotron has been working for more than twenty years. Recently it becomes difficult to maintain the control system for the operation. The AVF-cyclotron has important role as the injector of the Ring-cyclotron. In order to supply the stable beam and makes the operation of cyclotron more simply, it is necessary to unify the control system of AVF-cyclotron and Ring-cyclotron.[1] We shall replace the control system in the summer, 1995. At the same time, we shall update the power supplies and the RF system of AVF-cyclotron. These projects are expected to get higher quality of the accelerated beam for the high resolution measurements. Furthermore, we have some plans of feedback systems for the beam acceleration. The unification of the control systems is also important to construct feedback systems for the cascade accelerators. The summary of this project is as follows.

2. Computer system

The control system of AVF-cyclotron is connected to the network system of the computer-complex of the Ring-cyclotron facility. (Fig.1) The Universal Device Controller (UDC) controls the devices and collects the status of devices.[2] There will be 60 UDCs for the new control system of AVF-cyclotron. The UDCs are grouped according to the role so that the variety of UDC becomes minimum. A new Group Control Unit (GCU) is devoted to control the devices of the AVF-cyclotron and the ion-source. The performance of the main computer (SCU) is in a limit only for the operation of Ring-cyclotron. Obviously we expect the present computer is not suitable for the coming operation after the replacement of the control system. The main computer will be upgraded from micro VAX 4000/200 to micro VAX 4000/500. We shall make good use of the past main computer of the RCNP VMS cluster computing facility.

3. Power supply

The power supplies of AVF-cyclotron facility have been operated by setting the reference voltage with the pulse motor deriving system. This pulse motor system may be one of reason for difficulty of maintenance and instability of the accelerated beam. We shall reconstruct and update all of power supplies of AVF-cyclotron facility. The reference voltage for the power supply is set by the 16 bit digital-to-analog convertor and the output current is monitored by using the 12 bit analog-to-digital convertor.

4. Beam diagnostic system

The pulse motor deriving systems, such as the beam diagnostic system, are not replaced in this project. The UDC simulates the preset control sequence of the driving circuit. The output from the beam diagnostic system is measured by using updated current...
amplifier and transferred to the computer control system. The results of beam diagnosis are shown on the graphical display as used in the Ring-cyclotron facility.

5. Interlock system

The interlock system of AVF-facility has been very complicated and it is very important for the radiation protection. While we shall not update the interlock system in this project avoiding unexpected error in the interlock system, the new control system collects the information of the interlock system and informs the status of the cyclotron for the operators. This is a characteristic advantage of the computer control system.

6. Console

There are twin operator consoles for the Ring-cyclotron facility. When we unify the control system of AVF and Ring facility, the devices in the AVF facility can be controlled from the operator console of the Ring facility. However we must perform extensive operation to tune up the Ring-cyclotron using both of operator consoles. Therefore the twin operator consoles may not be enough for the future operation of cyclotron. We shall construct new console of the control system (Fig.2) The console of Ring-cyclotron is closely connected to the main computer by using special electric circuits. Already these special electric circuits give rise to difficulties of the maintenance of the control system. By this reason we shall purge these special electric circuits as much as possible from the new console. We adopt personal computers for the new console which are simply connected with the main computer through Ethernet.

Reference


Fig.2: View of new operator consoles.
Team development system for accelerator control software on the WAN

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1. Introduction

Highly efficient microprocessors have recently become available at low cost, thus improving the available semiconductor technology. As a result, for example, microprocessors such as the 80X86 and Pentium are improved versions of equipment used for personal computers before. The CPUs (Alpha-AXP, PowerPC, R4000 and etc.) are being manufactured with new architecture, such as RISC.

New operating systems (OS), such as WindowsNT and OS/2, are running on highly efficient CPUs. They have powerful graphical user Interfaces (GUI) with almost the same ability as that of the UNIX workstations.

It has thus become possible to build medium-size accelerator control systems based on personal computers. This was difficult in the past because the OS had no communication functions among standard applications. In accelerator control, it is often possible to use commercial products, except in special cases. When it is urgent to build a control system with few bugs, it is necessary to choose the reasonable software from among commercial packaged software. However, some programs must be made in-house for accelerator control. We therefore analyze the domain structure of the accelerator from the control side, thus necessitating an understanding of the structure of the objects and their relations.

LNS and KEK PF-Linac have started a new project for accelerator control. We have thus analyzed the domain of the accelerators from a mutual viewpoint, and have established a project to find some common object between them. One useful possibility could be a productive development of programming.

We therefore arranged a development environment using a wide area network (WAN) for the following purposes:

1) An analysis of the accelerator domain from the control side (using the OMT technique).
2) A cooperative verification of the developed program.
3) An efficient information exchange.

2. Features of WindowsNT

There are several kinds of OS that are used on personal computers. Generally, OSs during the early stage were made depending on the CPU architecture, and worked only for a specific CPU. Now, since there are several kinds of CPUs available for PCs, it is necessary to choose a reasonable OS for accelerator control that doesn't depend on the CPU architecture. We have therefore adopted WindowsNT for building this team-development environment.

WindowsNT has various good points that do not exist in personal computer OSs. We discuss those features which we should adopt for accelerator control.

1) Support for existing MS-DOS and Windows-based applications.
2) Processor-independence (It works on various CPU).
3) The network function is equipped as a standard.
4) The security function is enriched.
5) Preemptive multitasking.

With such specific features, switching over to the new system while inheriting conventional property is comparatively easy.

3. Team development environment

We have decided to use personal computers with WindowsNT, and to build a team development environment (see Fig. 1). Also, the specifications of the personal computer used for its purpose are given in Table 1. WindowsNT, itself, provides a multi protocol network...
function as the standard, and we faced few problems concerning the local-network environment. The network environment could be built only by installing an OS in each personal computer only. Also, as for the WAN connection, it became possible by setting some parameters.

Generally, WindowsNT is connected on NetBeui protocol. Routers on the WAN is protected from protocols, except for TCP/IP. Therefore, to connect between WindowsNTs on WAN it is necessary to use TCP/IP. Several of its files are explained below. Descriptions of the HOSTS file and the LMHOSTS file are necessary for the setting. The HOSTS is the file used to determine a computer name and an IP address in Internet. LMHOSTS is the file which refers to the computer name and IP address at the LAN manager.

Below is an example of these files.

Contents of HOSTS file.

<table>
<thead>
<tr>
<th>IP Address</th>
<th>Name</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>130.87.xxx.xxx</td>
<td>PF-Linac</td>
<td>#</td>
</tr>
<tr>
<td>130.34.xxx.xxx</td>
<td>LNS-Linac</td>
<td>#</td>
</tr>
</tbody>
</table>

Contents of LMHOSTS file

<table>
<thead>
<tr>
<th>IP Address</th>
<th>Name</th>
<th>extension</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>130.87.xxx.xxx</td>
<td>PF-Linac</td>
<td>#DOM:KEK</td>
<td>#</td>
</tr>
<tr>
<td>130.34.xxx.xxx</td>
<td>LNS-Linac</td>
<td>#DOM:THKLNS NT</td>
<td>#</td>
</tr>
</tbody>
</table>

We have carried out a test concerning connections between LNS and KEK PF-Linac.

A single-domain connection was made during an early stage. Then, a connection test among different domains was successfully. The models used to build each domain server are the following three kinds:

1) Master domain model.
2) Multi master domain model.
3) Complete trust domain model.

The single-domain model and 1) or 2) listed above don’t match our system, because all organization are located in the distance and are independent. Therefore, this time a complete trust domain model has been used. This model can be realized by setting the trust relations among each other. As a result, the resource that each has becomes capable of being shared.

4. The performance

The performance is measured based on the above-mentioned environment. Incidentally, the OS of the new version became smaller in memory size, and the speed was improved. We used WindowsNT Client3.5 and WindowsNT Server3.5 as an OS. The performance was measured in terms of the speed of writing and reading of data to the local disk and the remote disk over the WAN and the LAN. Since a measurement with the WAN and the LAN environment is influenced by the network traffic, it extracted the average value measured every hour. This result is shown in Fig.2.

It became clear from the results of the measurements that WindowsNT is equal to or more than twice as fast as Windows3.1. Also, it depends on the condition, we have recognized the result that LAN is faster at writing than the local disk of Windows3.1. The speed which is running on the WAN was about 5-20Kbyte/s, because it has bottlenecks on the routes of the Network as well as various
routers. The routing of the Network is shown in Fig.3.

Many people are presently using the Internet and Network, the traffic is thus quite crowded. To improve this situation, the backbone on the mutual network connection must be made thick by one who manage network systems. For us, this result is satisfactory, except when using multimedia, where we believe that it isn't sufficient.

scheduling functions, which in the commercial software have been used for efficiency of information exchange.

5. Operations

The possible operations on the WindowsNT WAN are listed below. OMT is the main application program, which runs on the WAN between LNS and KEK PF-Linac. OMT is being used for our team to develop in accelerator control programming(2).

1) File sharing by the mount with an identical volume.
2) Sharing of the Database servers.
3) Mail.
4) Schedule management.

A way of information exchange is necessary for us who are working at distant locations from each other. Mail and

6. Conclusions

A team-development environment using WindowsNT was completed on the WindowsNT Network. With this, a reinforcement of cooperative development in programming is possible, and a cooperative-development analysis for the accelerator domains will be promoted. The network environment of WindowsNT is excellent, and the performance is sufficiently practical, except for the communications required in real time, and a great deal of information communication.

7. References

Graphical Representation of Objects’ States for the PF Linac Control System

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Abstract
This paper describes our approach for creating a graphical representation of the states of accelerator objects. For every object which needs to display its state dynamics we create a chart element. Any changes in the object state are immediately represented on the chart of this object. We use the objects dependencies facility supplied by Smalltalk to keep track of the objects’ states changes. This allows us to remove any graphics related features from the Object Model of the accelerator. Thus, the Object Model can be developed separately and reused in a number of applications.

1. Introduction
Accelerator control requires a convenient graphical representation of the present state of the objects that the accelerator contains. For instance, there could be the possibility either to display accelerator sections, indicating the section state, or, a more detailed representation also including section’s objects. For accelerator subsystems, such as the vacuum system and rf system, it would also be convenient to represent the subsystem hierarchy, including the subsystem objects in order to gather information about their states. Usually, in the present control systems graphical routines are mixed with both code and data for the control, this makes it difficult to change the graphical part of the system without reviewing of the control data and code. In this paper we represent an approach that divides a visual representation from model. The Smalltalk language that we used (VisualWorks) provides convenient possibilities for such division. These are object dependencies concepts and application of this concept for the user interface creation: MVC (model view controller) concept [1, 2]. Two separate system part, model and interface, are represented below.

2. Model
The key point concerning the accelerator domain model is ControlObject class (model object class). This generic system class is used for all system objects representation. The accelerator, subsystem and subsystem objects are all ControlObject class instances. The ControlObject class defines a number of properties described in [4]. However, for the present consideration only the “state” property is important. This property contains symbolic values representing the current object state. The state examples are: “normal”, “alarm” and so on. The object state corresponds to the “state” variable of a ControlObject instance. Since this variable is updated every time some object value is changed, it always contains the object state valid at the moment. Further, an instance of ControlObject can have a set of dependent objects. The standard dependencies facility supplied by Smalltalk guarantees that if the “changed: #aspect” method is invoked for the object, every dependent receives an “update: #aspect” message. The aspect parameter is used to separate independent object modifications and to suppress
redundant updates [2]. The Dynamic model for the change-update method together with the Object Model for the ObjectChart (explained below) and ControlObject classes are represented in Fig. 1. We use Rumbaugh method notation [3].

3. Interface

The objects' states are represented in the chart (Fig. 3). A chart element contains fields for the name (top) and state (bottom). The state field dynamically represents the model object state. In the simplest case, it could be only a text string, like "normal", and "running"; however it is possible to map some states to pictures.

4. Update method

For a graphical representation of the accelerator object's states we create the ObjectChart class. An ObjectChart instance corresponds to an accelerator chart element; it is responsible for the dynamic representation of some object's state. The model object reference is contained in the "object" variable of the ObjectChart. To assign and get this variable we use methods "object:" and "object" correspondingly. When we set a new object to display by sending the "object:" message, the receiver is registered as a dependent of this object.

If the model object "state" variable is changed through the "state:" message, this object sends the message "changed: #state" to itself. That causes the message "update: #state" be sent to object dependent: ObjectChart. Having received an update: #state message the ObjectChart instance retrieves the state variable value from the model object which is stored in its "object" variable. After that, ObjectChart draws on the user terminal picture or text corresponding to the present model object state.

This method allows us to remove any messages responsible for graphics from the domain model. The domain model can be developed independently, and multiple graphical modules representing different aspects of its state can be easily connected to it. It is also possible to reuse graphical interfaces with different models. It is supposed that this approach is capable of reducing the system development and maintenance costs.

5. Conclusions

The method represented above could be used to display a large variety of control system aspects. First, it can represent accelerator subsystems with the "normal" or "alarm" states for every subsystem object. Also, it is possible to collect information about states of the accelerator sections. In this case the state resumes a summary of all the section objects states.

Although in this paper we allow only one object connection to an ObjectChart class instance, in the future we will discuss the possibility for a multiple objects connection. With multiple connections the problem of states priority appears. Another way to resolve the multiple objects problem is to create composite object in the domain model representing the objects aggregation.

6. References

7. Figures

change state/state(newState)

ControlObject
state

entry/changed(#state)

update(#state)

ObjectChart
state
entry/getNewState

update(#state)

ObjectChart
state
object
test

object:
update:

ControlObject
state
state:
state:
changed:

Fig. 1

States' Chart

RF system
Normal

Klystron #1
Normal

Klystron #2
Normal

Klystron #3
No object

Fig. 2
HIGH ACCURATE TIMING SYSTEM FOR THE SPRING-8 SYNCHROTRON

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Abstract

For the single bunch mode operation, the timing system for SPring-8 synchrotron is required high accuracy (low jitter) and high resolution. Prior to the timing system for SPring-8, we made a test timing system as a prototype. It achieved target specifications (jitter a. 20ps, resolution a. 20ps). In this paper, we'll report about the construction and some acquired data of the test timing system.

1. Introduction

SPring-8 has a "single bunch mode". In the single bunch mode, the injector (linac and synchrotron) injects 8 beam pulses into the storage ring. To make a single bunch, the beam pulse #2-#8 have to be injected at the timing when the bucket (which the beam pulse #1 is in) comes to the injection position of the storage ring.

The storage ring has 2436 buckets and the synchrotron has 672. So, the bunch in the synchrotron rounds 3 and 5/8 turns in the time the bunch in the storage ring rounds 1 turn. It means that for the effective single bunch injection, 8 beam bunchs have to exist in interval of 84 buckets (1/8 of 672) in the synchrotron. (Fig.1)

2. Requirement for the timing system

For this single bunch mode operation, following conditions are required.

(1) RF phase of the synchrotron and the storage ring are synchronized.

(2) Eight bunchs in the synchrotron are located in same interval correctly.

The 1st requirement is achieved, because the rf signal of the synchrotron is provided by the storage ring system. The 2nd one is satisfied if beam extracted from the linac is injected into the designed bucket in the synchrotron. The pulse length of the beam from the linac is 1nsec and the length of the bucket in the synchrotron is approximately 2nsec. (It's equal to the wave length of rf (=508.58MHz).)

So, the injection timing (from the linac ro the synchrotron) has to be adjustable in 100psec order timing with accuracy around 1/10 of the bucket length (2nsec).

3. Construction of the test system

Prior to the product for SPring-8, the test timing system was constructed. Specifications are:

Input signal
One-cycle signal (1Hz)
Master clock (508.58MHz)
Reset signal (1Hz)

Output signal
Linac trigger signals (8 pulses)
Synchronized start pulse (for monitor)
Synchronized clock (for monitor)
Jitter < +/- 100 psec
Resolution: 100 psec
Function: Generate 8 linac trigger signals (from
the linac to the synchrotron) every
16.7 msec triggered by 1-cycle signal.
(16.7 msec: Cycle of the linac extraction)
To adjust "linac trigger signals" with low jitter and
high resolution is the target of this test system. Major
components of this test systems are:
(1) Synchronize circuit
Make synchronized clock signals from external
clock (508.58 MHz) and one-cycle signal.
(2) Counter circuit
(a) Bunch interval counter
Generate "bunch interval clock" every 84
synchronized clocks. 1 cycle of this clock (6.05MHz)
is equal to the interval time of the bunch of the
synchrotron in the single bunch mode.
(b) One-turn counter
Generate 8 signals which represent bunch number
(#1-#8) which beam from linac will be injected into.
This signals are rotated from #1 to #8 switched by
"bunch interval clock". These signals are used in the
logic circuit to make linac trigger signals. This
counter has its own delay-line for its fine
adjustment.
(c) Turn-number counter
(d) Injection-number counter
Both counters ((c) and (d)) are decreased by "bunch
interval clocks". And they are also used in the logic
circuit.
(3) Logic circuit
Generate 8 linac trigger signals. There are 8 logic
circuits (#1-#8) and each logic circuit represents the
order of linac trigger (#1-#8). To select logic circuit
#1-#8, counter (b),(c) and (d) are used.
(4) Output circuit
Final sequence of the system. It generates 10 nsec
width pulses at the monomulti vibrator. It has a
delay-line. Range of this delay-line is selected from
0.1 nsec to 6.3 nsec by 0.1 nsec step. (It's selected by
dipswitches.) The resolution of this system depends on
this delay-line.
The feature of this timing system are:
(1) Frequency down converter isn't used, it minimizes
jitter and gets fine resolution.
(2) One high speed counter (ECL element) and some
cascade linked counters are used. These counters select
the logic circuit and control the timing of the linac
trigger pulse. This construction also minimizes jitter
and high accuracy.
(3) A delay-line is used in the output circuit. This
makes the adjustment of the delay timing easy.

![Fig.2 Synchronize circuit](image1)
![Fig.3 Construction of test timing system](image2)
4. Result of test system

To confirm reliability, miscounts were checked and jitter through the timing system was measured.

(1) Miscounts

The measurement system is shown in Fig.4. With a universal time-interval counter, time intervals between every linac trigger signals are measured. If there are N-times miscounts, time difference between maximum data and minimum data will be:

\[ N \times \text{cycle of clock} = N \times \left( \frac{1}{508.58\,\text{MHz}} \right) = N \times 1.966\,\text{nsec} \]

Acquired data (Table 1) are less than 1.96nsec. It means there were not any miscounts.

(2) Jitter

A measurement system is shown in Fig.5. A digital sampling oscilloscope is used for the measurement (connect "linac trigger signal" to the trigger channel and master clock (508.58MHz) to the channel for measurement).

Acquired data is shown in Fig.6. The width of the sine-curve represents jitter. Jitter is about 20psec after fine adjustment of the delay line, so this system satisfies the required specification for the single bunch mode operation.

5. Conclusion

The required specifications for timing system are achieved through the test system. The accuracy is around 20psec, and the resolution is less than 200psec. Now, the timing system for SPring-8 synchrotron are under manufacturing. The element for the delay-line in the output circuit will be changed in this machine. And this change will make the resolution higher up to 20psec.
VME BASED CONTROL SYSTEM FOR THE TRISTAN CORRECTION
DIPOLE POWER SUPPLY

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Abstract

The control system for the TRISTAN correction
dipole power supply was improved to cure the beam loss
during the energy ramp. The main part of it is based on
VME standard. This paper describes the system
configuration, the software and the operation with the beam.

1. Introduction

The TRISTAN MR has 520 correction dipoles named
correctors to control a closed orbit. Their power supplies
are placed in four buildings around the ring. Initially the
power supplies was controlled by a specially designed
Power Supply Control Module (PSCM) with Motorola
68B09 and driver units[1,2]. The module calculates the
current of the power supplies $I_j$ according to the formula

\[ I_j = A_j I_0 + \Delta I_j, \]

where $A_j$ and $\Delta I_j$ are constants which are
indexed by a power supply no. $i$ and $I_0$ is a wave
form (i.e. "pattern") in an accelerator cycle. $I_0$ is similar to
the current of the main dipole power supply and common
to all power supplies. In the energy ramp $I_j$ was uniquely
determined from the injection and flat top current because
free parameters were two, $A_j$ and $\Delta I_j$. For several years
after the commissioning of MR this system functioned
enough for the energy ramp. As the beam current
increased it was found that the beam lifetime at injection
was very sensitive to the RF voltage, the betatron tunes
and the vertical closed orbit. And the beam loss during the
energy ramp became troublesome. One of the cause of the beam
loss was considered the deviation of the closed orbit
from the optimum one at injection. This led to us to
develop a new control system of the correction dipole
power supply to control the closed orbit more finely.

In the new system the PSCM was replaced with a
VME based system while driver units remain unchanged.
We employed VME system because of its flexibility in
changing a software.

2. System Configuration

Fig. 1 shows the schematic diagram of the system.
The system consists of three parts, 1)VME system,
2)Control computer Hitachi HIDIC and serial CAMAC
system and 3)Driver units.

The VME system is Hitachi Zosen's Portable VME
system (HIMV-P254/N). The system consists of a rack
with 7 slot back planes, a CPU board Motorola MVME-
147S, a 100MB hard disk drive and a floppy disk drive.
The operating system is PDOS from EYRING Co..

The CPU board calculates the current of the power
supplies and write it to a digital output (Hitachi Zosen
HIMV630). The output-signals are transferred to the
driver unit through 21 parallel lines (12 bits data, 7 bits
address and 2 timing signals). The data of 72 power
supplies are sent sequentially on the lines. The timing
sequence of data transfer is emulated by a software so as
to fit the driver units. VMEbus interface, KSC 2917-Z1A
is used to communicate with the HIDIC through memory
modules. The clock interrupt, which is controlled by a
HIDIC, initiates a program. The maximum repetition rate
of the clock is 50Hz. So the CPU calculates and outputs
the data every 20ms. The interrupt is accepted by FORCE
SYS68K/IPIO-1.

HIDIC and serial CAMAC system are a part of
TRISTAN control system[3]. The 128KB memory
modules in the CAMAC crate, which are accessed from
both HIDIC and VME CPU, are used for the
communication between them.

The driver units are the part of original control system
with PSCM. They accept the data from the digital output
and distribute the data to each power supply.

3. Software

A.VME system

A device driver was written for VMEbus interface
KSC 2917-Z1A. This supports CAMAC 16 bit single
transfer and CAMAC 16 bit DMA transfer. The data-
transfer-time is about 50 μs/word for the single transfer
and 3.5 μs/word for the block transfer. The device drivers
of FORCE SYS68K/IPIO-1 and HIMV630 were prepared by
Hitachi Zosen.

Two functions are written as application software for
1)Cyclic operation and 2)Current-setting at static states.

1)Cyclic operation

A function is called in cyclic operation of MR such as
the energy ramp, the squeezing of the beam and the
setting current from flat top to injection. The cycle goes
by synchronously with the clock pulse. Whole accelerator
cycle is divided into 14 periods by 15 nodal points. The
time, which is measured by the number of the clock
pulse, and current at each nodal point is stored in a
"clock-current table" in the memory module. The current
of a power supply $I(t)$ at a clock $t$ is calculated as

\[ I(t) = \frac{I_0(t) - I_0(t_{n-1})}{I_0(t_{n}) - I_0(t_{n-1})} I_0(t_{n}) + \frac{I_0(t) - I_0(t_{n+1})}{I_0(t_{n+1}) - I_0(t_{n})} I_0(t_{n+1}) \]
during the energy ramp and
\[ I(t) = \frac{t - t_N}{t_{N+1} - t_N} I_N + \frac{t - t_{N+1}}{t_{N+1} - t_N} I_N^{+1} \]
in remaining periods, where \( t_N \) and \( t_{N+1} \) are the clocks at nodal point \( N \) and \( N+1 \) respectively. The clock \( t \) satisfies the condition \( t_N < t < t_{N+1} \). \( I_g(t) \) is the current of the main dipole power supply at clock \( t \). \( I_B \) at each clock is stored in the memory module.

The total processing time, which includes the above calculation, the data transfer from/to the memory module and the output of the data, is 8ms for 130 power supplies.

2) Current-setting at static states

Another function is called at injection and flat top. The current is changed from present set point to new point in the total steps \( N_{\text{step}} \). This function is initiated \( N_{\text{step}} \) times by the clock interrupt. At each step the function calculates the current by linear interpolation of present and new set point.

Fig. 1 Schematic diagram of the control system for the TRISTAN correction dipole power supply.
Programs are prepared for 1) Management of the clock-current table and 2) Control of the clock interrupt.

4. Operation

In the operation 11 nodal points are used during the energy ramp. The nodal points are denser in low energy region than in high energy region because the beam loss occurred very often below 1 GeV. Following procedures are taken in the beam tuning for the energy ramp.

1) The current which corresponds to the kick by the correctors at injection is set to all nodal points.
2) The closed orbit at injection c.o.inj is measured. Then the energy ramp starts.
3) The energy ramp is suspended at the clock corresponding to a nodal point and the closed orbit c.o.nod is measured. This procedure is repeated for all nodal points.
4) An orbit correction program calculates the kick of the correctors $\{\Delta \theta\}$ to correct the difference between c.o.nod and c.o.inj, where $\{\ldots\}$ means the list of the kick by the correctors. The $\{\Delta \theta\}$ at each nodal point is stored in a file.
5) The kick at each nodal point is calculated as $\{\theta_{inj}\} + \{\Delta \theta\}$, where $\{\theta_{inj}\}$ is the kick at the injection. The current corresponding to $\{\theta_{inj}\} + \{\Delta \theta\}$ is set in the clock-current table.
6) The procedure 2) and 3) are repeated to confirm that the closed orbit is really corrected.

Table 1 shows an example of the result of the above correction. $\sqrt{<\Delta y^2>}$ is the r.m.s. of the difference between the vertical closed orbit at injection and that at a nodal point. Average $< >$ was taken over the beam positions around the ring. Nodal no. 1 corresponds to the injection stage.

Actually, the closed orbit in the energy ramp being suspended is different from that in the energy ramp being in progress. But we have no way to measure the instantaneous closed orbit because the measurement takes about a minute in the present beam position monitor system.

We can not state clearly the effect of the correction on the beam loss. On one occasion the beam loss disappeared after that. On another occasion, in addition to the correction, another ways such as the change of RF voltage, the change of the betatron tunes and the optimization of the closed orbit at injection were needed to cure the beam loss.

Above correction is made at the beginning of a long operation period. Once $\{\Delta \theta\}$ is determined the procedure 5) is taken before every energy ramp because the closed orbit at injection is corrected to a standard orbit at every beam fill. Usually the re-determination of $\{\Delta \theta\}$ is not necessary for three to four months despite the change of the closed orbit at injection.

5. Acknowledgements

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6. References

Control System of SPring-8 Injector LINAC

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Abstract

In the present accelerators, it is necessary for us to construct the advanced control system. Because the beam specification is requested to get higher quality. The SPring-8 injector LINAC, will be completed in 1996, has also some requirements and future plans which except for the injection. Whatever requests, the control system have to keep up with an efficient improvement. It means that the control system must be constructed a flexible one. In this case, we have carried out the LINAC control system in accordance with the present state of the Software Technology [1].

In this paper, the status of our software project which accord with the Software Technology is described.

1 INTRODUCTION

Figure 1 shows the present state of Software Technology. The system of until 1990's have discussed one's problems which like as follows.

- **Closed System Environment:** The hardware and the software in the system depend on the supply of industrial makers. On these system, it is so robust that we have a hard time of maintenance.

- **System Design using Process Standard:** In many case, revisions happen in the software process logics, but most of processes intertwine with other processes. So revisions of software are difficult. We have a hard time of maintenance, again.

- **Inconsistent Project Team:** The system that is imagined by designers, programmer and coordinators differ from the ideal system that is imagined by users. When the system operate, many users will complain about it. Until the system operate, the project staff have to play a designer, programmer, coordinator and user. In the 1990's, the project have to be a elitism.

Now, the Object Engineering has become the mainstream. This is good approach to the above problems. And it introduces Data Oriented Approach (DOA). This approach is based as follows.

- The fundamental data in the system is stable. Compare with the system process, almost one's data do not rearrange. It is effective that the data is standardized.

Our software project suits the using DOA. Because the LINAC component process, called Object, will replace many times for the beam requirement, however almost fundamental LINAC data do not rearrange. We have carried out the LINAC control system in accordance with DOA.

2 DATA ORIENTED APPROACH

2.1 DOA Framework

Figure 2 shows the framework of DOA. (a) is the general DOA framework for business, and (b) is SPring-8 LINAC DOA framework [2]. At the general, many problems in the system are able to be stored on a operation. However our project is new one, so it is difficult to expect and pick up all the system problems. (Whatever happens, on the commissioning etc., the system problems have to be recorded and be reflected in next revision.) On DOA, the modeling is based on the picked up problems. Our DOA is shown next section.
2.2 LINAC System Modeling

In general DOA framework, "Cooperative Modeling" means examining of the system problems, and make a rough system modeling. It means the same as "LINAC System Modeling" in our DOA. We think that the our control system problems as follows.

- **Computer Network speed and reliability:**
  The LINAC control data have to send quickly and reliably.

- **High portability of hardware and OS:**
  The system have to be quick to adapt to the trend of hardware and OS on VME's.

- **Flexible control system:**
  Whatever requests, the control system have to keep up with a efficient improvement.

As a solution to these problems, we got three keywords in the process of "LINAC System Modeling". They are, Communication Process [3], C language Device Drivers [4], and Object Oriented Programming (OOP) [5]. At the follows modeling, they are modeled the details.

2.3 LINAC Machine Modeling

This modeling make the keywords the details.

- **Communication Process:**
  Assuming that Linac is constructed by similar simple components, we got unification command of constructed all devices. That is SPRing-8 LINAC machine Control Commands (SCC). Further, every behavior of all devices is also standardized in SCC. We think that SCC is the most stable data in our system and SCC is the standardized message for communication between objects. So, whatever we start to think, SCC is based on one's discussion.

For Network speed, we selected the connectionless type Network protocol. The connectionless type service(UDP/IP) has smaller over head, and it is faster than connection-type(TCP/IP) service in our traffic condition. But it will happen that transport error, loss of packets and mistake, because of the case of error check in UDP/IP. It is necessary to reinforce the error check. So it motivated us to develop the SPRing-8 LINAC machine Control Datagram (SCD) protocol. The Communication Process play to send SCC through the our Network protocol SCD. And the Communication Process is interface of EWS and VME.

- **C language Device Drivers:**
  When the VME CPU board power and Operation System (OS) do not reach the user's requirement, the system have to be quick to adapt to the trend of hardware and OS on VME's. We must consider high portability of hardware and OS. Figure 3 shows the example of modification of CPU boards. If Device Drivers of constructed VME system are written by Assembler language, when CPU boards are modified high power CPU, all Device Drivers have to be also modified. Because Device Drivers by Assembler language correspond only one CPU. We tried Device Drivers by C language. So that, when CPU boards are modified high power CPU, we will modify only an interface part by Assembler language. The system will get high portability of the hardware and OS.

- **Object Oriented Programming:**
  For the expansive and efficient at the system, OOP is adopted. First, we design the Super Class "MACHINE" that is core of Object. Figure 4 shows the Super Class "MACHINE" and the Sub Classes of it. Main attributes of "MACHINE" are the "parameter and status" and the "Behavior". The "parameter and sta-
"status" means the operation elements of Object, and the "Behavior" means the transitional status of Object standardized by SCC. So that, the Super Class can recognize SCC. The Super Class is inherited to Sub Classes.

These Object is constructed on VME software which like figure 5. As the LINAC hardware component and Object in the VME are in a one-to-one ratio, if the LINAC hardware component, GUN etc., is replaced, Object in the VME is also replaced.

### 2.4 Prototyping and Test

At our system using DOA, the modeling designer, coordinator and programmer is not a same person. So the designer showed prototype software which is reflected modeling. The programmer read the prototype source software, and understand its modeling concepts. At the same time, the designer and coordinator explained to the programmer the constructed LINAC devices and its operation. The programmer understand the user's concepts, too. This flow repeated several times. The software that is imagined by programmers became more and more like the designer's image.

### 3 CONCLUSION

The software project in our system, it is quite large, should carry out the using DOA.

We have SCC which base on our common concept. It is getting easy to model the system. And, we could make efficiently the software which is imagined by designer and coordinator. When the operation start, the system will happen many problems and troubles, because of new system. However the system will be able to correspond flexibly. Next step, we have to model for database in accordance with DOA.

### 4 REFERENCES

Analysis of the PLC Object Model in the PF Linac

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Abstract
Device controllers (front end) for the KEK PF Linac, which has been operated for more than ten years, had to be renewed, because there is no longer support from hardware manufacturer. To reduce maintenance costs, device controllers are planned to be replaced by PLC (Programmable Logic Controller). Investigations launched in the late 1990s for the PLC have carried out in order to make sure of the I/O stability and network possibilities. In this paper, the software for the PLC is discussed based on the OOP concept.

1. Introduction
An Object oriented approach to a PLC control(device control) system analysis and design was adapted to the Linac. The old console system has a graphic display written using FBHG (Fujitsu High grade modular Basic). It has not been very simple to change the display and it's programs, which were written in structured FBHG. To change the conventional language to the new OOP language is a big paradigm shift, and there are two aspects which are good and not good. One aspect is high productivity at OOP, though more learning cost for users is needed. We are therefore providing a top class which can inherit objects for users without any programming on the GUI windows. Users can make a control and display windows very easily and quickly by just copying a visual object from it's mothers class inheriting method and properties. After naming the object and changing some properties if necessary, it can be run as a user's program.

2. About the PLC
The performances of the PLC is almost good enough for controlling the magnet power supplies, vacuum systems and klystron modulators as a slow speed control. Mostly, Since PLC can be connected to Ethernet these days, it is now possible to be controlled from computers, even though each maker has its own network. In the PF linac, the stability was actually measured and compared with the products of a couple of makers. Although the PLC is not for a high-speed multi-purpose machine interface, DAC and ADC modules are stable enough for magnet control. This PLC commercial product has been commonly used in chemical plants and other wide fields. The price is cheaper than other interfaces, like VME or CAMAC, and maintenance is more easy.

3. PLC networking and speed
The PLC which we have selected has two CPUs: one is for I/O, and the other is for communications. TCP/IP and UDP are available protocol used to communicate with other computers on Ethernet. The PLC has its own programming and tools inside, and allows itself to be an intelligent controller using a ladder program. For all channel scans on MS windows3.1 with a pentium 90MHz CPU, 10 to 20 refreshes are proceeded. That is a sufficient scan speed for an operator when he adjusts the magnet current or other. In the system of the PLC and host computers, the PLC is the bottle neck at communications specified in a data/command transfer. The host computer has several device-control network segments, which are managed in serial; there would be no collisions in it's communication packet.

4. GUI object model
The common classes for linac control were analyzed and implemented using MS Visual C++ on Visual BASIC based on OMT (Object Making Technique) [2,3]. In the accelerator domain it is possible to be defined in two major classes as the device class and the generic class. The device class may have several derived sub-classes; the other super classes, like communications, components and other related classes. These classes were developed as a control pack which appear on the toolbox for Visual Basic when it is in the interpreter mode.

— 304 —
The basic model of top classes and its relations are shown in figure-1.

5. Device class of the Linac

Device class; klystron, magnet, vacuum, gun, monitor and others are defined and coded as a super class on the control pack. The instances (real object) are derived in the GUI windows from its control pack: for example, the magnet class has its sub class (such as Q-magnet, STC-magnet and Bending-magnet). Each device class may use a PLC object for communicating between them. It is defined so that the PLC class is related the other super class.

6. PLC class

PLCs are produced by several companies, and there are no standards among the manufacturers. A PLC support many I/O modules; such as DI/O, DAC, ADC and IRQ-module. The PLC is the super class, and the I/O modules are defined as belonging to the sub-class. The PLC top class can communicate to the PLC communication class. These PLC classes should be installed on the device layer. In the PF Linac, device classes are set on the Human interface layer, and the device class of the GUI should communicate with PLC device class.

7. Implementation

It is being planned to install the PLC for the Linac device controller, which will be connected with about 400 sets of magnets and 200 sets of vacuum systems and 60 sets of klystrons which are slow devices in control. In October 1995, a prototype is going to control the vacuum system at the 2nd sector of the Linac. In advance to the hardware system, software development has completed its first version based on the Object models shown in the OMT. Since Visual BASIC has a simple inheritance system, a Mother class has been coded using visual C++, and was made as *.VBX tool on Visual BASIC. Visual BASIC has limitations in memory size and execution time when there are many objects derived from the mother class. PLC and other objects are shown in figure-2.

8. Results and conclusions

Sufficient speed to control the magnet current setting was achieved based on Ethernet communications between PC and PLC. There are a reasonable number of PLC connections we can run in series because of PLC communications speed. We could actually make standard class for the PLC and GUI device object or class. The standard class brings out a nice reusable object, which makes the control system very flexible. OOP also gives users an easy way to make modification and to produce a highly productive control system for accelerator users or machine operators.

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Control system of a high energy beam transport system of HIMAC


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Abstract
The control system of the high energy beam transport system of HIMAC consists of a UNIX computer and a large scale interface system. Lengthy procedures, such as start-up or shutdown all the devices, can be done by only one command followed by sequential procedures in the interface system. Man-machine interface is concentrated on a console to operate easily. Total system eventually realizes the simplified operation and highly reliable performance. In this system, however, a special operation is required because of radiotherapy.

Introduction
The Heavy Ion Medical Accelerator in Chiba (HIMAC) is a complex of an injector linac cascade, two synchrotron rings, a high energy beam transport system and an irradiation system [1,2]. Each system is called subsystem, and is controllable independently. Another computer system, a supervisor system, is monitoring all the subsystems, and also working as an interface between the sub-systems.

Beams extracted from the rings are transported to four irradiation ports of three therapy rooms, and three experiment ports through the high energy beam transport (HEBT) lines. The constituents of the HEBT system are 16 bending magnets, 69 quadrupole magnets, 39 steering magnets, their power supplies including those for the suppression coils for residual magnetic field and correction coils, 30 beam monitors, 16 vacuum units, 16 NMR sets and many other devices. The HEBT control system was required to have functions of simplified and rapid operation of the devices, software interlocks to keep patients safe and highly reliable performance because of a medical machine. The medical use also requires a special operation related with beam irradiation for treatment. In this paper, features of the system and its operation are reported.

The HEBT control system
The control system is divided into the main computer system and the interface system as shown in Fig.1. MELCOM70-MX5700II (Mitsubishi Electric Corporation) is in use as the main computer. The interface system, called MELTAC-RIO system, connects the computer and most devices of the HEBT. The computer has other interface ports of GPIB and PIO. GPIB and PIO are used for communication with NMR devices and with an interlock system, respectively. There are two sets of console as man-machine interface. These consoles are corresponding to beam lines from the upper and lower rings, respectively. Each console has 20” and 14” displays, and 3 rotary encoders. The displays are equipped with touch-panels. The computer system is connected to the supervisor system with LAN (Ethernet). Radiation dose is monitored not only at the irradiation control room but also on the consoles of the HEBT system through a LAN installed exclusively for monitoring the dose.

The interface system, MELTAC-RIO, consists of a communication unit and a group of distributed remote I/O (RIO) units. The communication unit works to arrange and manage data flow from the computer to RIO, and vice versa. Data from RIO is reformatted to be transmitted to the computer cyclically in every 200msec interval. The transmission cycle of 200msec is enough fast to monitor the system status. The computer interrupts the communication unit to send the commands (IT-message) to operate the devices. The computer can also send a file including parameters such as maximum and minimum currents, and repetition number for initialization, thus complicated procedure can be handled. The communication unit is connected to the computer with a data bus, MDWS-60.

Ten RIO units are distributed in this system as shown in Fig.1. Each unit is connected to various devices through three kinds of data bus, PIO or MELSENET or I/O bus. The PIO connects the magnet power supplies and the relevant RIO units. DI and DO cards mounted in the units receive and transmit digital signals based on contacts or open collectors. In order to initialize the magnets, the RIO units sequentially control

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- 306 -
the power supplies according to the parameters of the initialization as mentioned above. Maximum 30 magnets can be initialized at the same time by only one command. Therefore, an arbitrary number of magnets can be initialized in short time by repeating the command. Local control panels (LCP) are distributed on the floor of the beam lines for the operation of the beam monitors and vacuum system, because it is necessary that the beam monitors and the vacuum system are locally operated in their maintenance. The devices of the vacuum system are controlled by a programmable logic controller (PLC) installed in a LCP. Four LCP’s are linked in a circle, and the master LCP is connected to the RIO unit with the MELSECNET. The MELSECNET is exclusively designed for communication of the PLC. In case of the beam monitors, the DI and DO cards and buffer memories are mounted in the LCP’s, not in the RIO units. Only master cards are installed in the RIO units to communicate with the LCP’s through the I/O bus.

This MELTAC-RIO system deals with a large amount of data such as magnet currents, magnet status, pressure in beam ducts, beam profiles, and of operation information such as power supply ON/OFF commands, magnet initialization commands and so on. In order to realize rapid operation and monitoring, this system are cyclically processing data under a single task software using cpu’s of i-80386. The cycle runs every 100msec interval in the communication unit, and 50-70msec in the RIO units. The data is transmitted between the RIO units and the communication unit cyclically through data buses, called SE-BUS3. There are three groups of the SE-BUS3, in order to reduce the amount of data of each data bus, and realize a rapid response. The data buses are summarized in Table 1, all of them being Mitsubishi
Table 1 Summary of Data Bus

<table>
<thead>
<tr>
<th>Data Bus</th>
<th>MDWS-60</th>
<th>SE-BUS 3</th>
<th>MELSECNET</th>
<th>I/O BUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium of</td>
<td>Coaxial cables</td>
<td>Optical fiber</td>
<td>Optical fiber</td>
<td>Optical fiber</td>
</tr>
<tr>
<td>Transmission</td>
<td></td>
<td>cables</td>
<td>cables</td>
<td>cables</td>
</tr>
<tr>
<td>Transfer Rate</td>
<td>15.36Mbps</td>
<td>2Mbps</td>
<td>1.25Mbps</td>
<td>1Mbps</td>
</tr>
<tr>
<td>Method of</td>
<td>Cyclic File</td>
<td>Cyclic</td>
<td>Cyclic</td>
<td>Polling/Selecting Method</td>
</tr>
<tr>
<td>Transmission</td>
<td>IT-Message</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Electric Corporation standard. Note that the cyclic data process and data transmission can make a maximum load of the computer independent of the amount of data, and realize stable and reliable performance.

Operation and control

Beam tunings for the horizontal or vertical course can be done independently at each console. The devices of the HEBT system are hierarchically classified with "systems", "groups" and "blocks", as in other sub-systems 3). A block unit uniquely corresponds to a beam course. So the block classification makes it easy to switch the beam course from one to another.

The operation of starting up the whole HEBT system for new beam conditions is performed with the help of an operation parameter file. The file includes the setting values such as excitation currents of the magnets, high voltage of the beam monitors. In this operation, the magnets are initialized before excitation, and the beam monitors become ready to use by being applied suitable voltage. In about five minutes, devices are ready after the operation. Then a beam course is selected before tuning beam. Beam tuning is done for all the beam courses connected to the scheduled therapy rooms in advance of the treatments. It takes about 25 minutes for relevant beam course. Since the beam course selection is carried out by only exciting the switching magnets, the therapy room can be changed by only switching the beam course in 5-7 minutes.

Only medical operators are allowed to open the beam shutters in clinical patients irradiation. On the other hand, operators of the accelerator must handle the shutters to tune the beam. In order to prevent wrong operations, we allow opening the shutters from one console at a time, either HEBT or irradiation console. Both control systems can always close the beam shutters. Furthermore, the operators of either control system can command not to change any operation parameters of upstream sub-systems during the treatments.

Software interlocks close or prohibit from opening the beam shutters under a few conditions of the HEBT system, in order to prevent unwanted irradiation of beams. The conditions are as follows. (1) No beam course is selected. (2) Magnets and/or power supplies of the selected beam course are out of normal conditions. (3) Any gate valve of the beam course is close. (4) The computer or the supervisor system does not work. (5) The computer is disconnected from the supervisor system. Therefore the software interlocks exclude wrong operations or abnormal conditions of the HEBT system.

Summary

In the HEBT control system, a large scale interface system, and its single task processes realize simplified and rapid operation with stable performance. All the operation functions are put together on the displays equipped with touch-panels and the rotary encoders as man-machine interfaces. These features make the operators possible to operate easily and uniformly. The software interlocks are excluding wrong operations due to human errors or machine failures. Overall the HEBT control system is reliable and easy to handle, and shows good performance.

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Present Status of HIMAC Synchrotron Control System

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Abstract

HIMAC synchrotron has been in operation since late 1993. Daily operation for irradiation of clinical trial have been executed satisfactorily. Present status of HIMAC synchrotron control system is summarized.

INTRODUCTION

As a medically dedicated accelerator, Beam must be supplied from HIMAC for treatment quite reliably. Requirements for beam energy and intensity can vary from patient to patient. Research programs which have been carried out nights and weekends also widens the variety. Under these circumstances, HIMAC synchrotrons have been operated to deliver beams for clinical trial and basic research experiments in a rather stable manner.

Of course, the individual hardware (magnets, power supplies, etc.) must be able to perform very well in order to realize stable operations. In achieving the reliable beam supply, however, synchrotron control system plays important part because it integrates the functioning of synchrotron components. Design plan and preliminary results were presented in the previous reports.[1,2] Operational experience and improvement plans are described in this report.

INITIAL TRACKING CONTROL

Synchrotron control system of HIMAC has been in operation since fall, 1993, when commissioning began. During commissioning,[3] the most crucial task of the control system was to assure tracking of BM and QF/D magnets excitation, because the scheme was to set current pattern precisely matched and to converge actual output current pattern to the preset one via repetitive, or ‘self-study’, control. Mechanism is an iterative application of the following procedure: The control system sets the current and voltage pattern of desired excitation to a power supply, then the system detects deviation \( \Delta I \) at 1,200 Hz, or each firing pulse of thyristors, and, after averaging over several cycles, it calculates modified voltage pattern to correct current deviations. The calculation involves the presumed response characteristics of the magnet & power-supply system, and tuning was done in cut and try method prior to the beam test. Even with the pre-tuning, two aspects remained to be answered by the beam; to find an appropriate current setting pattern and to assure effective convergence of the iteration.

Although we had started from the desired values of magnetic field and the approximate expression of the current vs. magnetic-field relation from actual field measurement, it turned out that simply applying “proportional” current setting among BM and QF/D magnets apparently suffice. Here, flat base and flat top values of currents are given and the ramping between them are adjusted in such a way that the ratio of current value to flat top value in terms of surplus from flat base value at each point is kept across BM and QF/D. This is certainly less accurate than the case from magnetic field, but more straightforward and practical in operation’s viewpoint.

It was later tested with higher excitation than original 230 MeV/u or most used 290 MeV/u level, e.g., 600 and 800 MeV/u, and results were quite successful, even the field saturation effect contributes non-trivial extent at these higher excitation. Thus, semi-empirical method worked well on the first aspect of the problem: finding appropriate current

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The second part was much more complicated and not yet fully understood, because the power supply itself has its own built-in voltage regulation circuitry and thus the result is a mixture of two mechanism. However empirically, convergence is obtained for each operational patterns without re-adjusting parameters for iterative "self-study" procedure. Further study is expected to exploit the feature.

STABILITY AND REPRODUCIBILITY

After the commissioning, priority of the control was given to stable and reproducible beam supply.

Clinical irradiation is scheduled weekly from Tuesday to Friday with accompanying dose measurements, and beam condition should be kept constant during the period. A patient is usually treated with 18 fractions that spans six weeks, although each fraction is normally 3-5 minutes irradiation. Since the adjustment and fixation of the patient takes typically as much as 20 minutes, beam irradiation is required to start and complete immediately after these preparatory procedure.

In this context, it is an essential performance for HIMAC that the accelerator complex keeps overall tuning for a long time and delivers beam of same conditions without re-tuning. The observation at the early stage of operation was that when the accelerator devices were kept turned-on without beam, which is stopped right after the extraction from ion source, beam was immediately delivered to the final focus when the beam stopper at ion source was opened after an overnight break.

It is also confirmed that a "file" of actually tuned operation parameters enables reproduction of the beam, thus once parameters were well-tuned, simply recalling filed parameters and setting those values secure beam delivery.

At present, carbon beams of 290, 350, and 400 MeV/u are in daily use for clinical irradiation, while other beams such as helium, neon, and silicon have been studied and provided for experimental research. For these beams, we have files of 6 MeV/u (flat base level), 100, 230, 290, 350, 400, 600, and 800 MeV/u for charge-to-mass ratio $\varepsilon = 0.5$, with basically well-adjusted parameters. Essentially, no fine tuning is necessary for different ion species, as far as $\varepsilon = 0.5$. For argon and other ions with $\varepsilon < 0.5$, one or two energy points have been studied and filed. New energy point can be developed from the existing files using the above mentioned procedure, which takes several hours.

Another evidence for stability is the fact that rf acceleration without beam feedback signal is routinely realized for a wide range of intensity; $5 \times 10^5$ to $1 \times 10^{10}$ ppp. In all, this means that the stability and reproducibility of the synchrotron was good enough to meet the requirement of medical application as well as research usage.

SEQUENCE AND FAULT HANDLING

One of the most practiced operation at HIMAC synchrotron is, as seen from the above, setting all devices to a reference value obtained from the file. This procedure can be done with a single set of touch operation. In the early stage of commissioning to routine operation, it sometimes got stranded and the software system of synchrotron hung-up. This was primarily caused by inappropriate handling of the sequence in the device control computers. Although corrective measures were taken, it was realized that momentary load can be larger than expected for some of the device controllers. Therefore, possible upgrade is under consideration for performance improvement.

It is important to locate fault condition that occurred during beam delivery, and to identify the cause quickly. Present control system provides error message with presumed items for each device. Recent recurrent troubles of device level include:
- decreased water-flow at magnet,
- thermo-control error at power supply, and
- rf cavity voltage over.

These were caused by defective hardware, and presumably terminated with correction on the problematic part of the hardware. On the other hand, system problem such as communication trouble happens, although sporadically. It does not seem to be a traffic congestion, but incompatible implementation of the communication protocol that is responsible, although it remains to be identified. Meanwhile, re-setting relevant computer of device control level can be postponed, since each device is set to keep operating as is when link between the controller and higher level computer is lost.

DEVICE CONTROLLERS

VME systems with MVME-147S CPU and FDI/FDO modules function for current pattern...
control of synchrotron magnets and for event timing generator rather reliably. They are operated with PDOS real-time OS. Additional work station for file management serves also for development and trouble-shooting tool.

In RF/BT system, peak load seems somewhat critical, but routine operation is performed without troubles after system tuning. The rf T-clock frequency was elevated to 50 kHz for smoother transition from B-clock region and thus for smaller beam losses. While it helped, present scheme of memory module operation limits flat top time shorter than needed for 0.3 Hz synchrotron operation, thus it returned to original 10 kHz clock.

MAN-MACHINE INTERFACE

For man-machine interfacing, four VS3100 VAX Stations are used for displaying system status, beam monitor results, current setting patterns, etc. It was found that with original 16 MB memory resource/station is inadequate to respond with operator's request. Therefore, it was enhanced to 32 MB per station and now works basically fine.

Two stations are allocated for two rings each, and interface with operator by accepting touch-panel input or equivalent mouse operation. Among the panels they provide, Pattern Editing, COD, & Tune are the special feature of the synchrotron control, while the others are basically common with other sub-systems, i.e., Linac and HEBT. Those are File List, Device Status, Fault/Not Ready List, Alarm Message List, Trend Monitors, Vacuum System, System Layout, Profile, and Slit & FCN panels.

MAIN CONTROL

The main control, CS, is VAX4000/300 with 64 MB memory, and is managing all the sequence operations and periodic data taking, as well as individual device control. It has communication with "SV", supervisory node of control system of HIMAC accelerator as a whole. Table 1 shows the processes that are running for these tasks. It is now under performance analysis to improve system throughput further.

IMPROVEMENT PLANS

In addition to what are mentioned above, a few items are considered for improving operationability and control system performance. One of the important change is "stream-lining" of pattern setting sequence, for both with and without synchrotron repetition cycle time change. Another is realization of synchronized switching of magnet and rf patterns. These improvements will enable faster and more independent change of synchrotron operational parameters such as energy, repetition cycle, etc.

Modification to facilitate new functions, e.g., respiration triggered beam control, is in progress, too.

<table>
<thead>
<tr>
<th>Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSMP</td>
<td>System Self Management</td>
</tr>
<tr>
<td>MDMP</td>
<td>Master Display Management</td>
</tr>
<tr>
<td>FMMP</td>
<td>File and Memory Management</td>
</tr>
<tr>
<td>FLSP</td>
<td>File Load &amp; Save</td>
</tr>
<tr>
<td>IDCP</td>
<td>Independent Device Control</td>
</tr>
<tr>
<td>MDCP</td>
<td>Monitor Display and Control</td>
</tr>
<tr>
<td>DOCP</td>
<td>Device Operation Control</td>
</tr>
<tr>
<td>SOCP</td>
<td>Sequential Operation Control</td>
</tr>
<tr>
<td>TSCP</td>
<td>Timed Sequence Control</td>
</tr>
<tr>
<td>RECP</td>
<td>Rotary Encoder Control</td>
</tr>
<tr>
<td>TCCP</td>
<td>TCP/IP Communication Control</td>
</tr>
<tr>
<td>SVC</td>
<td>'SV' Communication Control</td>
</tr>
<tr>
<td>AEHP</td>
<td>Alarm and Event Handling</td>
</tr>
</tbody>
</table>

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Development of Dynamic Pattern I/O Modules for Advanced Accelerator Operation


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Abstract

Dynamic control of beam parameters (energy, C.O.D. etc.) is essential for advanced utilization of synchrotron beam. DPI/DPO modules are now under development to switch among various excitation patterns of main magnets and rf system while the synchrotron is operating.

DPI/DPO are VMEbus modules which provide maximum 20-bit parallel input/output port with independent 16-bit control signal port, where up to about 125kHz external clock is applicable. Dynamic switching of output pattern and other intelligent functions are performed by two RISC microprocessors, one for control and the other for calculation.

1. INTRODUCTION

Operation of synchrotron magnets are characterized by repetitive pattern which consists of injection, acceleration, extraction, deceleration and reset of beam. In order to accelerate the beam without losses, each field of lattice magnets, BM and QF/QD, should be excited in a matched strength. This is called "tracking". Power supplies of lattice magnets, accordingly, should be precisely controlled in synchronization with the 1200Hz trigger timing pulse of 24 phase thyristor converter for forcing power source.

HIMAC has already made use of FDI/FDO modules which were developed for this purpose [1]. Present control system of magnet power supplies works well, including event triggers that are generated from another FDO module for injection etc. However, an advancement in heavy ion therapy requires more flexible and dynamic control of synchrotron operation, as the beam delivery with pulse-to-pulse energy shift is envisaged for cancer treatment irradiation of three-dimensional scanning for HIMAC and Particle Therapy Project in Hyogo prefecture [2].

An rf system should also be operated in coordination with main magnet excitation pattern, but the clock system differs from that of main magnet power supply. T clock of about 50kHz and B clock of max. 120kHz are used for rf control. Further, B clock is of bi-directional operation to stand with fluctuation of magnetic field for both acceleration and deceleration of beam. Although the dual memory mechanism is utilized and the digital control system operates successfully [3], dynamic pattern switching is not fully realized.

Dynamic switching of these patterns (both magnets and rf) is demanded in various aspects of beam operations. For example, it is required to switch an arbitrary combination of magnets simultaneously during beam tuning or to use a set of excitation patterns as mentioned above. Usage is also expected to measure beam parameters, chromaticity e.g., to initialize magnets, and to achieve digital feedback control (Iterative control or Self-study control).

Thus a dynamic pattern switch/selection is inevitable in advanced synchrotron control, which is now possible with the help of recent high-performance processors. In order to select various excitation patterns of main magnets and rf system dynamically, DPI/DPO modules are now under development. This paper describes DPI/DPO modules, with emphasis on the hardware aspect of DPO, which is developed prior to DPI.

2. FEATURES OF THE DPO

A lot of high performance RISC microprocessors for embedded system has flourished in a wide range of electronic appliances. After our investigation of abilities to handle many external interrupts and to control timer/counter substantially, we have made a choice of Hitachi Super-H (SH) series CPU which uses a 32-bit RISC core optimized for high speed and low power consumption. Another advantage of SH-1 CPU is several on-chip peripherals to eliminate many additional devices.

For a dynamic selection of a required excitation pattern from several tens to hundreds of patterns, it is necessary to discriminate many commands and to prepare enough amount of memory to store all relevant data. For this purpose 12-bit external control signal and 16MB memory are employed.

VSBbus is the subsystem standard of VMEbus.
It is provided to form a digital feedback loop by interconnection between DPO and DPI, which is expected to correct C.O.P, for example, in real-time. Iterative control of magnet power supplies [4] will be also benefited by the DPI-DPO direct connection.

Table 1 shows the outline specification of DPO. And the block diagram is shown in Fig.1.

2-1. CPU and Memory

Multiple CPU system is provided for this module. SH-1 CPU serves to control communications with VMEbus, VSBbus and all input & output ports. SH-1 also manages SH-2 CPU which is provided for dedicated calculation. To avoid bus contentions of multiple CPU system, separate local bus is provided for each CPUs.

16MB DRAM will be used in 3 byte-word format pattern memory to cover system requirement of rf and BM operation. User supplied programs can be loaded into the DRAM of SH-1 or the dedicated SRAM of SH-2 and executed from local CPU, respectively.

Each CPU responds to commands and environment parameters placed in each 32kB dual ported SRAM which serves the accesses from the VMEbus or the local bus through the arbitration logic which intervenes synchronously with one for another when simultaneous accesses occur.

SH-2 is provided on the mezzanine board to be changeable to SH-3 CPU in future.

Input/output ports are also provided on the other mezzanine board in order to change RS485 to TTL or other interfaces.

2-2. External clock

4 bits are provided for external clocks.

- Pattern start signal (Master Clock or RF Capture)
  It corresponds to repetitive cycle of synchrotron operation, typically ~1Hz.
- Base clock (1,200Hz or 50kHz)
  1,200Hz is fundamental clock distributed from PLL.
- Incremental B clock for rf (B+ clock)
- Decremental B clock for rf (B- clock)
  Maximum speed of B clock is presumed to be 120kHz in order to cover the BM excitation rate of 2.4T/sec at 0.2G/pulse clock.

2-3. External control signals

12-bit signal is decoded and recognized as following various events. These events are executed after next Master Clock except for Change signals that are executed immediately.

- Start & Stop
  Command to start or stop pattern output/input to devices altogether.

- Pause & Rerun
  Command to break temporarily or rerun pattern output for measurement of beam life etc.

- Selection of pattern
  Command to select any excitation pattern. Decoding method is effective to expand the range of selection, although a surplus strobe signal is necessary. It is capable to select not only any single excitation pattern but also a set of patterns and to operate partly any grouped magnets by means of masking bit, of which feature is applied to Start or Stop event when the initialization of a part of magnets is required.

- Change signal from T clock to B clock
- Change signal from B clock to T clock

2-4. Looked-Up Table

LUT is a memory to convert any data placed on the address line to another data immediately. This feature is useful to convert an accounted value of B clock to the rf frequency which is not always linear. 80k steps of table is required when BM is excited up to 1.6T at B clock of 0.2G. Then dual 80k x 20-bit memory is provided, of which one serves to make data output and the other receives next data simultaneously.

2-5. Software functions of DPO

1) SH-1 CPU for control

- Communication with Host CPU of IOC on VMEbus
- Communication with SH-2 CPU for calculation
- Execution of event signal
- VMEbus and VSBbus control
- Initialization and placing data on LUT
- Smoothing control of pattern
- Data output synchronized with external clock

2) SH-2 CPU for calculation
- Communication with SH-1 CPU for control
- Calculation of feed-back control or data filtering
- Smoothing calculation of pattern

3. CURRENT STATUS AND DISCUSSION

DPO with basic firmware will be prepared for performance test by the end of this year. DPO will also provide a function of timing pattern generator which produces dynamically various event control timings. System considerations, such as pattern data-base construction and management, division of tasks among host computer and DPI/DPO, are necessary to specify further details and to establish the best way of usage.

High-speed digital feed-back control with high
accuracy is attractive to challenge many technical matters of instabilities in various synchrotron operation. We expect that the combination of DPI/DPO will be useful to reduce beam ripple or to stabilize beam position by means of high-speed data acquisition and processing.

ACKNOWLEDGEMENTS

We would like to appreciate those who developed the present control system of HIMAC and enlightened us with profound understandings and discussions; Especially, Mr. N.Tsuzuki of Fuchu Works, Toshiba Corp. (rf control), Mr. S.Sakamoto of MTT Instr. Inc. (FDI/FDO system), Mr. T.Nakayama of Hitachi Inf. & Cont. Systems Inc. (magnet p/s system) and Prof. K.Sato of Osaka University are acknowledged with sincere gratitude.

We would like to thank Dr. K.Kawachi, Dr. S.Yamada and members of Accelerator Physics & Engineering Division of NIRS for discussions.

REFERENCES

[2] A.Itano et al., in these proceedings.

TABLE 1 Outline Specification of DPO

<table>
<thead>
<tr>
<th>Main Board</th>
<th>Mezzanine Board for calculation</th>
<th>Mezzanine Board for I/O adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>SH7034(SH-1)</td>
<td>SH7604(SH-2)</td>
</tr>
<tr>
<td></td>
<td>• 4kB On-chip RAM</td>
<td>• 4kB cache memory</td>
</tr>
<tr>
<td></td>
<td>• 64kB On-chip ROM</td>
<td>• Hardware multiplier</td>
</tr>
<tr>
<td></td>
<td>• Hardware multiplier</td>
<td>• Hardware divider</td>
</tr>
<tr>
<td></td>
<td>• 9ch. Ext. interrupt handler</td>
<td>• 15ch. Ext. interrupt handler</td>
</tr>
<tr>
<td></td>
<td>• 4ch. DMA controller</td>
<td>• 2ch. DMA controller</td>
</tr>
<tr>
<td></td>
<td>• 5ch. Timer/Counter</td>
<td>• 16bit Counter</td>
</tr>
<tr>
<td></td>
<td>• 16bit Timing pattern gen.</td>
<td>• Watch-dog timer</td>
</tr>
<tr>
<td></td>
<td>• Watch-dog timer</td>
<td>• 1ch. Serial comm. port</td>
</tr>
<tr>
<td></td>
<td>• 2ch. Serial comm. port</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Universal I/O ports</td>
<td></td>
</tr>
</tbody>
</table>

| Clock       | 20MHz (16MIPS)                  | 28.7MHz (25MHz)                  |
| SRAM        | 128kB with zero wait state      | 256kB with zero wait state       |
| DRAM        | 16MB with zero wait state       |                                   |
| Dual-ported SRAM | 32kB with one clock wait state | 64kB with one clock wait state  |
| LUT SRAM    | 384kB with 20bit U/D counter    |                                   |
| Front panel functions | 16bit Status LED | Reset switch |
| Bus spec.   | VMEbus IEC622 compatible slave interface (A24,D16) | VMEbus IEC622 compatible master/slave interface |
| Operating condition | Power source: 5V±5%, typ. 3A | 5V±10%, typ. 1.5A (I/O isolation p/s supplied from front connector) |
|             | Temperature : 0°C–50°C          |                                   |
|             | Humidity : 30%–90% (Non-condensing) |                                   |
CONSTRUCTION OF A REMOTE CONTROLLED MONITORING SYSTEM WITH GPIB DEVICES AND EPICS

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+National Laboratory for High Energy Physics (KEK), Tsukuba-shi, Ibaraki-ken, 305 Japan

Abstract

The Experimental Physics and Industrial Control System (EPICS) has been used for the accelerator control system in recent years. EPICS has rich set of tools to create application with Graphical User Interface (GUI). It reduces the load of complex programming for GUI and shortens the application development period. This paper will describe the remote temperature monitoring system using EPICS.

1. Introduction

Slow drift of a beam orbit in TRISTAN Main Ring is observed during a long time operation. It caused the degradation of the performance of the machine.

One reason for this slow drift has been thought as the temperatures of magnets in the ring. Drift of temperature can affect the orbit of beam through the thermal expansion of electromagnets and its supports. We build a system to monitor the temperatures in the accelerator tunnel to study correlation between the temperature drift and the beam orbit drift.

Thermocouples are used as temperature measurement device. Data collected by thermocouple controller are sent to a VME computer through GPIB/LAN (local area network) linker. User can control and monitor this system by EPICS tools.

2. EPICS

EPICS\(^{32}\) is a scalable, distributed process control system that is built on a software communication bus called Channel Access. EPICS architecture includes the UNIX workstations for executing high level applications (including operator interfaces), and single board computers as front end computers, called Input Output Controllers or IOCs. The single board computers in VME crates are used as IOC. Communication among the distributed components is over TCP/IP sockets, via ethernet or FDDI.

Figure 1. Functional subsystem layout of EPICS. The only sequencer runs on both OPI and IOC.

The EPICS architecture provides a wide range of functionality, rapid application development and modification, and extensibility at all levels to meet the demands of experimental physics. The hardware and software for each functional subsystem were selected to meet these requirements. The subsystems are: the Distributed Database, the Display Manager, the Alarm Manager, the Archiver, the Sequencer, and Channel Access (see Figure 1). These functional subsystems greatly reduce the need for programming. Sequential control is provided through a sequential control language, allowing the application developer to express state diagrams easily. Data analysis of the archived data is provided through an interactive tool. The system is scalable from a single test station with a low channel count to a large distributed network with thousands of channels. All data is passed through the channel access protocol. One can extend the basic EPICS system in IOC by creating new database record types, calling 'C' subroutines from the database, extending the
driver support and creating independent VxWorks task.

3. Monitoring System

We built a monitoring system for the temperature measurement with EPICS. The reasons why we employed EPICS are:
1) No need for programming except driver support.
2) Easy modification for the monitoring system.
3) Easy addition for the measurement channel.

![Temperature Monitor](image)

Figure 2. Control panel. The display panel for the current value of the temperature comes out if the DISPLAY button is pushed.

3-1. System functions

The functions of this monitoring system are:
1) Device control
   Transmit the GPIB command set on the control panel created by the display manager to the measurement system for the temperature (Figure 2 shows the control panel).
2) Status/Data Display
   Display the current temperature and plot its last 200 seconds' history.
3) Data Archiving/Retrieving
   Record the temperature data measured by the measurement system for the temperature into the disk. And readout and displays the recorded data.
4) Alarm Notification
   Send the message to the specified user by an e-mail if there is no answer form IOC to OPI or the data from the measurement system for the temperature is same as previous data including the time stamps.

![System architecture](image)

Figure 3. System architecture.

3-2. System architecture

This system consists of workstation, VME single board computer, GPIB/LAN linker, computing data logger, sensor terminal, and thermocouples. Figure 3 shows the arrangement of these components.

The functions and names of each component are:

Workstation
HP 9000 workstation model 735/755 is used as an Operator Interface (OPI) in EPICS, and runs the UNIX operating system and a number of EPICS tools such as the archiver, the display manager and the alarm manager.

VME single board computer
FORCE CPU40 is used as an Input Output Controller (IOC) in EPICS, and runs the VxWorks real-time kernel and a number of EPICS programs such as the distributed database and the sequencer.

GPIB/LAN linker
SONY Tektronix ET488 exchanges the data from the data logger through GPIB to output to ethernet and performs a GPIB controller.
Computing data logger, sensor terminal, thermocouples

ADVANTEST TR2731, TR2741 and thermocouples compose a measurement system for the temperature.

Network

The network among the workstation, the VME crate and GPIB/LAN linker is ethernet on which the transmission speed is 10 Mbps.

3-3. Data acquisition

The process of data acquisition is as follows.

1) The operator initiates the start command for data acquisition on the control panel, to process the database record.

2) The database record issues the GPIB command which starts the sensor terminal or programming for the data logger.

3) The data logger starts the sensor terminal, complying with the GPIB command from the database record.

4) The sensor terminal collects the data from the thermocouples which are in the accelerator tunnel.

5) The temperature data collected by the sensor terminal are sent back to the IOC (database) via GPIB/LAN linker.

4. Conclusion

By using EPICS, there was no need of coding except the driver support for the GPIB controller, device support for the data logger and sequential control.

Another measurement point can be added to the system just adding a new record to the EPICS run-time database. User can easily modify the operator interface (control) panel using EPICS tools. Furthermore, by connecting the GPIB controller to LAN directly, we can place the GPIB devices in many places.

Acknowledgments

We would like to thank Prof. R. Sugawara and Prof. H. Fukuma for their encouragement and support during this work.

References


Beam Current Limitations due to Single-Beam Collective Effects in the Ion Storage Ring of RIKEN RI Beam Factory Project

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Abstract
Single-beam collective effects limit the beam current when beams are served for colliding experiments in the presently designed ion ring. For the some hundreds MeV/u ion beam making the betatron tune shift -0.2, longitudinal instabilities occur with growth times of 0.02 s, and the transverse resistive wall instability with growth time of 1 s. The electron cooling with cooling time of 0.01 s at the full momentum spread $10^3$ of the ion beams can damp the instabilities. Then, the luminosity is much less than $10^{9}$ cm$^{-2}$s$^{-1}$ on the heavy ion side. A proposal about the lattice of the ring is made to improve the luminosity.

1. Introduction
The RIKEN Accelerator Research Facility group has been proposing "RIKEN RI Beam Factory" as a next facility-expanding project [1]. The factory takes the aim at providing RI beams of the proposing "RIKEN RI Beam Factory" as a next facility-expanding experiments arc carried out at two interaction sections (IS) in accumulated and accelerated in the other one. The colliding Storage Rings (DSR). Electron beams from a 300 MeV linac are beam through a superconducting ring cyclotron, an accumulator-booster-cooler ring, and, or an RI beam generator. The beams are injected to the one of a twin storage ring that is called Double Storage Rings (DSR). Electron beams from a 300 MeV linac are accumulated and accelerated in the other one. The colliding experiments are carried out at two interaction sections (IS) in DSR. On the other hand, ion beams are injected to both the rings for ion-ion merging experiments. Both the lattices of the rings have been designed to be the same. Table 1 shows the parameters of DSR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference of a ring</td>
<td>178.694 m</td>
</tr>
<tr>
<td>Max. magnetic rigidity</td>
<td>12.76 Tm</td>
</tr>
<tr>
<td>Radius of curvature</td>
<td>8.506 m</td>
</tr>
<tr>
<td>Beam energy (injection—top)</td>
<td>0.4 → 1.2 GeV/u</td>
</tr>
<tr>
<td>Beam energy (top—ring)</td>
<td>0.15 → 0.82 GeV/u</td>
</tr>
<tr>
<td>Electron</td>
<td>0.3 → 2.5 GeV</td>
</tr>
<tr>
<td>Betatron tune (v / v)</td>
<td>6.350/5.763</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>0.0424</td>
</tr>
<tr>
<td>Natural chromaticity (ζ, ε)</td>
<td>0.181/7.43</td>
</tr>
<tr>
<td>Beta function at IS (βp, β)</td>
<td>0.60/0.60 m</td>
</tr>
<tr>
<td>Dispersion at IS (η, μ)</td>
<td>0.000.0 m</td>
</tr>
<tr>
<td>Max. stored electron beam current</td>
<td>0.3 A</td>
</tr>
<tr>
<td>Number of bunches (ion/electron)</td>
<td>30/15</td>
</tr>
<tr>
<td>Electron rms emittance (e, e)</td>
<td>8 x 10^{-10} mrad</td>
</tr>
<tr>
<td>at 0.3 GeV</td>
<td>530 x 10^{-9} mrad</td>
</tr>
</tbody>
</table>

Colliding experiments require beams of high luminosity and small momentum spreads. For this, ion beams are intensifi ed and cooled down so that the full momentum spread may become at most $10^4$ and the transverse emittance may become $1 \times 10^4$ mrad, before the injection to the ring. They are bunched with the full bunch length of 40 cm in the ring. The qualification always does not increase the luminosity, because it makes single-beam collective effects strong and the effects limit beam currents.

Here, current limitations of ion beams and electron beams are estimated which are due to beam-beam effects during the collision, the direct space charge effects, and beam instabilities in the presently designed ion ring, but not in the electron ring. Instabilities are treated of just in the injection energies, because the lower the beam energy, the more easily instabilities occur. Both the lightest ion and the heaviest ion are treated of in order to watch the dependence on ion species. The luminosity is evaluated for the threshold beam currents. Finally, a proposal is made to improve the luminosity.

2. Electron Beam Current Limitations
In DSR a 15-bunched electron beam circulating in the one ring collides with a 30-bunched ion beam circulating in the other ring at two IS's with zero colliding angle. The linear tune shift of the ion due to the beam-beam effect is described as follows under the assumption where the charge distribution of the electron round beam is Gaussian with the rms $\sigma_p$, in the radius direction [2]:

$$
\xi = \frac{(1 + 2\beta_p\beta_e)\eta_p r_p \gamma}{4\pi\sigma_p^2 \beta_p}.
$$

where $\beta_p$ and $\beta_e$ are velocities of the ion and the electron beams normalized by the light velocity $c$, respectively, $\beta$ the beta function at IS's, $N_e$ the number of electrons per bunch, $r_p$ the classical proton radius, $Z/A$ the charge to mass ratio of the ion, and $\gamma$ the ion mass normalized by the rest mass. The stability of the lattice of the ion ring requires

$$
|\cos \phi - 2\pi \eta_p | \leq 1.
$$

with $\mu$ is half the phase advance of the ring. One has the following requirement, reserving a little safety margin:

$$
\xi \leq 0.05.
$$

With substitution of $\sigma_p^2 = \epsilon \mu |\beta_p|^2$ to Eq. (1) (the beta function of the electron ring at IS is designed to be equal to that of the ion ring), the threshold number of the electrons per bunch is evaluated as shown in Table 2.

<table>
<thead>
<tr>
<th>Ion/electron</th>
<th>300 MeV $e^-$</th>
<th>2.5 GeV $e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\times 10^9$</td>
<td>$\times 10^9$</td>
<td>$\times 10^9$</td>
</tr>
<tr>
<td>$400$ MeV/u $He$</td>
<td>$3 \times 10^9$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>$150$ MeV/u $He$</td>
<td>$2 \times 10^9$</td>
<td>$1 \times 10^9$</td>
</tr>
</tbody>
</table>

On the other hand, the stored current of the electron beam is expected to be at least 300 mA, when the beam of 300 MeV is injected in the ring. Then, the number $N_e$ becomes $7 \times 10^9$. The electron bunch population $N_e$ shown in Table 2 is limited by the value further.

3. Ion Beam Current Limitations
3.1 Incoherent betatron tune shift due to direct space charge
For a round beam whose charge distribution is assumed to be

- 318 -
Gaussian with the rms $\sigma_n$ in the radius direction and parabolic with the full bunch length in the longitudinal direction, the incoherent betatron tune shift of ions with small betatron frequency $f$ with the full bunch length in the longitudinal direction, the amplitude due to direct space charge is described by

$$\Delta v = \frac{3}{4} \frac{N_n}{n} \frac{r_f}{1 + (r_f/2)^2},$$

(4)

where $f$ is the average beta function of the ion ring, $N_n$ the bunch population of ions, and $n = (1/\gamma R) B$ the bunching factor, $R$ being the average radius of the ring. Here, one properly uses the equality $4\pi\rho^2 = s_f$ on treating of ion beams whose charge distribution is not Gaussian. When resonance compensation is carried out well, the shift of $|\Delta v| < 0.2$ is tolerable. Then, the bunch population $N_n$ is limited as follows:

$$N_n \leq \frac{5 \times 10^5}{150 \text{ MeV/u} \cdot \text{He}^+},$$

(5)

### 3.2 Impedance budget

The lattice of DSR has been being optimized nowadays. The structure of the vacuum chamber and the numbers of elements have not yet determined. Here, the beam coupling impedances with the chamber are estimated under a rough assumption of them.

Longitudinal broad band impedances of bellows and flanges, transition sections, slits of vacuum ports, and clearing electrodes of disk type are evaluated with the theoretically derived equations [4], [5], [6], and [7], respectively. Longitudinal impedances of strip-line monitors are estimated with the equation [8].

A candidate of the RF cavity for the ion ring is a $\lambda/4$ coaxial cavity with the use of a perpendicular bias field on the ferrite [9]. The higher order cavity modes are strongly suppressed with the damper [10]. The longitudinal impedance of the RF cavity for DSR is assumed to be like that of the 50 MHz 150 kV prototype synchrotron cavity [11], but the frequencies of HOM are not yet determined. Here, the beam coupling impedances without perturbation are calculated with the program ZAP [14] which has been modified to be applicable for ion beams by the authors.

### 3.3 Longitudinal instabilities

The microwave instability is undesirable, because it induces the bunch lengthening when the bunch population goes beyond a threshold, and the lengthening decreases the luminosity.

The threshold peak current $I_c$ is given with Keil Schnell criterion under the parabolic momentum distribution [12].

$$\frac{2T_v}{m_0 v^2} \frac{\beta_f}{\beta_0 n} \frac{\sigma_p}{\sigma_p} |Z_{\text{in}}| = 0.6,$$

(7)

where $e$ is electronic charge, $\sigma$ the slippage factor, and $\Delta p/\sigma$ the FWHM momentum spread. The equation (7) shows

$$N_n \leq \frac{5 \times 10^5}{150 \text{ MeV/u} \cdot \text{He}^+},$$

(8)

It is known that the microwave instability does not occur for the ion bunch population making the betatron tune shift $|\Delta v| < 0.2$.

When a bunched beam circulates with the angular frequency $\omega_n$ in a ring, it can have following longitudinal frequency components without perturbation:

$$\omega_n = \omega_n (n \pm m, n \pm m),$$

(9)

where $B$ is the number of bunches, $p = 0, \pm 1, \pm 2, \ldots$, $m, n (m = 0, \pm 1, \pm 2, \ldots)$ the coupled-bunch mode, and $(n \pm m, n \pm m)$ the synchrotron mode. With perturbation, the frequency is coherently shifted, in the Sacherer-Zotter formalism [13], by

$$\Delta \omega_n = -\frac{\zeta_n}{\beta_n} \left( \frac{Z_{\text{in}}}{Z_{\text{ef}}} \right) V |\n|,$$

(10)

$$\left( \frac{Z_{\text{in}}}{Z_{\text{ef}}} \right) = \frac{\sum h_n/\omega_n \left( \frac{a_n/\omega_n}{\phi_n} \right)}{\sum h_n/\omega_n},$$

(11)

where $h$ is the RF harmonic number, $V$ the peak RF-voltage, and $\phi_n(\omega)$ the spectral power density of the $n$-th synchrotron mode.

$$\delta (\omega_n) = \frac{\pi}{16} \left( \frac{Z_{\text{in}}}{Z_{\text{ef}}} \right) |\n|,$$

(12)

Then, the bunch population is limited as follows:

$$N_n \leq \frac{5 \times 10^5}{150 \text{ MeV/u} \cdot \text{He}^+},$$

(13)

Therefore, single-bunch and multi-bunch instabilities may be induced for the bunch population making the tune shift $|\Delta v| < 0.2$. The growth times of the most unstable mode each $n$-th mode are shown in Table 5 and Table 6, which are calculated with the program ZAP [14] which has been modified to be applicable for ion beams by the authors.

### Table 3: The imaginary parts of the longitudinal impedances $\Im(Z_{\text{in}}/\omega)$ of the ion ring of DSR at the low frequency.

<table>
<thead>
<tr>
<th>Injection energy</th>
<th>150 MeV/u</th>
<th>400 MeV/u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space charge</td>
<td>1900</td>
<td>860</td>
</tr>
<tr>
<td>Bellows</td>
<td>-1.4</td>
<td>-2.0</td>
</tr>
<tr>
<td>Flanges</td>
<td>-0.04</td>
<td>-0.05</td>
</tr>
<tr>
<td>Transition sections</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Slits of vacuum ports</td>
<td>-0.002</td>
<td>-0.003</td>
</tr>
<tr>
<td>Clearing electrodes</td>
<td>-0.14</td>
<td>-0.21</td>
</tr>
<tr>
<td>RF equivalent Bb</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>Strip-lines</td>
<td>-0.05</td>
<td>-0.07</td>
</tr>
</tbody>
</table>

### Table 4: The imaginary parts of the transverse impedances $\Im(Z_{\text{in}}/M1/\omega)$ of the ion ring of DSR at the low frequency.

<table>
<thead>
<tr>
<th>Injection energy</th>
<th>150 MeV/u</th>
<th>400 MeV/u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space charge</td>
<td>6600</td>
<td>5300</td>
</tr>
<tr>
<td>Broad band</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
</tbody>
</table>
Table 6: The growth times $\tau$ of the most unstable mode(m,n) of the longitudinal multi-bunch instabilities each n-th mode.

<table>
<thead>
<tr>
<th>Mode(m,n)</th>
<th>400 MeV/u $\gamma_{n0}$</th>
<th>150 MeV/u $\gamma_{n0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode(0,1)</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>Mode(0,2)</td>
<td>0.05</td>
<td>0.4</td>
</tr>
<tr>
<td>Mode(0,3)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Mode(0,4)</td>
<td>0.9</td>
<td>0.6</td>
</tr>
</tbody>
</table>

3.4 Transverse instabilities

As in the longitudinal direction, a bunched beam can have following transverse frequency components without perturbation:
\[ \omega_t = \omega_0 + \gamma_v - \gamma_c + \omega_c(\beta) \]

With perturbation, the frequency is coherently shifted, in the Sacherer-Zolter formalism [13], by
\[ \Delta \nu = \frac{\gamma_v - \gamma_c}{\gamma_v} \left[ \sum_{k=1}^{1} \frac{Z_k}{\gamma_k} \right] \]

where $E$ is the beam energy per nucleon, and $\omega_0$ the chromatic shift $\omega_0 = \gamma_v - \gamma_c$, $\xi$ being the chromaticity. The above equations are applicable to the single bunch, also. Transverse single-bunch instabilities occur when the coherent frequencies of two neighboring low-order modes shift to become equal, for example at $\Delta \nu = \omega_v$, [11]. They are called mode-coupling instabilities induced through the broadband impedances. The threshold peak current is described by
\[ \nu = \frac{\gamma_v - \gamma_c}{\gamma_v} \left[ \sum_{k=1}^{1} \frac{Z_k}{\gamma_k} \right] \]

Then, the bunch population is limited as follows;
\[ \nu = \frac{4 \times 10^{-5}}{5 \times 10^{-1}} \left( \frac{400 \text{ MeV/u}}{150 \text{ MeV/u}} \right) \nu_{v0} \]

Even for the bunch population making the tune shift $|\Delta \xi| = 0.2$, however, the coherent tune shift is
\[ \Delta \nu = 0.06 \nu_{v0} \left( \frac{400 \text{ MeV/u}}{150 \text{ MeV/u}} \right) \]

which is less than the incoherent betatron tune shift. Landau damping is expected to suppress the instabilities. Transverse coupled bunch instabilities are induced through the resistive wall impedances and RF narrow band ones. Here, as one has no data about the latter, the growth times of the instabilities just through the former are evaluated. The resistive wall impedance contributes mainly the mode $n=0$ because of its sharp peak at the zero frequency. Without the chromaticity, the most unstable mode is known to be the mode(23, 0) or the mode(24, 0) because of 30 bunches and the betatron tunes on the two sides of 6. For the bunch population making the tune shift $|\Delta \xi| = 0.2$, the growth times are estimated as shown in Table 7. The avoidance of the instabilities is dependent on the chromaticity.

Table 7: The growth times $\tau$ of the most unstable mode(m,n) of the transverse coupled bunch instabilities.

<table>
<thead>
<tr>
<th>Energy Ion</th>
<th>400 MeV/u $\gamma_{n0}$</th>
<th>150 MeV/u $\gamma_{n0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode(23,0) or Mode(24,0)</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

3.5 Electron cooling

The electron cooling is applied to damp the longitudinal and transverse instabilities. The cooling time is required to be less than half the growth time [16]:
\[ \tau < \frac{\nu_{v0}}{2} \]

4. Luminosity

The length of the collision region is two-thirds of the ion full bunch length, because of the normalized velocity $\beta = 0.5$ corresponding to the lowest beam energy. When the detectable collision region is longer than it, the luminosity is described by [17]
\[ L = \frac{N_e N_e f_{\gamma_b} B}{2 \pi c^4 \sigma_{\gamma_b} \sigma_c} \]

where $f_{\gamma_b}$ is the revolution frequency of the ion beam. When the electron cooling with cooling time of 0.01 s is used to damp the instabilities, the bunch population making the tune shift $|\Delta \xi| = 0.2$ is available. Then, the luminosity is shown in Table 8.

Table 8: The luminosity $[cm^{-2} s^{-1}]$ for the bunch population making the tune shift $|\Delta \xi| = 0.2$.

<table>
<thead>
<tr>
<th>Ion x electron</th>
<th>300 MeV $e$</th>
<th>2.5 GeV $e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 MeV/u $\gamma_{v0}$</td>
<td>$3 \times 10^{30}$</td>
<td>$2 \times 10^{30}$</td>
</tr>
<tr>
<td>150 MeV/u $\gamma_{v0}$</td>
<td>$9 \times 10^{29}$</td>
<td>$1 \times 10^{29}$</td>
</tr>
</tbody>
</table>

5. Conclusion

In the presently designed ion ring of DSR, the longitudinal single-bunch and multi-bunch instabilities are induced for the bunch population making the betatron tune shift $|\Delta \xi| = 0.2$ and the bunch length of 40 cm. The transverse multi-bunch instabilities may be induced, which is dependent on the chromaticity. The electron cooling with the cooling time of 0.01 s can damp the instabilities. The luminosity for 150 MeV/u is much less that $1 \times 10^{10}$ cm$^{-2}$ s$^{-1}$. In order to improve the luminosity, the design of DSR lattice should be modified as follows; 1) the beta function at IS is reduced by one order, 2) the optics of the lattice of the electron ring is variable enough to increase the emittance of the 300 MeV electron beam up to around $0.5 \times 10^{10}$ m rad, 3) the number of bunches of both the beams are increased by a few times.

References
A resonant extraction technique for a compact synchrotron; asymmetric driving of two sextupole magnets

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Abstract

A technique for third-order resonant extraction for a compact synchrotron is presented. Two sextupole magnets are asymmetrically driven for two purposes, one of which is to excite the third-order resonance and the other is to correct for chromaticity. The positions of these two sextupole magnets are decided so that the outgoing branches of the separatrices at the deflector are superimposed for all momenta. This arrangement is effective to realize a compact synchrotron, which needs less space to install magnets, and has a high efficiency of extraction and good quality of the extracted beam.

1. Introduction

Resonant extraction methods have been widely applied not only to physics experiments but also to medical applications [1,2]. The resonant extraction utilizes a nonlinear resonance of the betatron oscillations. A nonlinear magnetic field brings about the resonance and makes the separatrix, which is defined as the boundary between stable and unstable betatron oscillations in the phase space. The separatrix size decreases as the deviation of the tune from the resonant condition becomes smaller. As the tune depends on the particle momentum through a finite chromaticity, the separatrix size also depends on it. The dependency of the separatrix size on the particle momentum causes a change in the orbit gradient of the extracted beam at the deflector position. Any change of beam characteristics can lower the extraction efficiency, which is sometimes disadvantageous for the beam user. Usually, it is necessary to control the chromaticity during the extraction procedure.

When a synchrotron utilizes the third-order resonant extraction, two sets of sextupole magnets have been installed, one of which act as the corrector of the chromaticity, while the other act as the exciter of the third-order resonance. Two sextupole magnets must be installed at a symmetrical position in the synchrotron as the corrector of the chromaticity and driven of same strength so as to cancel the contribution to the third-order resonance each other. As a result, at least three sextupole magnets, one exciter and two correctors, are needed. Frequently, four sextupole magnets, two exciters and two correctors, are installed to control the chromaticity and resonance independently.

In order to realize a high quality beam or flexible control, synchrotrons such as for accelerator physics or high energy physics must have many components. These synchrotrons become large in order to get enough space for the components and operations may become rather complicated. The size of the synchrotron should be made as small as possible to reduce the cost, including both the machine construction and the civil engineering aspects [3]. It is necessary to develop a method which realizes a high quality beam with fewer components.

This paper proposes a technique for third-order resonant extraction with the chromaticity correction for a compact synchrotron. Two sextupole magnets for the exciters of the third-order resonance serve simultaneously as the correctors of the chromaticity. In order to reduce the extracted beam emittance, the positions of these two sextupole magnets are decided so that the outgoing branches of the separatrices at the deflector are superimposed for all momenta. By combining the above technique with the extraction scheme under a constant separatrix [4], it is expected that a low emittance beam can be easily extracted with a high efficiency.

2. Third-Order Resonant Extraction with the Chromaticity Correction

At the third-order resonance, the stable areas are triangles and the separatrices are straight lines (Fig.1). We consider the third-order resonance driven by a single sextupole of normalized strength $S_n$ given by:

$$S_n = \frac{B_p}{2} \beta^3$$

where $B_p$ is the magnetic rigidity of the beam and $\beta$ is the horizontal betatron amplitude function at the sextupole magnet. The integral of the second horizontal derivative of the vertical component of the magnetic field, $B''$, is evaluated over the length of the sextupole magnet.

Fig.1 Separatrices of the third-order resonance in the normalized phase space. Dotted lines show the separatrix for an off momentum particle.

More generally, we have to consider the third harmonic of the sextupole magnetic field distribution in the betatron phase around the machine. When there are $m$ sextupoles of strength $S_i$ and normalized strength $S_{ni}$ at phase $\phi_i$, the resulting effect of these sextupoles has a strength $S$ and a phase $\phi$ with:

\[ S = \sum_{i=1}^{m} S_{ni} \cos(3\phi_i - \phi) \]

\[ \phi = \sum_{i=1}^{m} \phi_i \]
\[
S \exp(3j\phi) = \sum_{n} S_n \exp(3j\phi_n) = \sum_{n} b_n^3 S_n \exp(3j\phi_n). \quad (2)
\]

In this equation, phases are taken from the considered point. In general, according to the difference of the phase advance from each sextupole \( \phi_n \), the resulting phase \( \phi \) changes by each normalized sextupole strength \( S_n \). Some synchrotrons utilize this character to rotate the separatrix and change the orbit gradient of the extracted beam [5]. When the phase difference between each sextupole is \( \pi/3 \), the resulting phase does not change for strength of each sextupole and then the separatrix does not rotate.

In the following study, we restrict ourselves to the case of a ring which has superperiods of even number and two sextupole magnets installed on opposite sides of the ring. The phase difference between the two sextupole magnets is nearly \( \pi/3 \), because one turn phase advance is \( 2\pi/3 \), near the resonance condition. As the Twiss parameters at these sextupole positions are equal, the separatrix size \( \varepsilon \) and the chromaticity \( \xi \) (defined as \( (\Delta v/v)/(\Delta p/p) \)) become:

\[
\varepsilon = \pi/\sqrt{3(S_1 + S_2)}
\]

\[
\xi = \xi_{\text{orbit}} + \frac{1}{4\pi^2} \beta \eta (S_1 + S_2)
\]

where \( S_1 \) and \( S_2 \) are the strengths of these two sextupole magnets, \( \beta \) and \( \eta \) are the betatron and dispersion functions (defined as \( \Delta x/\Delta p/p \)) at these sextupole magnets. \( \nu \) and \( \delta \) are the tune and its deviation from the resonant condition. \( \xi_{\text{orbit}} \) is the part of the chromaticity without the sextupole magnets contribution, natural chromaticity. In Eq. (3), the plus (minus) sign is taken when the number \( n \) of the phase difference between the two sextupole magnets, \( n\pi/3 \), is even (odd). When this sign is minus, the separatrix size and the chromaticity can be tuned independently by selecting \( S_1 \) and \( S_2 \) carefully.

The difference between the strengths of these two sextupole magnets becomes large when a rather large chromaticity change is needed. Then the strength of one of the sextupole magnets becomes strong. In this case, trajectories of the extracted particles curve in the phase space due to the higher order term of the nonlinear resonance. Trajectories curved like this are not suited to the extraction. So this technique is not proper for a ring of large chromaticity.

3. Superimposing the Separatrices at the Deflector

In order to reduce the extracted beam emittance, i.e., the phase space area of the extracted particles at the deflector position, the outgoing branches of the separatrices are superimposed. This condition is derived for the ring of finite chromaticity [6]. In this study, the chromaticity is corrected by the technique shown above.

The normalized horizontal phase plane \((X,Y)\) is defined as:

\[
X = \frac{x}{\sqrt{\beta}} \quad \text{and} \quad Y = \frac{\alpha x + \beta x'}{\sqrt{\beta}}
\]

where \( x \) and \( x' \) are the real horizontal position and orbit gradient respectively, and \( \beta \) and \( \alpha \) are the Twiss parameters at the considered point.

When the phase difference between the two sextupole magnets is \( \pi/3 \), one of the branches of the separatrix is parallel to the \( Y \) axis in the normalized phase plane at the position of these sextupoles. Two other branches incline from \( Y \) axis for \( 2\pi/3 \) and \( 4\pi/3 \) radians. So the inclinations of these three branches are \( \tan(\pi/2) \), \( \tan(7\pi/6) \), and \( \tan(11\pi/6) \).

The separatrix rotates with the phase advance from these sextupole magnets. So the inclinations of the branches are \( \tan(\pi/2-\phi) \), \( \tan(7\pi/6-\phi) \), \( \tan(11\pi/6-\phi) \), where \( \phi \) is the phase advance from one of the sextupole magnets to the considered point.

Generally, a synchrotron has finite values for the dispersion function and its derivative. So the location of the separatrix in the phase plane varies with the particle momentum. When the chromaticity is corrected and the separatrices for all momenta are congruent, the condition to superimpose the separatrices around the deflector for all momenta is that one of the branches of the separatrix is parallel to the shift of the separatrix with the momentum through the dispersion function (Fig.2). The equation of the condition is:

\[
\eta = \frac{\tan(\theta - \phi) - \alpha}{\beta} \quad \text{with} \quad \theta = \frac{4m}{6} \pm \frac{\pi}{6} \quad (5)
\]

where \( \phi \) is the phase advance from one of the sextupoles to the deflector, \( \alpha \) and \( \beta \) are the Twiss parameters at the deflector, \( \eta \) and \( \eta' \) are the dispersion function and its derivative at the deflector. In the above equation, \( m \) is an integer which satisfies the condition \( \phi - \pi/2 < \phi < \phi + \pi/2 \). If the position of the deflector is fixed, we can superimpose the separatrix by selecting the position of two sextupole magnets according to Eq. (5).

4. Application to a Compact Synchrotron

This technique has been studied for a lattice of a compact synchrotron dedicated to medical use [7]. In order to reduce the size of the synchrotron and simplify its control, this synchrotron employs a combined function lattice. The circumference is 22.9 m. The bending magnets have \( n \)-indices for focusing and defocusing the beam. The horizontal tune is 1.75 and the vertical tune is 0.85. In the extraction period, two trim quadrupole magnets change the horizontal tune to nearly 1.67. The third-order
resonant extraction is raised by a transverse perturbation of the radio frequency and the separatrix is kept constant. The effects of the present technique are analyzed through computer simulations.

The two sextupole magnets are treated as thin lenses. The momentum spread is assumed as $\Delta p/p = \pm 0.2\%$. Emitance of the beam is assumed as 24\mum\mm\Mrad. The positions of the two sextupole magnets are selected according to Eq. (5). Horizontal tune is selected as 1.67, nearly $10\pi/3$, in order to get proper turn separation; here the turn separation is defined as an increment of the betatron amplitude at the deflector position. Twiss parameters at the deflector and sextupole magnets are shown in Table 1.

<table>
<thead>
<tr>
<th>Twiss parameters</th>
<th>deflector</th>
<th>sextupole magnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>2.96 m</td>
<td>1.42 m</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-1.55</td>
<td>0.83</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1.55 m</td>
<td>1.48 m</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>0.39</td>
<td>-0.32</td>
</tr>
</tbody>
</table>

The strengths of the two sextupole magnets are -0.95(m$^2$) and 12.05(m$^2$). These are selected so that the chromaticity of the synchrotron vanishes and the separatrix size becomes 24\mum\mm\Mrad.

Results of the simulation show that the separatrices for all momenta are almost congruent and the trajectories of all extracted particles are superimposed (Fig.3).

5. Conclusion

A technique for third-order resonant extraction was given. Two sextupole magnets were driven asymmetrically, and served the two purposes, one of which is to excite the third-order resonance and the other is to correct for chromaticity. The positions of these two sextupole magnets are decided so that the outgoing branches of the separatrices at the deflector are superimposed for all momenta. This technique was applied in a compact synchrotron. Computer simulations showed that the separatrices for all momenta were almost congruent and that the trajectories of all extracted particles were superimposed. High extraction efficiency and low extracted beam emittance would be expected.

Acknowledgement

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References

Particle Orbit Simulation for High Energy Heavy Ion Implanter

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1. Abstract

We have studied an Interdigital-H type Quadrupole (IHQ) linac structure for application to heavy ion implanters. It is possible to vary the output energy by changing the voltage between gaps only. Operating frequency of this IHQ linac is 30 MHz and the synchronous phase is -30° with the exception of -90° at the first gap that works as a bunching section. The calculated results show that the output energy can be varied from 0.48 MeV (30 kcV/u) to 1.6 MeV (100 kcV/u) for 16O+.

2. Introduction

The Heavy ion accelerator technology has been expected to be used in the industrial fields. Conventionally, electrostatic accelerators and cyclotron have been used in those fields. Heavy ion linear accelerators, however, gradually have been developed and used in those industrial applications. In particular, radio frequency quadrupole (RFQ) linacs have been developed and adopted for ion implantation in recent years [1, 2]. However, An RFQ has a problem for low acceleration rate. To solve this problem, we used an IHQ linac that is better than other kinds of linac for acceleration rate. This linac has the drift tube with finger tips to focus the particles, and can vary the output energy so as to be suitable for industrial applications.

Normally drift tube linac is not suitable for variable energy accelerator, because cell length is not appropriate for particles when the gap voltage is changed. Therefore the particle is lost gradually, and it is not able to vary the output energy if there are many cells in the cavity. For the linac we have developed, particles can pass through all drift tubes without many particle losses because of small gap numbers. Consequently, this linac accelerates the particles with variable output energy.

This paper presents the calculated results of beam simulation.

3. Calculation and results

Table 1 shows the principal parameters for IHQ linac.

<table>
<thead>
<tr>
<th>Principal Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge to Mass Ratio</td>
<td>q/A</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>MHz</td>
</tr>
<tr>
<td>Input Energy</td>
<td>keV/u</td>
</tr>
<tr>
<td>Output Energy</td>
<td>keV/u</td>
</tr>
<tr>
<td>Synchronous Phase</td>
<td>deg.</td>
</tr>
<tr>
<td>Maximum Gap Voltage</td>
<td>kV</td>
</tr>
<tr>
<td>Number of Cell</td>
<td></td>
</tr>
</tbody>
</table>

This linac accelerates the particles from 0.24 MeV to 1.6 MeV (maximum) for 16O+. There are 10 cells in the tank and the length needed to accelerate is 0.53 m, but the cavity length is 1.04 m as the electric quadrupole lens is mounted in the cavity. Therefore, acceleration ratio is 1.31 MV/m (2.57 MV/m for only acceleration section). The operating frequency is 30 MHz and synchronous phase is -90° at the first gap and -30° at the other gaps.

By using these parameters, the calculation was done the thin lens approximation. Fig. 1 shows the output energy distribution with different values of gap voltage. V is the normalized gap voltage (1.0 is the designed value) and E is the output energy. It was shown that the total output energy can be changed from 0.48 MeV to 1.6 MeV.

Fig. 2 shows the transmission as a function of gap voltage. The transmission for the drift tube with finger tips is better than the other at the high energy region. Therefore focusing with the finger tips is effective for high gap voltage. On the other hand, for the low gap voltage, no - finger - type is superior to the other because the particle is not lost so that the rf defocusing may be weak if the force due to the
finger is not added. However, as the transmission is good, it is not so problem for using the beam practically.

4. Conclusion

A new drift tube linac that can vary the output energy by changing only gap voltage was presented. This accelerator is suitable for the industrial application because of the advantage of high acceleration rate (1.31 MV/m). The calculation of beam dynamics shows the following results:

- The output energy can be varied from 0.48 MeV (30 keV/u) to 1.6 MeV (100 keV/u) for $^{16}$O$^+$.  
- The electric quadrupole field made by finger tips is effective at high gap voltage.
- The cavity length (with the sections that electric quadrupole magnets are mounted) is 1.04 m because of the high acceleration rate.

5. References

Abstract

The preliminary lattice design for the 3 GeV booster and the 50 GeV main ring in the JHP synchrotron complex has been done. The 3 GeV booster accelerates protons from 200 MeV to 3 GeV with the repetition rate 25 Hz, and injects them to the 50 GeV main ring. The 50 GeV synchrotron has no transition energy because of the imaginary-γ optics.

1 Introduction

The JHP accelerator complex mainly consists of the injector linac, the 3 GeV booster and the 50 GeV main ring [1]. The 3 GeV booster is a rapid cycle synchrotron with the separated function magnets. Each magnet is excited by an independent pulse power supply which is linked each other by multi network system [2]. Therefore we can use regular FODO lattice, and vary the horizontal tune and vertical tune independently.

The main ring has a novel lattice structure [3]. In this lattice, we can choose the value of the transition γ as we like. This value in the 50 GeV main ring is an imaginary number. In this report we represent the lattice design of the 3 GeV booster and the 50 GeV main ring. The optics code SAD (Strategic Accelerator Design) is utilized to optimize the parameters and to do the particle tracking.

2 3 GeV Booster

The 3 GeV ring is operated in a very high repetition rate 25 Hz which needs high rf acceleration voltage of 400 kV [4]. Thus the ring needs to have enough drift space for the rf cavities. In this ring, 24 straight sections each of which length is 6.57 m gives enough space for the rf cavities and the injection and extraction systems. Magnetic field of the bending magnets is rather weak (B=0.95 T) so that the rapid cycle operation is possible. The requirement that the ring is fitted into the KEK-PS tunnel makes the superperiodicity of the ring 4. The overview of the ring is shown in fig 1, and the betatron functions are shown in fig 2.

The nominal tune are selected as (ωx, ωy) = (7.3, 4.3). The γt is 7.13 which is substantially larger than γ=4.20 at the top energy. Table 2 shows the lattice parameters of the 3 GeV ring.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>339.36 m</td>
</tr>
<tr>
<td>superperiodicity</td>
<td>4</td>
</tr>
<tr>
<td>structure</td>
<td>FODO</td>
</tr>
<tr>
<td>number of cells</td>
<td>24</td>
</tr>
<tr>
<td>maximum γ</td>
<td>4.20</td>
</tr>
<tr>
<td>γt</td>
<td>7.1</td>
</tr>
<tr>
<td>nominal tune</td>
<td>(7.3, 4.3)</td>
</tr>
<tr>
<td>natural chromaticity</td>
<td>-8.4, -6.3</td>
</tr>
</tbody>
</table>

3 50 GeV Main Ring

Protons are accelerated from 3 GeV to 50 GeV in the main ring. At the top energy, γ is 54.3. In a conventional way of designing a lattice by using regular FODO cell, γt approximately equals to the horizontal tune ωx. It is difficult to avoid transition energy in the regular FODO lattice, because ωx is about 20 - 30 in a machine of this scale.
Therefore, an imaginary-$\gamma_i$ lattice is employed to eliminate the transition energy. The momentum compaction factor is given by

$$\alpha = \frac{1}{\gamma_i} = \frac{1}{C} \int \frac{\eta(s)}{\rho(s)} ds,$$

where $\eta(s)$ is the dispersion function, $\rho(s)$ is the radius at the orbit position of $s$ in the ring and $C$ is the circumference of the ring. A high $\gamma_i$, i.e. a low $\alpha$ can be obtained when the dispersion at the bending magnets are small.

In order to get this optics, we use a unit cell as shown in Fig 3. This unit cell consists of three DOFO normal cells; $Q_0$, $Q_D$ and $Q_{DX}$. The $\gamma_i$ is optimized so that its absolute value is less than 100 by using these quadrupole magnets.

The circumference of this ring is 1442m which corresponds to the harmonic number $h=34$. Since we need at least four straight sections, we take superperiodicity of 4. The 90° arc consists of six unit cells mentioned above. A bending angle of each bending magnets is 3.75°. There are four straight sections for the injection and the extraction systems, rf cavities and devices to prepare the polarized beam. We are also investigating the possibility of employing superferric magnets, but here we report the feasibility of the ring using normal conducting magnets. In this scheme, there are strong constraints in designing the lattice: magnetic field of the bending magnets should be less than 1.8 T, and field gradient of the quadrupole magnets should be less than 25 T/m. Therefore length of the bending magnets is 6.2m; relatively strong quadrupole magnets which are in the insertions and the missing bend cells have the length of 2m; the length of the remaining quadrupoles are 1.5m. Length of the arc and the straight sections are 300m and 60.5m respectively. There are four normal cells in each straight section. Each cell has 5.56m drift space in which one can locate the extraction septa and kickers.

Two operating modes are considered with the same the lattice: a dispersion free mode and a high intensity mode. In the dispersion free mode, the dispersion in the straight sections are zero for the polarized beam experiments. But for the high intensity mode, we require minimum $P_{\text{max}}$ instead of dispersion free straight sections in order to reduce beam loss.

Since the natural chromaticities are high, the tune spread due to the momentum spread is not negligible; chromaticity correction is essential. The correction is performed by two family sextupole magnets SF and SD. SF’s are placed on both side of QFX’s, and SD’s are placed closed to the QD’s in the missing bend straight sections. The necessary field strength of these sextupole magnets to correct the chromaticity as zero are not so high (SF: 29T/m, SD: 59T/m²) because of the high dispersion in the missing bend sections. With these non-linear elements, we obtain enough dynamic aperture [5]. Table 3 shows the lattice parameters of the 50 GeV main ring in both operation modes.

### 3.1 Dispersion Free Mode

To provide the dispersion free straight sections, we set the horizontal phase advance in the arc to integer; $\psi_{\text{arc}} = 5\times$$2\pi$. Vertical tune is changed by using the all quadrupole magnets in the ring. On the other hand, horizontal tune is adjusted by varying the quadrupole magnets only in the straight sections. Therefore, it is favored that the maximum value of the betatron functions become large when the horizontal tune is changed widely. A tunability of this operation mode is tested on several operating points at which the tunes in the arc are $(\nu_r, \nu_v) =$...
Table 2: Parameters of the 50 GeV main ring

<table>
<thead>
<tr>
<th></th>
<th>dispersion free mode</th>
<th>high intensity mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference</td>
<td>1449 m</td>
<td></td>
</tr>
<tr>
<td>superperiodicity</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>structure</td>
<td>3-cell DOFO</td>
<td></td>
</tr>
<tr>
<td>number of cells</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>maximum γ</td>
<td>54.3</td>
<td></td>
</tr>
<tr>
<td>γ_i</td>
<td>27i</td>
<td>51i</td>
</tr>
<tr>
<td>nominal tune</td>
<td>(24.25, 20.70)</td>
<td>(22.73, 22.66)</td>
</tr>
<tr>
<td>natural chromaticity</td>
<td>-32, -34</td>
<td>-30, -31</td>
</tr>
</tbody>
</table>

(5.0, 4.8), (5.0, 4.6), (5.0, 4.4), (5.0, 4.2).

Fig 4 shows the betatron functions at the operating point \((\nu_x, \nu_y) = (24.25, 20.70)\).

Figure 4: Beam optics functions of the 50 GeV main ring in the dispersion free mode.

With this optics, \(\gamma_i = 27i\), \(\beta_x^{\text{max}} = 32\text{m}\) and \(\beta_y^{\text{max}} = 37\text{m}\). Even if we change the \(\nu_x\) and \(\nu_y\) 23.25 - 24.75 and 20.70 - 23.06 respectively, \(\beta\)'s do not exceed 40m. Also the dynamic aperture at each operating point is calculated respectively after the chromaticity correction is performed, and is found to be larger than the acceptance. Thus substantial tunability is obtained with this operation mode.

3.2 High Intensity Mode

To keep the beam loss small in the high intensity mode, the beam size is desired to be small. Then we need to make \(\beta\) as small as possible i.e. to make \(\beta^{\text{max}}\) flat all over the ring. To do this, we sacrifice the benefit of the dispersion free straight sections; but we still require the imaginary-\(\gamma_i\) lattice. Fig 5 shows the optics of this mode. One can find that no \(\beta\) modulations.

The dispersion function in the straight sections take non zero values; but these values are not so high that the injection and the extraction can be done in these sections. A tunability of this mode is tested as well as the dispersion free mode. We vary the tune \(\nu_x = 22 - 24\), \(\nu_y = 21 - 24\), and find that \(\beta\)'s are less than 32m. Dynamic aperture is examined in several operating points and found to be larger than the acceptance.

4 Summary

The 3 GeV booster has been designed with regular FODO cell structure. It will be constructed in the KEK-PS tunnel. The 50 GeV main ring has been also designed with the imaginary-\(\gamma_i\) lattice. We investigated feasibility of 50 GeV main ring with imaginary-\(\gamma_i\) optics, and found that it has enough tunability and dynamic aperture.

References

BUNCH LENGTHENING OF THE NIJI-IV


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Abstract

The bunch length and the beam sizes in the single bunch operation on the storage ring NIJI-IV dedicated to FEL were measured and analyzed by using theories of the potential well distortion. The measured bunch length were in good agreement with the theoretical fitting curve with the longitudinal coupling impedance of $14\,\Omega$, and the microwave instability was not found at beam current of below $8\,\text{mA}$. The measured beam sizes in the both directions were constant at below $8\,\text{mA}$. It was convinced from the measured bunch length and the horizontal beam size that the energy spread is not increased at the beam energy of $310\,\text{MeV}$.

1. Introduction

The NIJI-IV is a compact storage ring dedicated to free-electron lasers (FELs). Lasings of FEL at 595 nm and 488 nm in the visible wavelength region and at 352 nm in the UV region were achieved up to 1994[1,2,3].

Generally, the potential well of the vacuum chamber causes the bunch lengthening. On some storage rings, the microwave instability brings about the turbulence bunch lengthening with increase of energy spread above a threshold current. Since these effects decrease peak current and FEL gain, it is important that these effects are investigated.

In this paper, the beam current dependencies of the beam size and the bunch length are discussed taking into account the distortion of the potential well theoretically. The threshold current of the microwave instability was not found at the beam current of below $8\,\text{mA}$. A longitudinal coupling impedance $|Z/n|$ obtained from the theoretical fitting curve of the distortion of the potential well was about $14\,\Omega$. The large widening of the beam size measured was not found in both directions in the single bunch operation. The energy spread is not increased.

2. Theory of bunch lengthening

The bunch lengthening was studied by Hansen[4], Sachera[5], Chao[6] and others. In single bunch operation, the coupled bunch instability does not occur, so only the potential well distortion should be taken into account as a cause of the bunch lengthening. Below a certain threshold current, the bunch lengthening due to the distortion of the potential well by the vacuum duct is given by

$$\left(\frac{\sigma_{\text{j}}}{\sigma_{\text{nj}}}\right)^3 - \left(\frac{\sigma_{\text{R}}}{\sigma_{\text{nj}}}\right)^3 - \frac{1}{Z/n} \frac{R}{\sqrt{2\pi} v_0 E} \left(\frac{\sigma_{\text{R}}}{\sigma_{\text{nj}}}\right)^3 = 0$$

(1)

where $E$ is the beam energy, $\sigma_{\text{j}}$ is the standard deviation of the natural bunch length, $\sigma_{\text{R}}$ is the standard deviation of the bunch length, $R$ is the average radius of the storage ring, $e$ is the electron charge, $|Z/n|$ is the longitudinal coupled impedance, $v_0$ is phase oscillation wave number $\alpha$ is momentum compaction factor[4]. The criterion of the threshold current $I_\text{th}$ of the microwave instability is described by

$$I_\text{th} \approx \sqrt{2\pi} \frac{\sigma_{\text{j}}}{R} \frac{E\alpha}{|Z/n|} \left(\frac{\sigma_{\text{E}}}{\sigma_{\text{nj}}}\right)^2$$

(2)

The energy spread $\sigma_{\text{E}}$ increases above the threshold current as follows.

$$\left(\frac{\sigma_{\text{E}}}{\sigma_{\text{E0}}}\right) = \left(\frac{\sigma_{\text{j}}}{\sigma_{\text{nj}}}\right)^2 \left(\frac{\sigma_{\text{E0}}}{\sigma_{\text{nj}}}\right)^2$$

(3)

where $\sigma_{\text{E0}}$ is the energy spread determined from the radiation damping and the quantum excitation.

3. Measurement of bunch length

Time structure of the synchrotron radiation from an electron bunch at a bending section was observed by using a fast avalanche photodiode (ANTELL-270, rise time below 90 ps) and a sampling oscilloscope (HP-5490, sampling head 6740 with the frequency response of 50GHz). The bunch forms obtained with decrease of beam current were analyzed and their standard deviations were evaluated. Figure 1 shows the current dependence of bunch lengthening measured in the single bunch operation. The threshold of the bunch lengthening was not found in the measured beam current of below $8\,\text{mA}$. The dash line
was a fitting curve by the EQ(1). The longitudinal coupling impedance $|Z_{n}/n|$ obtained from the fitting curve was about 14 Q. A longitudinal coupling impedance $|Z_{n}/n|$ of a smooth vacuum duct with a finite conductivity $\sigma_{con}$ is written by

$$\frac{Z_{n}}{n} = \frac{1-i}{b} \sqrt{\frac{2\pi \sigma_{con}}{\beta y}} Z_{0} \left( \frac{1}{4} + \ln \frac{b}{\alpha} \right)$$

(4),

where $\gamma$ is the relativistic energy, $\beta$ is the ratio of the electron velocity to the light velocity, $Z_{0}$ is the free space impedance 377 Q, $b$ is the radius of the vacuum duct cross section, $a$ is radius of the transverse beam size, $n$ is mode number[7]. The longitudinal impedance of the bellow is written by

$$\frac{Z_{n}}{n} = -i b_{total \ length \ the \ bellow} \ln \frac{b}{b_{circumference}}$$

(5),

where $b'$ is outer radius of the bellow[7]. Generally, the longitudinal coupling impedance of smooth vacuum duct is much smaller than one of the bellows. On the NIJ1-IV, if the all vacuum chambers except for the bellows are smooth, its impedance is below 1 Q by EQ(4). The impedance of the bellows is about 2 Q by EQ(5). The longitudinal impedance 14 Q obtained from bunch lengthening measurement is much larger than the estimated one. In practice, the chambers with the screen monitor( screen monitor inputs and outputs owing to obtaining the position of the injection beam) are unsmooth and there are 6 screen monitors in the ring. It is not large compared with the values of the other rings, for example 20 Q for the SRS[8], 30 Q for SPEAR- I [9] and 40 Q for SOR[10]. Under the observed current( below 8mA), turbulence bunch lengthening was not observed. The threshold current estimated by EQ(2) is about 18mA. The measured result is reasonable for the estimated value. This means that the energy spread is not increased under 8mA. It is important that the degradation factor $f$ [1] of FEL gain is not decreased.

4. Measurement of the beam size

The beam size at the bending section was obtained from the synchrotron radiation through a focusing lens by a CCD(charge coupled device) camera. The focusing length, the length between the radiation point and the lens, and the length between the lens and the CCD camera are 0.5m, 1m and 1m, respectively. The beam profile with the same scale was displayed on the camera. It is convenient that the camera has linearity on the relation between the light intensity and the output signal. This relation was investigated by using the some neutral density filters and the synchrotron radiation from the bending section. The beam profile is kept for long time at low beam current of 0.1mA and can be used as a standard light source. Figure 2 shows the relation between the light intensity and the output signal. The output signal of the camera is proportional to the light intensity. Figure 3 shows examples of the light intensity in horizontal and vertical direction. The beam profiles in the both direction can be fitted by the Gaussian distribution. Figure 4 shows the relation between the beam current and the beam sizes $\sigma_{x}$ and $\sigma_{y}$ in both directions in the single bunch operation. The large widening of the beam size was not found in both directions. It means that the energy spread is not increased and the microwave instability does not occur at below 8mA. It is shown that the emittance growth due to the effect of the intrabeam scattering also is very small. The emittance growth estimated from the theory of the intrabeam scattering is increase of a few percent at 8mA.
bunch operation on the storage ring NH1-IV dedicated to FEL were measured and analyzed by using theories of the potential well distortion. The threshold current was not found at the beam current of below 8mA and the microwave instability does not occur. The longitudinal coupling impedance $|Z_{pp}|$ obtained from the theoretical fitting curve was about 14 $\Omega$. The impedance of the bellows is about 2 $\Omega$. The longitudinal impedance is 14 $\Omega$ obtained from the measurement is much larger than the estimated one. It is considered that the difference of the impedance is due to the unsmooth chambers. The large widening of the beam size measured was not found in both directions in the single bunch operation. The energy spread is not increased and the microwave instability does not occur at below 8mA. The emittance growth due to the effect of the intrabeam scattering also was very small. The emittance growth estimated from the theory of the intrabeam scattering is increase of a few percent at 8mA.

References


Basic Design of an Asymmetric Double Slow Extraction System for the KEK-PS

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Abstract
Simultaneous extraction to two beam lines of the KEK 12GeV Proton Synchrotron (KEK-PS) has been theoretically calculated. Unlike double extractions at other facilities, the two extraction lines are not equal in resonant phase. The test operation is also reported.

INTRODUCTION
Resonant slow extraction is widely used in almost all existing synchrotrons. Some of them have two extraction lines, and extract beam to both of lines simultaneously in order to save on the operation time. ZGS at ANL, reported by E. A. Crosbie and Y. Cho et al.[1], was initially designed for double extraction. Its two extraction lines were set just at opposite sides of the ring, and other elements were also symmetrically positioned. SPS at CERN, reported by M. Gyr et al.[2], had two lines which were not diametrically symmetric. In order to realize equality of the two lines in resonant phase, they divided the set of F-quadrupoles into 2 halves and excited them with slightly different currents. At the KEK-PS the new slow extraction line (EP1)[3] for the newly built North Counter Hall was constructed in 1991, besides the EP2 for the East Counter Hall. The present lay-out of the KEK-PS is shown in Figure 1. Each extraction line has its own independent extraction system designed for single extraction; they are not symmetrically positioned. However, strong request for a longer machine time makes double extraction an urgent theme. We report on the possibility of double extraction with minimum change to the present system.

BASIC DESIGN OF DOUBLE EXTRACTION
The extraction system of the KEK-PS was designed based on theoretical studies by K. Endo and C. Steinbach [4], utilizing the half-integer resonance (2ννh=15). One perturbing quadrupole magnet (EQ) is inserted into the lattice in order to produce a half-integer stop-band. One octupole magnet (OCT) is excited in order to separate phase space into stable and unstable regions. The tune is then approached slowly to the half-integer, the stable region becomes ever smaller, and particles are ejected from the machine. The shaven beam at the first septum, ESS (electro-static septum), is deflected by 5 magnetic septa (named Septum A, B, C, D and E)(Figure 2) and guided to the extraction channel.

\[ \frac{\Delta Y}{\Delta X_{X=0}} = \tan \mu_j = \frac{\sin(2\mu_j)}{1+\cos(2\mu_j)} \]  

Here, X and Y are coordinates defined by the following well-known equations:

Figure 2 Septum array of a slow extraction line (EP1).
\[
X = x/\sqrt{\beta} \\
Y = \sqrt{\beta} \left[ x' + (\beta/\alpha) x \right],
\]

(2)

where \(\alpha\) and \(\beta\) are the unperturbed twiss parameters. An unperturbed lattice means that \(EQ\) is zero, and thus has no half-integer step-band. The \(2\mu_j\) is \((3/8)\pi\) at single extraction, as shown in Figure 3. In order to guide the extracted beam through the septum array \(2\mu_j\) must satisfy

\[
0 < 2\mu_j < \pi.
\]

(3)

The next step was to perform a single-particle tracking simulation. The main lattice magnets (56 quadrupoles and 48 dipoles) were used in the calculation as thick lens matrices. Their higher order components were approximated with two thin multipoles set at both ends of each magnet. Sextupole magnets for chromaticity control and perturbations (\(EQ\) and \(OCT\)) were approximated as thin-lens components. The strengths of \(EQ\), \(OCT\) and the sextupoles were set at the values used for a single extraction (their strengths were 0.03 m\(^{-1}\) and 4.0 m\(^{-3}\), respectively [5] and the horizontal chromaticity was -6). We calculated the outgoing separatrix lines in the x-x' plane of two particles. One has a Courant-Snyder invariant of zero and a momentum displacement of -0.08%; the other has a Courant-Snyder invariant of \(3\pi\) mm mrad and a +0.08% momentum displacement. Figure 4 (b) shows the separatrices of single extraction. Here, \(ESS\) was set so that the step-size was about 10 mm. Figure 4 (a) shows the separatrices at \(EP_1\) when \(EQ\) and \(OCT\) of \(EP_2\) were used. Figure 4 (c) shows separatrices at the \(EP_2\) when \(EQ\) and \(OCT\) of \(EP_1\) were used. The resonant phase \(2\mu_j\) is \(-\pi/8\), \((3/8)\pi\) and \((7/8)\pi\) for (a), (b) and (c), respectively. Table I shows the performance of extraction in three cases. Case (b) was the best. Although case (c) was acceptable, case (a) was not. Therefore, the setting of \(EQ\) and \(OCT\) for \(EP_1\) is one possible solution.

For double extraction it would be important to enlarge the step-size because the same step-size would be shared with two extraction channels. We calculated two ways to enlarge the step-size. One way is to also excite \(OCT\) for \(EP_2\) besides \(OCT\) for \(EP_1\). Another is to set the \(ESS\) far from the equilibrium orbit (identical to reducing the bump height). As listed in Table II, the first way is better because the step-sizes at \(EP_1\) and \(EP_2\) were well balanced.
Table I  Extraction parameters at the entrance of the ESs of EP1 and EP2.

<table>
<thead>
<tr>
<th>perturbation for EP2</th>
<th>EP1</th>
<th>EP2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picture in Figure 3</td>
<td>(a)</td>
<td>(b)</td>
</tr>
<tr>
<td>resonant phase 2\mu_j (rad)</td>
<td>\pi/\lambda</td>
<td>(7/8)\pi</td>
</tr>
<tr>
<td>Extraction Bump (mm)</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>(mrad)</td>
<td>1.1</td>
<td>-1.2</td>
</tr>
<tr>
<td>step-size (mm)</td>
<td>7.5</td>
<td>9</td>
</tr>
<tr>
<td>angle divergence (mrad)</td>
<td>1.23</td>
<td>0.65</td>
</tr>
<tr>
<td>Expected beam loss (%)</td>
<td>22%</td>
<td>4%</td>
</tr>
</tbody>
</table>

Table II Extension of the step-size by (1) exciting OCT of EP2 or by (2) lowering the extraction bump.

<table>
<thead>
<tr>
<th>method</th>
<th>(1)</th>
<th>(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>extraction line</td>
<td>EP1</td>
<td>EP2</td>
</tr>
<tr>
<td>Bump height (mm)</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>step-size (mm)</td>
<td>9.5</td>
<td>8.5</td>
</tr>
</tbody>
</table>

EXPERIMENTAL RESULTS

For double extraction we started from single extraction for EP1, and then gradually raised the local bump orbit for EP2 to share the step-size of the extracted beam. Here, the servo-spill control system [6] for EP1 was used. The extracted beam intensity for EP1 and for EP2 changed with the bump height at EP2, as shown in Figure 5. The required bump height of EP2 was higher by 16mm and steeper by 4mrad than that of EP1, as had been predicted. However, the step-size at EP2 appeared to have a long tail, which was not expected.

The parasitic use of an internal target (triple extraction) was also successful.

Under long-term operation, double extraction was less stable to same external disturbance than single extraction. External disturbances, such as drifting of the magnetic field or emittance change due to the condition of the injectors, easily change the intensity ratio of EP1 to EP2, because they are asymmetric. To stabilize double extraction for daily operation, we need another kind of feed-back system.

When a very small amount of the beam was extracted to EP2 (less than a twentieth of EP1), double extraction was stable because of the long tail of the step-size at EP2. However this was though to be scattered protons mainly at the magnetic septa of EP1, which therefore would when the beam loss at EP1 is improved.

CONCLUSION

We succeeded to extract beams to two lines within a short period (less than a day). For its daily use, an improvement of the servo control system or of more stabilization of the entire machine is desired.

Although this solution is not the best, it is possibly a solution involving a minimum change of the present system. If we can afford other resonances, \nu h=20/3 or \nu h=16/3 there might be better solutions, where the resonant phases of EP1 and EP2 are identical. However, we should redesign most of the system for the third-integer resonant extraction.

REFERENCES

LOW-EMITTANCE SLOW EXTRACTION USING HALF-INTEGER RESONANCE

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I INTRODUCTION

At the KEK-PS a resonant slow extraction using a half-integer resonance \((2v + h = 15)\) has been in operation. This article deals with a particular problem concerned with the separatrix dependency on chromaticity of resonant extraction. That dependency was first calculated by H. Bruck et al. [1] and later by W. Hardt [2] for \(1/3\)-integer resonant extraction. They showed that the outgoing separatrices of different momentum overlap under a certain condition (overlap condition). It is desirable to obtain a separatrix branch with low divergence at the first septum (usually ESS) position in order to minimize particle losses on it. Although the design of a resonant slow-extraction system is usually done by numerical ray-tracing, analytical guide formulae for a simple estimation of the parameters is desirable. Unfortunately, the overlap condition has never been calculated for half-integer resonant extraction. This seems to be due to a difficulty in treating the parabolic form of the separatrix arm, to a straight separatrix arm of the third-integer resonance. In addition, twiss parameters \((\alpha, \beta, \gamma)\) introduced by Courant and Snyder [3], and the chromaticity go to infinity when the tune approaches to a half-integer. The formulae given in this article have been applied to parameter setting of resonant slow extraction at the KEK-PS.

In half-integer resonant extraction at the KEK-PS, one perturbing quadrupole magnet is inserted into the lattice in order to produce a half-integer stop-band. The total tune \((v)\) is quite close to a half-integer \((2v + n)\). One octupole magnet is excited in order to separate phase space into stable and unstable regions. The tune is then approached slowly to a half-integer value, and the stable region becomes smaller and smaller as the tune approaches this half-integer, and the particles are ejected from the machine. This is the process of extraction.

Although particles with different momenta are usually extracted at the same time, they follow different separatrices in phase space. The difference in the angle at the ESS is the dispersion angle of the extracted beam, which is responsible for the angle divergence of the beam. One reason for the displacement is a difference in their tune, which produces a difference in the stable area in the separatrix. Another reason is a displacement by the the dispersion function. These effects are schematically shown in Figure 1. Although the first displacement depends on the chromaticity and the second one does not. Therefore, when one choose the chromaticity properly, the separatrix arms of different momenta overlap as shown in Figure 1. Actually in half-integer resonant extraction, the separatrix arms do not overlap, but only cross, because the separatrix arms are not straight lines. However, this is practically sufficient for efficient slow extraction.

III CALCULATION OF SEPARATRIX

Here, the twiss parameters and chromaticity \((\xi)\) of the unperturbed lattice are assumed to be known. Since an unperturbed lattice has no perturbation quadrupole, it also has no half-integer stop-band. Using the formula calculated by T. Suzuki and S. Kamada [4], the separatrix line in the unperturbed normalized phase space is expressed as

\[
\begin{align*}
(a) & \quad y = \frac{1}{\sqrt{\alpha^2 - 1}} \\
(b) & \quad y = \frac{1}{\sqrt{\alpha^2 - 1}} \\
(c) & \quad y = \frac{1}{\sqrt{\alpha^2 - 1}}
\end{align*}
\]

Figure 1 Separatrices in unperturbed normalized phase space. The machine parameters of the KEK-PS are used. (a) Separatrices with different emittance: 0 and 3n mm mrad. (b) Displacement by the dispersion (momentum displacement was +0.4% and -0.4%). (c) The outgoing separatrix lines are crossing at the ESS edge. One separatrix is of a particle with zero emittance and zero momentum displacement. Another separatrix is of a particle with 3n mm mrad emittance and -0.27% momentum displacement.
Coordinate \((X, Y)\) is defined according to a well-known form:

\[
X = x/\sqrt{B} \quad \text{and} \quad Y = \sqrt{B} \left[ x' + (p/a) x \right].
\]

(2)

The two phases \((\mu_1, \mu_2)\) are the unperturbed betatron phase advance from the entrance of the ESS to the octupole magnet and to the perturbation quadrupole magnet, respectively. The strength of these perturbations are represented by \(D\) and \(B\), which are defined by

\[
D = \left( \frac{1}{12\pi} \right) \left( \Delta B_2 \right) \frac{1}{B} \quad \text{and} \quad B = \left( \frac{1}{2\pi} \right) \left( \Delta B_2 \right) \frac{1}{B}. \]

(3)

(4)

Since the unperturbed tune \((\nu)\) has almost a half-integral value \((n/2)\), \(\varepsilon (n/2) - 1/2\) is very small.

We treat the case when the perturbed tune of a particle with zero momentum displacement \((dP/P = 0)\) is just \(n/2\), which means that the separatrix has just zero stable area. However, a particle with \(\delta \neq 0\) has a finite stable area \((\pi E_{\text{max}})\) because of the chromatic tune shift. We first calculate the separatrix when \(\delta = 0\). In this case \(\varepsilon = B\) and the separatrix is expressed as

\[
-X \sin \mu_1 + Y \cos \mu_1 = \sqrt{\frac{D}{2B}} \left( X \cos \mu_1 + Y \sin \mu_1 \right)^2. \]

(5)

On the other hand, when \(\delta \neq 0\), \(\varepsilon\) is written as \(\varepsilon = B - \xi\) using unperturbed chromaticity. Therefore, the separatrix is

\[
-X \sin \mu_1 + Y \cos \mu_1 = \sqrt{\frac{D}{2B}} \left( X \cos \mu_1 + Y \sin \mu_1 \right)^2 + \xi (B - \xi) \left( \frac{D}{2B} \right) \left( X \cos \mu_1 + Y \sin \mu_1 \right)^2. \]

(6)

The displacement due to the dispersion function \((\eta_1, \eta_2)\) is taken into the calculation due to the dispersion in the unperturbed normalized phase space \((H, \beta)\). Since equilibrium orbit is displaced by \((H_0, \beta_0)\), the \(X\) and \(Y\) of equation (6) should be replaced by \(X - H_0\) and \(Y - \beta_0\), respectively. We now define the \(Y_s\) so that the \((X_s, Y_s)\) satisfy equation (5) and \((X_s, Y_s + h'_6 + h''6 + \ldots)\) satisfy equation (6). Here, \(h'_6\) is the dispersion angle of the extracted beam in normalized phase space. Upon subtracting equation (5), and omitting more than the 2-nd order terms to \(\delta\), we obtain

\[
H \sin \mu_1 + (H' - \xi) \cos \mu_1 = \xi \sqrt{\frac{B}{2D}} \left( X \cos \mu_1 + Y \sin \mu_1 \right) \left( X \cos \mu_1 + Y \sin \mu_1 \right), \]

(7)

To simplify the equations, we rewrite them using

\[
X^* = \sqrt{\frac{B}{2D}} X, \quad Y^* = \sqrt{\frac{B}{2D}} Y, \quad H^* = \sqrt{\frac{B}{2D}} H, \quad H'^* = \sqrt{\frac{B}{2D}} H', \quad h^* = \sqrt{\frac{B}{2D}} h' \quad \text{and} \quad \xi^* = \xi \sqrt{\frac{B}{2D}} \]  \]

(8)

(9)

so that they contain neither \(B\) or \(D\) explicitly. Equations (5) and (7) become

\[
2(-X \sin \mu_1 + Y \cos \mu_1) = (X \cos \mu_1 + Y \sin \mu_1)^2, \]

(10)

\[
H \sin \mu_1 + (H' - \xi) \cos \mu_1 = \xi \left( \frac{1}{\Delta B_2} \right) \left( X \cos \mu_1 + Y \sin \mu_1 \right) \left( X \cos \mu_1 + Y \sin \mu_1 \right). \]

(11)

The sign of equations (8) is selected in order that \(X^*\) times \(X^*\) should be positive. Only one of two solutions of equation (10) is correct; that is

\[
Y^* = \xi \cos \mu_1 X^* + \sin \mu_1 Y^* \]

(12)

here

\[
F = 1 - 2\sin \mu_1 \cos (\mu_1 + \mu_2) \cos ^2 \mu_2. \]

(13)

Equation (11) is solved straightforward manner using equation (12) as

\[
(H' - \xi) \cos \mu_1 + H \sin \mu_1 = \xi \left( \frac{1}{\Delta B_2} \right) \left( X \cos \mu_1 + Y \sin \mu_1 \right) \left( X \cos \mu_1 + Y \sin \mu_1 \right). \]

(14)

As has been explained, since the separatrices cross when \(h^* = 0\), setting \(h^*\) to 0 gives the crossing condition of the separatrices at the ESS.

\[
\xi \mu_1 \left( F \cos \mu_1 \cos (\mu_1 + \mu_2) \sin ^2 \mu_2 \right) - X^* \cos \mu_1 \sin \mu_1 \left( H' + \xi \right) \left( \Delta B_2 \right)^{-1/2}. \]

(15)

This is one goal of this article. However, in the calculations some small effects are ignored, such as the momentum dependence of \(\mu_1, \mu_2, \alpha, \beta, \gamma, \eta_1, \eta_2, D\) and \(B\), and the change of \(\xi, \eta_1, \eta_2\) due to the perturbation quadrupole, and a higher order effect to \(\eta\). Although it is possible to use them in the calculation, the resultant equation is too complicated. A computer-tracking simulation would be more suitable to obtain more accurate solution. It would be helpful if we have a more simple, but less accurate, formula for the crossing condition. In the limit \(X^* = 0\), which means that all separatrices pass the equilibrium center, equation (15) becomes much more simple as

\[
\xi^* = H' \sin \mu_1 \cos \mu_1 \]

(16)

We next calculate the chromaticity dependence of the angle divergence. The momentum spread of the extracted beam at one instance \((\Delta \xi^{\text{max}})\) is determined by the emittance and chromaticity. The angle divergence at the ESS edge \((\Delta Y^\text{normal} \text{ized phase space})\) is the product \(\Delta \xi^{\text{max}} \beta'\). Since \(\Delta Y^\text{normalize}d\) is not constant during the extraction, we calculate the spread at the middle, where the \(\Delta Y\) is maximum. The \(\Delta \xi^{\text{max}}\) is determined from the emittance \((\pi E_{\text{max}})\), maximum Courant Snyder invariant), which is
\[ n \varepsilon_{\text{max}} = (4/2/3)(\varepsilon(\varepsilon-B)^{1/2}/[D(\cos^2(\mu_j-\mu_i) + (\varepsilon B))^{1/2} \cdot (4/2/3)(\varepsilon^* \varepsilon_{\text{max}})^{1/2} \cdot [D/D(\cos^2(\mu_j-\mu_i))]]). \quad (17) \]

Therefore,

\[ \delta_{\text{max}} = [(3/4)^2/(\varepsilon \varepsilon_{\text{max}} D/B) \cos(\mu_j-\mu_i)]^{2/3} \varepsilon^* \varepsilon^{1/2}. \quad (18) \]

However, when the right side of the above equation is larger than the full momentum spread of the circulating beam \( (|\Delta P/P|_{\text{max}}) \), \( \delta_{\text{max}} \) is equal to \( |\Delta P/P|_{\text{max}} \). When \( \delta_{\text{max}} \) is smaller than \( |\Delta P/P|_{\text{max}} \), the momentum center of the extracted beam shifts from the beginning of the extraction to the end (when the circulating beam is not accelerated during slow extraction).

### III APPLICATION TO THE KEK-PS

The parameters of the KEK-PS are:

\[ \alpha = 2.20; \quad \beta = 15.8 \text{m at the ESS} \]
\[ \mu_j = (105/28)\pi; \quad \beta = 0.051 \]
\[ \mu_i = -(75/28)\pi; \quad D = 100/\text{m} \]
\[ x_s = 32 \text{mm}; \quad \eta = 1.86 \text{m} \]
\[ \eta' = -0.1076 \text{ mrad} \]

Inserting these parameters into equation (15) gives \( \xi^* = 24 \), i.e. \( \xi = 0.88 \). This means that the angle divergence is zero when the chromaticity is set at the small positive value: 0.88. When we use the simple equation (16) the result is \( \xi = 0.41 \).

The maximum angle divergence \( \Delta Y_{\text{max}}/\sqrt{\beta} \) is calculated using the parameters of the KEK-PS at the top-energy: \( n \varepsilon_{\text{max}} = 3\pi \text{ mm.mrad} \) and \( |\Delta P/P|_{\text{max}} = 0.8\% \). The result is shown in Figure 2.

The chromaticity dependence of the extracted beam size was observed at the KEK-PS while extracting 3.5GeV protons. The extracted beam profiles at several timings during the slow extraction was measured by the SWIC (Segmented Wire Ionization Chamber) at the down stream of the last magnetic septum (betatron phase advance from the ESS was about \( 3/4 \pi \)). The horizontal beam profiles are shown in Figure 3. Although the beam width was smaller at a small positive chromaticity, the measurement missed the chromaticity which would have given the minimum. The shifts in the beam position from the start of extraction to the end was a reflection of the shift in the central momentum of the extracted beam. When the chromaticity was zero, the beam was split at the start of extraction because of the non-linear chromaticity. This curious beam behavior was reproduced in a computer-tracking simulation.

![Figure 2](image1.png)

**Figure 2** Maximum angle divergence at the ESS as a function of the horizontal chromaticity (\( \xi \)).

### IV CONCLUSION

The crossing condition of the separatrix arms of the half-integral resonance was analytically calculated.

This has already been utilized at the KEK-PS during the extraction of protons and a light-ion beam with smaller rigidity. Unfortunately, at the time of top-rigidity the power supply of the chromaticity control sextupoles is not powerful enough to over-cancel the negative chromaticity to positive. However, below 10GeV (proton) this condition can be realized, and produced a dramatic improvement in the extraction efficiency and emittance of the extracted beam.

### REFERENCES


![Figure 3](image2.png)

**Figure 3** Horizontal beam profile of the extracted beam at the SWIC. The chromaticity was -7, -3.5, 0, +3.5, +7 from the left. The time from the top trace to the bottom trace was about 2 seconds. The full-scale of the horizontal axis is about 80mm.
The effect of trapped ions is shown to cause a serious problem in NTT normal-conducting accelerating ring (NAR), which adopted extremely low injection energy (15 MeV). Although the large beam size at injection reduces the effect of ions, the ions seem to affect the beam more seriously than expected from the calculation. In this paper, ion trapping effect in NAR are examined both theoretically and experimentally.

1. Introduction

To reduce the size and cost of the injector LINAC, we adopted low injection energy (15 MeV) for NAR, which is used for SR applications at final energy (800 MeV). To remove ions, twelve sets of button type electrodes are placed in the ring of 52.8 m circumference and are always used. However, a couple of phenomena which seem to be caused by trapped ions are observed. Generally speaking, lower energy electrons are more liable to be affected from trapped ions but the evaluation is not so simple because the energy dependent electron beam size also has an important effect.

At 15 MeV, the large beam size at injection preserves over a long period because of the long radiation damping time. Therefore, the size of trapped ions is also large and the ion density is low. The larger beam size result in smaller effect on electron beam. On the contrary, the experiment shows that ion trapping problems are serious though the electron beam size is large at injection. Short life time and lack of appropriate monitors make the analysis more difficult.

According to the calculation of beam potential, the possibilities that the clearing electrodes are not placed properly and that ions are accumulated in the bending sections where the potential is deep are pointed out.

To avoid the effect of ions, we examined to adopt the partial fill operation which is a well known method to avoid ion trapping. The calculation and preliminary experiment showed that this method is not effective at injection whereas it is effective in storage.

In this paper, ion trapping effect observed in NAR is described. Outline of NAR and calculated result of the beam potential are presented in section 2 and the effect of trapped ions is numerically examined in section 3 and 4. Experimental result is shown in section 5. The effect of partial fill is tested in section 6. Ion trapping effect in NAR is compared to the effect in Super-ALIS in section 7.

2. Beam Potential

Lattice functions, beam size, and beam potential are calculated and shown in Fig. 1 for one fourth section of NAR. Lattice functions are re-calculated assuming the conditions used in injection experiment.

Beam size at injection is computed from the following formula,

$$\sigma_x = \sqrt{\varepsilon_x \beta_x + (\sigma, \eta)^2}$$

$$\sigma_y = \sqrt{\varepsilon_y \beta_y},$$

where $\varepsilon_x$ and $\varepsilon_y$ are the horizontal and vertical emittances, and $\sigma, \eta$ is the energy spread. Whereas these emittances and energy spread during storage can be calculated theoretically, they depend on various conditions at injection. Therefore, two possible cases were examined. In case 1, $\varepsilon_x = 10 \times 10^4$ (mm-rad), $\varepsilon_y = 1 \times 10^4$ (mm-rad), $\sigma, \eta = 5 \times 10^4$ are assumed while $\varepsilon_x$ is replaced by $2.5 \times 10^4$ in case 2. Horizontal emittance is large because electrons are injected by bumping closed orbit in horizontal plane.

Beam potential is computed against these two cases assuming elliptical (rectangular) vacuum chamber and beam (Fig. 1). The inner surface of vacuum ducts including the bending sections have nearly the same size except the section where RF cavity is located and RF knock out electrodes are placed. Then the size of vacuum duct is approximated to be constant rectangular shape of 120 x 58 mm$^2$. Beam current is assumed to be 100 mA.

To remove ions, button type electrodes are placed at both ends of long straight sections (nearby QD) and in the middle of short straight sections (nearby QFC). The positions of these electrodes are also shown in Fig. 1.

3. Neutralization Factor

Neutralization factor ($\beta$) is defined as $n_t / n_e$ where $n_t$ is the number of trapped ions and $n_e$ is the number of electrons. The

![Fig. 1 Lattice functions, beam size, and beam potential](image-url)
neutralization factor at injection is roughly estimated with ion clearing electrodes. Assuming that the residual gas molecules are CO, the ionization time ($t_{ion}$) which is the average time required for an electron to ionize a molecule is about one second. If there is no mechanism to clear ions, neutralization factor increases in proportion to elapsed time from injection and reaches as large as 100% in one second. On the contrary, if a molecule ionized and trapped by the electron beam drifts along the electron beam with the thermal velocity (a few hundreds meters per second) and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. Therefore, the neutralization factor approaches to the equilibrium and is cleared at the electrodes which are placed in four to five meters intervals, an ionized molecule remains trapped for 10 msec. 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However, considering the expected life time of vacuum pressure is longer than 10 seconds, the observed life time is still short even when the ion clearing electrodes are used.

The rising time of DCCT is about 100 msec which is too slow to observe the transition current just after injection. Then, the RF pick up signal of the electron beam is observed with spectrum analyzer which is set to measure RF acceleration frequency (125 MHz) with zero span mode (Fig. 3). The signal is thought to be proportional to the square of the current. As the vertical axis in Fig. 3 is in logarithms scale, the current graph is expected to be straight as long as the beam current decreases with constant lifetime. On the contrary, the slope gets steeper about 30 m sec (without ion clearing) and 50 m sec (with ion clearing) after injection.

This life time change is thought to be due to ion trapping effect from the following reasons. One is that the effect gets weaker if the ion clearing electrodes are used. Another reason is that the timing when the electron beam begins to be affected is consistent with the intervals required to produce ions of a few % neutralization. Estimated from the tune shift calculation in section 2, it is possible that the life shorten due to the tune shift induced by trapped ions of a few % neutralization.

Ion production rate at injection may be larger than the rate calculated in section 3 because much electrons which cannot be captured by RF bucket or have large amounts exist and ionize molecules, though these electrons are lost after a while and do not contribute to the beam current.

Even when the ion clearing electrodes are used, Fig. 3(a) shows the similar shape as that of Fig. 3(b) (without clearing). This indicates that ions cannot be removed well even if the clearing electrodes are used.

Therefore, the assumption that ions can drift along the electron orbit freely and clear at the electrodes does not seem valid. As expected from the calculation of case 1 in section 2, ions might be accumulated at neutralization pockets where beam potential is deep.

These interpretations are presumptions and are not proved yet. However, no other interpretation is presented thus far.

6. Partial Fill Operation

It is well known that partial fill operation is an effective method to remove trapped ions. This method is examined as a measure to avoid ion trapping effect at injection. Partial fill operation in storage is also

---

![Fig. 2](image2.png)

**Fig. 2**

Current decrease after injection

Upper line: ion clearing on
Lower line: ion clearing off

Horizontal: 100 msec/div
Vertical: 20 mA/div

![Fig. 3](image3.png)

**Fig. 3**

RF pick-up signal of electron beam
(a) upper - ion clearing on
(b) lower - ion clearing off
investigated for the purpose of confirming the effect of this operation.

First of all, the effect of partial fill is numerically estimated. Fig. 4 is a calculated result in storage (800 MeV). The partial fill operation can be effective to remove ionized light molecules such as H₂. At injection energy (15 MeV), ion motion always remains stable. The difference is caused by the difference in beam size. At 15 MeV, because of the large beam size, the focusing force per bunch is too weak for ions to escape the electron orbit while the ions are drifting between bunches.

The effect of partial fill operation is also examined experimentally. To perform partial fill operation in our system which adopts one pulse multi-turn injection, LINAC must be operated in a burst mode. That is, the electrons extracted from an electron gun are modulated by the radio frequency of NAR and partially removed in a period of the harmonic number of NAR. The partial fill operation functions well, however, the present injected current is about 30 - 50 mA, which is less than the normal operation (over 100 mA). RF pick up signal shows the bunch is filled as expected even if electrons are accelerated.

The effect of partial fill operation to avoid ion trapping with little current is examined by worsening vacuum pressure. Some of vacuum pumps are turned off to enhance ion trapping effect. When more than three bunches omitted, beam profile observed with CCD camera is always stable even if the vacuum pressure is worsened. In full bunch operation, beam profile blinks if the vacuum pressure is worsened. Inferring from the calculation described above, this phenomenon seems to be due to two beam instability caused by light molecules such as H₂. Beam current was about 30 mA in this experiment.

We also compared the full bunch operation mode and 5 bunches omitted mode at 15 MeV injection. In both operation, the current increased with ion clearing electrodes on. This shows that ions are trapped without ion clearing electrodes.

Although this partial fill experiment is preliminary, partial fill operation is not shown to be effective to remove ions at 15 MeV. This result is consistent with the calculation.

7. Comparison to Super-ALIS

Maximum 200 mA beam current is performed in Super-ALIS, which also used 15 MeV injection energy. One of the differences from NAR is its circumference. That is, from eq. (2), tune shift is proportional to the number of electrons stored as long as the other conditions, such as the beam size or neutralization factor, are the same. If the beam current is the same, the number of electrons is proportional to ring circumference. Therefore, tune shift in NAR of 52.8 m circumference is expected three times as large as that of Super-ALIS of 16.8 m. The other difference is the places of ion clearing electrodes. Super-ALIS has clearing electrodes along the orbit in the bending sections as well as button type electrodes at the straight sections. In NAR, button type electrodes are located only in the straight sections.

8. Conclusion

In NAR, ion clearing electrodes are placed at twelve points and are always used. Even if the clearing electrodes are used, the lifetime at injection is very short due to the ion trapping effect. The possibility that ions are trapped in the bending sections where the beam potential is deep is presented. Partial fill operation mode is examined to remove trapped ions but is not shown to be effective at injection. Although ion trapping effect is not clearly analyzed, the elucidation and countermeasure of this problem are expected to improve NAR beam current.

Acknowledgment

The authors would like to express our appreciation to SR operators who cooperated in acquiring the experimental data.

References

Beam Test of the RF Feedback for KEKB in TRISTAN MR

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Abstract

The RF feedback system for the KEK B-Factory (KEKB) has been tested using the beam of the TRISTAN Main Ring (MR). The coupled-bunch instability of the −1 mode was excited by intentionally detuning the RF cavities; it was then successfully damped by reducing their impedances with the RF feedback.

I. Introduction

A luminosity goal of KEKB is $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, which requires the beam currents of 2.6 A for the 3.5 GeV positron ring and 1.1 A for the 8.0 GeV electron ring. Under usual operation, the cavity is detuned to present a matched load to the power source. For KEKB, the detuning is very large due to the high beam currents. The detuning gives the difference in the real part of the cavity impedance at the upper and lower sideband for each mode, and causes the longitudinal coupled-bunch instability. One technique to avoid the instability is to use an RF feedback around the cavity, which can reduce the cavity impedance at the synchrotron sidebands [1]. We are developing an RF feedback system using a parallel comb-filter, which enables us to adjust the feedback phase at the sideband frequencies even if a frequency-dependent group delay is present around the feedback loop.

The parallel comb-filter feedback was tested through a choke-mode cavity, and proved to be effective in reducing the cavity impedance [2]. Then, the feedback was tested using the beam of the TRISTAN MR. The purpose of the beam test was to confirm that a coupled-bunch instability caused by the cavity impedance could really be eliminated by reducing it by means of RF feedback.

II. Excitation of Instability

Under usual MR operation, an amount of cavity detuning is so small compared to the revolution frequency that the instability associated with the accelerating mode does not appear. One RF station was therefore shut off from operation, and its idling cavities were substantially detuned to make the beam unstable. An RF station has two accelerating units, each comprising a pair of nine APS (alternating periodic structure) cells. A total of thirty six cells were detuned by $-88 \text{ kHz} = f_{\text{rev}} - f_1$ in order to set the resonant frequency of the cavities to the upper synchrotron sideband of the $-1$ mode. Fig. 1 shows the magnitude and real part of the cavity impedance for detuned thirty six cells, with or without RF feedback. The growth time of the $-1$ mode dipole oscillation was calculated from the expression for equally spaced rigid bunches [3], using the machine parameters given in Table 1. The growth time due to the detuned cavities was 7.7 ms and that due to the operating cavities was 43.0 ms, giving the total growth time of 6.5 ms. The radiation damping time was 20 ms. An estimated growth time of any other mode was much slower than 20 ms.

![Fig. 1. Magnitude and the real part of the cavity impedance for detuned thirty six cells, with or without RF feedback.](image)

Table 1
Machine parameters during the beam test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$ beam energy</td>
<td>8.0 GeV</td>
</tr>
<tr>
<td>$e^-$ beam current</td>
<td>6.0 mA</td>
</tr>
<tr>
<td>Number of bunch</td>
<td>4</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$1.493 \times 10^{-3}$</td>
</tr>
<tr>
<td>RF frequency</td>
<td>508.0 MHz</td>
</tr>
<tr>
<td>Revolution frequency</td>
<td>99.3 kHz</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>11.6 kHz</td>
</tr>
<tr>
<td>Energy loss/turn</td>
<td>7.4 MeV</td>
</tr>
<tr>
<td>Cavity voltage</td>
<td>90.0 MV</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td>30000</td>
</tr>
<tr>
<td>Shunt impedance/m</td>
<td>22.5 M$\Omega$/m</td>
</tr>
<tr>
<td>Coupling factor</td>
<td>1.3</td>
</tr>
<tr>
<td>Detuning frequency</td>
<td>$-87.7 \text{ kHz}$</td>
</tr>
<tr>
<td>Growth time of $-1$ mode</td>
<td>6.5 ms</td>
</tr>
<tr>
<td>Radiation damping time</td>
<td>20 ms</td>
</tr>
</tbody>
</table>

III. Feedback System

Fig. 2 shows a block diagram of the RF feedback system used in the experiment. Since only the $-1$
mode could be unstable, only one channel of the parallel comb-filter was used. The RF switch was used to open and close the feedback loop. In order to detect the growth and damping of the $-1$ mode oscillations a spectrum analyzer was used in zero-scan mode. Since there was no external signal to the system, only when the $-1$ mode was excited on the cavity, the system operated so as to cancel it.

Fig. 2. Block diagram of the RF feedback system used in the beam test.

IV. Experimental Results

The experiment was carried out at 8 GeV with four equally spaced electron bunches, which make the beam current of about 6 mA. Although it could be increased to over 10 mA, the $-1$ mode oscillation was most severe around 6 mA. Fig. 3 shows the spectra of the beam-induced cavity voltages. The revolution harmonics of the beam current are shown in Fig. 3 (a), where the highest peak results from the impedance of the cavities tuned at the RF frequency. Fig. 3 (b), (c) and (d) show the signals around $f_{rev} - f_{rev} = 508.48$ MHz. When the cavities were not detuned, only the steady spectrum of the revolution harmonic was seen at 508.48 MHz (Fig. 3 (b)). When the cavities were detuned by $-88$ kHz, the instabilities, especially of the $-1$ mode, appeared as shown in Fig. 3 (c). The spectrum disappeared after the feedback loop was closed (Fig. 3 (d)). With the feedback, however, there appeared the bump between the revolution harmonic ($f_{rev} - f_{rev}$) and its upper sideband ($f_{rev} + f_s$), a cause of which is not clear yet. One may also note that, when the loop was closed, the noise floor was raised due to the noise amplification around the loop.

Fig. 4 shows the amplitude versus time of the $-1$ mode oscillation, which was excited by detuning the cavities without feedback. The increase of the amplitude was limited by some unknown damping mechanism, and turned to the decrease. Then, at a certain small amplitude, where a growth rate exceeded a decreasing damping rate, the amplitude began to increase again. This behavior repeated with a period of about 80 μs. The beam thus survived in spite of being unstable, though the life time was shortened to several tens of minutes from a normal value of several hundred minutes.

Fig. 3. Spectra of the beam-induced cavity voltages.

Fig. 4. Amplitude versus time of the $-1$ mode oscillation excited by the detuned cavities without RF feedback.

The damping rate of the $-1$ mode, $\alpha_{-1}$, and the damping time $\tau_{-1}$ are given by

$$\alpha_{-1} = \alpha_{rad} + \alpha_{imp} + \alpha_{FB}, \quad \text{(1)}$$

$$1/\tau_{-1} = 1/\tau_{rad} + 1/\tau_{imp} + 1/\tau_{FB}, \quad \text{(2)}$$

where $\alpha_{rad}$ is the radiation damping rate, $\alpha_{imp}$ the damping rate due to cavity impedance and $\alpha_{FB}$ the
damping rate due to RF feedback. \( \tau_{rad}, \tau_{imp} \) and \( \tau_{FB} \) are the damping time due to radiation, cavity impedance and RF feedback respectively. A negative \( \tau_{imp} \) indicates the excitation of instability, and an unstable oscillation will occur when

\[-\tau_{imp} < \tau_{rad} + \tau_{FB}.\]  

(3)

The idling cavities were detuned by -88 kHz throughout the feedback experiment. Fig. 5 shows a typical amplitude behavior of the \(-1\) mode oscillation. The amplitude began to increase exponentially when the loop was opened at 0 ms, and turned to decrease when the loop was closed at about 90 ms. This figure clearly shows the effectiveness of the RF feedback. The bottom figures show expanded views just after the loop off and on.

\[I_b = 6.21 \text{ mA}, \text{Gain} = 13.3 \text{ dB}\]

Fig. 5. Amplitude versus time of the \(-1\) mode oscillation when the feedback loop was opened, and then closed after a short period of time.

The growth time was measured from the initial slope of the increasing amplitude when the feedback loop was opened. The measured growth time was 9.9 ms on the average of ten measurements, and varied between 9.1 ms and 11.0 ms. The growth time, obtained from the estimated \( \tau_{rad} \) and \( \tau_{imp} \), was 9.7 ms, which agreed well with the measured value.

The damping time was measured from the initial slope of the decreasing amplitude when the feedback loop was closed. In order to exclude any nonlinear effect from the measurements, the loop was closed while an amplitude was still very small. The measurement was repeated two or three times for each loop gain of 13.3, 15.3, 17.3 and 22.3 dB. Fig. 6 shows the measured and estimated damping times as a function of the loop gain. The crosses show the measured points, while the solid line represents the damping time derived from the estimated \( \tau_{rad}, \tau_{imp} \) and \( \tau_{FB} \). The broken line represents the estimated minimum damping time, which would be obtained with an infinite loop gain.

\[\text{Loop Gain [dB]}\]

Fig. 6. Measured and estimated damping times as a function of the loop gain.

V. Discussion

A threshold gain is defined here as a loop gain at which a combined damping time of \( \tau_{rad} \) and \( \tau_{FB} \) is equal to a growth time, \( -\tau_{imp} \). The measured threshold gain was about 12 dB, which was in good agreement with the estimated threshold of 12.5 dB. However, in the region above the threshold, the measured damping times were much shorter than the estimated ones. Besides, some of the measured points are found below the broken line. This may suggest that the experiment included some factor which we did not take into account.

Since the measured damping time varied more than we had expected, we felt concern about the stability of the feedback system operating at a very low RF power. If the gain fluctuation was the only cause of the measured damping time variation, a range of fluctuation would be about 10 dB. Later we measured the system stability under very low power operation, and found out that either the frequency converter or the parallel comb-filter had a rather large phase fluctuation. Though we have not yet evaluated its effect on the gain variation, it may be responsible to some extent for the measured damping time variation.

VI. Acknowledgments

We would like to thank the members of the operating group for their help in carrying out the beam test.

References

NEW CONCEPTS FOR THE SIMULATION OF BEAMS IN CYCLOTRONS

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Abstract

New concepts have been introduced in a code for the simulation of particles in a cyclotron using transfer matrices. For the simulation the cyclotron is split into several sectors, and the calculation of the particle motion is based on tables of equilibrium orbit data at the sector boundaries, completed by tables describing the properties of the betatron oscillations. For the betatron oscillation part the new method uses three parameters that represent the focusing strengths of three thin lenses, at the start, in the middle and at the end of each sector. The new scheme has proven to be superior to the old approach based on tables of transfer matrices.

1 Introduction

A numerical integration code is normally used for calculating particle motion in a cyclotron. The particle motion in transverse and longitudinal phase space can be simulated precisely by integrating equations of motion step by step. Huge processing time is required for simulating beams consisting of many particles which have different initial conditions. The use of transfer matrices for the simulation of beams can reduce the computing time drastically. Various cyclotron orbit codes [1] [2] [3] using transfer matrices have been developed at different laboratories. The simulation code called MATADOR [4] using first order transfer matrices has been developed to study the beam behaviour in the cyclotrons of the PSI high intensity accelerator facility. The program MATADOR has shown its merits on various problems, however, modifications of the geometric layout or an adaptation of the simulation code to other cyclotrons appeared to be cumbersome. Usually, the tables of transfer matrices produced by the orbit integration program could not be used directly in the simulation. A laborious procedure of manual smoothing of these data was often needed. Otherwise the simulation, introducing additional errors from interpolation, would show unrealistic wild oscillations of the particles.

The new representation of the transfer matrices is based on three independent parameters which are smoother functions than the elements of the transfer matrices themselves. As an additional advantage it fulfills the symplectic condition of the particle motion stating that the determinant of a transfer matrix must be exactly one. Using this new approach should give the modified simulation code the high flexibility and portability that were missing.

2 The Transfer Matrices and Their Representation

In the transfer matrix approach the motion of each particle is split up into a part describing the motion of the equilibrium orbit of the corresponding energy and another part for the difference between the actual orbit and the equilibrium orbit. The difference part can be approximated by linear betatron oscillations represented by difference vectors in \((x,p_x)\) and \((z,p_z)\) phase space. The difference vectors at the end of a section can be obtained from the corresponding initial vectors by matrix multiplications:

\[
\begin{pmatrix}
  x_1 \\
  p_{x1}
\end{pmatrix}
= \begin{pmatrix}
  R_{11} & R_{12} \\
  R_{21} & R_{22}
\end{pmatrix}
\begin{pmatrix}
  x_0 \\
  p_{x0}
\end{pmatrix}
\]

\[
\begin{pmatrix}
  z_1 \\
  p_{z1}
\end{pmatrix}
= \begin{pmatrix}
  R_{11} & R_{12} \\
  R_{21} & R_{22}
\end{pmatrix}
\begin{pmatrix}
  z_0 \\
  p_{z0}
\end{pmatrix}
\]

To find the first order transfer matrices \(R_x\) and \(R_z\) and the equilibrium orbit data the orbit integration program has to calculate a central orbit and a pair of neighboring orbits for a sufficient number of energies. According to Liouville’s theorem the value of the determinant of a transfer matrix must be precisely one. Taking into account this law \((R_{11}R_{22} - R_{12}R_{21} = 1)\) one of the matrix elements becomes redundant. We have therefore searched for a method to define a general two-by-two matrix using three independent parameters. In the formulation we have found the three parameters correspond to values with a physical meaning. The formula that defines the transfer matrix based on three free parameters is given by:

\[
\begin{pmatrix}
  R_{11} & R_{12} \\
  R_{21} & R_{22}
\end{pmatrix}
= \begin{pmatrix}
  1 & 0 \\
  -F_3 & 1
\end{pmatrix}
\begin{pmatrix}
  1 & D \\
  0 & 1
\end{pmatrix}
\times \begin{pmatrix}
  1 & 0 \\
  -F_2 & 1
\end{pmatrix}
\begin{pmatrix}
  1 & 0 \\
  0 & 1
\end{pmatrix}
\begin{pmatrix}
  -F_1 & 1
\end{pmatrix},
\]

where \(F_1, F_2\) and \(F_3\) are the focusing strengths of three thin lenses, assumed to be located at the start, in the center and at the end of each section, while \(D/2\) is the length of the two drift regions in between the lenses. The drift distance \(D\) is given by the spanning angle of the transfer section and the radius of the
Figure 1: Comparison of the two versions of the beam simulation system. In the former procedure the transfer matrix elements for arbitrary energies were interpolated directly from the transfer matrix tables, which originated from the orbit integration code called FIXPO, but which in many cases required a manual smoothing procedure in between. The new scheme conveys the transfer matrix information as tables of focusing strengths for thin lenses created in the data preparation program MATPREP. These sets of focusing strength data are used for the energy interpolation in the modified program called MATADOR95. In MATADOR95 the reconstructed transfer matrices are then based on interpolated values of the focusing strength parameters.

Figure 2: Energy dependence of the transfer matrix element $R_{12}$ for the transfer section from one of the acceleration gaps to the center of the following sector magnet in the PSI Injector II, derived from magnetic field data. The strong oscillations seen in this function pose problems for its interpolation.

3 Implementing the New Parameterization of Transfer Matrices

A flow chart underlining the differences between the two representations of the transfer matrices is shown in Fig. 1. A transfer matrix table is created in the orbit integration code called FIXPO. The table contains a large number of parameter sets to cover all the transfer sections and a number of energies corresponding to the number of turns of an accelerated beam.

Because these raw data have to be interpolated, a time consuming manual smoothing procedure is required in most cases to make them usable for the simulation program. Figure 2, as an example, shows the energy dependence of the element $R_{12}$, which is the coefficient of $x_1p_3$, in the transfer matrix for the transfer section from one of the acceleration gaps to the center of a sector magnet in the PSI Injector II cyclotron. The strong fluctuations shown in this figure make it clear that the interpolation of such a function can pose problems. As an additional disadvantage of the old scheme, the property of the transfer matrix, that the determinant is equal to one, gets lost due to the interpolation process.
In the new scheme the program MATPREP prepares tables of focusing strength parameters based on the raw transfer matrix tables. The energy dependence of these focusing strength parameters, for the same transfer section as in Fig. 2, is shown in Fig. 3 and Fig. 4. The energy dependence is much smoother than in Fig. 2. Thus, the errors in the energy interpolation of the focusing strength can be reduced in comparison to the case where the matrix element is interpolated itself and no need occurs for a manual smoothing procedure. In the new scheme the determinant of all interpolated transfer matrices now remains exactly one. In the modified code of MATADOR 95 the sets of focusing strength parameters are interpolated, and after the interpolation the transfer matrix is reconstructed by using the equation (3).

The physical meaning of the focusing strength parameters is illustrated in Fig. 3 for the horizontal and in Fig. 4 for the vertical focusing. In both cases the first parameter (F_{ix} or F_{iz}) is almost zero, as its azimuth is located in the field free region. For the second and third focusing strength parameters the x-direction and the z-direction show different characteristics. The third parameter shows a strong focusing in the z-direction explained by the fact that it is located on the magnet centerline. For the z-parameters, the second one, F_{iz}, is the largest due to the vertical focusing produced by the angle between the orbit and the magnet edge.

4 Conclusions

The new concept that represents beam transfer matrices based on three free parameters has been successfully implemented in the particle simulation program MATADOR 95 at PSI. Results from test simulations are similar to the ones from the earlier program, but the new program can be considered to be more reliable due to its guarantee that the determinant of a transfer matrix equals one. The fact that the focusing strength parameters are naturally smoother functions than transfer matrix elements avoids the need for a manual processing of the results from the orbit integration program. This provides more flexibility to study variations of the accelerator geometry and easily enables the use of the new code for arbitrary cyclotrons.

5 References

Bunch Deformation of a Multi-Bunched Beam in TRISTAN Accumulation Ring

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Abstract
A remarkable bunch deformation has been observed in the TRISTAN Accumulation Ring (AR) during multi-bunch operations. When two bunches that have different populations are stored in the ring, the bunch length of the smaller current bunch is larger than that of the larger one. In some cases, longitudinal distributions of electrons exhibit two peaks. These phenomena can be explained by the effect of wakefields due to higher order modes of accelerating cavities. We tried to determine the frequency of the mode and the strength of the wakefield that is responsible for the phenomenon with a test bunch method.

I. Introduction
When an electron storage ring is operated in a single bunch mode, the current dependence of the bunch length is explained by the potential well distortion and the microwave instabilities. These theories were successfully applied to the bunch lengthening in the AR [1]. On the other hand, a remarkable bunch deformation was observed when several bunches were stored in the AR [2]. In some cases the longitudinal distributions of electrons exhibit two peaks or tabletop-like shape in four bunch or eight bunch mode operations. These phenomena were explained qualitatively with the potential well distortion due to the long range wakefield, however, its source has not yet been determined.

In this paper, the bunch deformation when two bunches are stored in the ring is discussed. Because the deformation of each bunch was stable over the synchrotron oscillation period, it is quite natural to think that the deformation is caused by the potential well distortion due to high-Q components in the ring. In the AR, the higher order modes (HOMs) of the accelerating cavities are one of the candidates. We tried to determine the frequency of the HOMs and the strength of the fields which induce the bunch deformations.

The machine parameters and the experimental conditions are listed in Table 1.

II. Observation of Bunch Shape
There are two RF sections in the AR. Each section contains four APS (Alternating Periodic Structure) type cavities, each of which has 11 accelerating cells. It is reported that the maximum beam current is limited by the coupled bunch instabilities which arise from higher order modes (HOMs) of the cavities [3], we therefore drove only one RF section to avoid the instabilities.

The longitudinal distributions of electrons were observed by focusing the visible light on a streak camera. Synchrotron radiation (SR) from a bending section is led to an optical stage located on a ground level and split into two lines. One line of them is used for the streak camera or a high speed photodiode, and the other is for a photon counting system. In the multi-bunch operation, a streak camera detects the bunch shape while the photon counting system measures the population of each bunch. In the photon counting method, the flux of SR is attenuated down to a level at which the output of the photon detector corresponds to one photon detection. The time differences between the arrival time of a photon at the detector and the timing signal synchronized to the bunch revolution are digitized and collected numerically.

Figure 1 shows an example of longitudinal beam profile of two bunches observed by the streak camera (Hamamatsu C1587 with M1955 synchroscan unit). The vertical axis represents the longitudinal distribution and the horizontal axis shows the vertical distributions of the bunches in successive revolutions.

III. Determination of the Higher Order Mode
A. Principle of Test Bunch Measurement
We found that longitudinal bunch shapes of the multi-bunched beam resembled a bunch shape with a double peak.
RF system proposed for the suppression of the longitudinal coupled bunch instabilities [1]. We consider a simple model in which the bunch shape is determined by the accelerating rf and a higher order mode of a cavity. The voltage seen by the beam is expressed as

\[ V(\phi) = V_0 \{ \sin(\phi + \phi_0) + k \sin(n\phi + n\phi_0) \} , \]

where \( \phi_0 \) is the synchronous phase, \( \phi_n \) the phase of the HOM field, \( kV_0 \) the peak voltage of the HOM, \( n\phi \) the phase of the HOM which has the frequency \( fn_{RF} \). For any RF waveform, the electron line density is given by [5]

\[ \pi(\phi) \propto \exp \left\{ -\frac{eV_0}{2}\int_0^1 \{ V(\phi) - V_\nu \} d\phi \right\} , \]

and

\[ Y^2(\phi, \phi_0) = \frac{1}{V_0^2} \int_0^1 \{ V(\phi) - V_\nu \} d\phi \]

where \( \frac{2\pi}{p} \) is the rms momentum spread of the bunch and \( eV_\nu \) is the energy loss per turn mainly due to the synchrotron radiation.

In order to determine the frequency and the strength of the field, we thought up a test bunch measurement method. We inject a large current bunch which generates a field and also inject a sufficiently small current bunch whose field is negligible. The shape of the small current bunch is deformed due to the field, we therefore can estimate the frequency of the mode by selecting the distance between the two bunches. In the following part of this paper, we call the large current bunch the main bunch, and the small current bunch the test bunch.

If we assign TM020 mode as a HOM field which affect the bunch shape, \( f_{HOM} = 1210 \text{ MHz} \) and \( n = 2.381 \) is obtained. We assume \( \phi_0 = 0 \) to maximize the effect of the HOM and assume \( k = 0.1 \) as an example. Figure 2 shows calculated bunch shapes of the test bunch in successive 10 rf buckets after the main bunch. The bucket number 0 means the position of main bunch and the bucket number 1 means the bucket is just after the main bunch, and so on.

Figure 2. Simulation of the bunch shapes of the test bunches with the bucket number 1 to 10. The bunch shapes are normalized with \( \int \pi(\phi) d\phi = 1 \). The abscissa shows longitudinal position in units of radians.

There are two method to estimate the HOM frequency. One of them is to measure the peak position of the bunch, and the other is to measure the bunch length. In both methods, the Fourier transform of the obtained data gives us an information of the frequency of the mode. According to the sampling theorem, the highest frequency we can determine is half of the rf frequency, and the higher frequency that causes an aliasing. Therefore, we have to determine the real frequency by any means.

We chose to measure the peak position of each bunch because the simulation suggests that the effect of the HOM appears more sensitively in the peak position than in the bunch length.

B. Experimental Setup

In the test bunch measurement, a large dynamic range is required and the streak camera is not appropriate for this purpose. We used a high speed PIN photodiode (AI-68, Antonides Research) which has a rise time of 35 ps and the photosensitive area of 0.01 mm². The output of the photodiode was led to a digitizing sampling oscilloscope (Hewlett Packard HP54121T). The trigger signal synchronized to the bunch revolution was generated by a circuit which divides the RF signal by the harmonic number of the ring. The time jitters of the divider were measured to be about 3 ps in standard deviation with a histogram function of the oscilloscope. We also used a photon counting system to measure the bunch shape, however, it has an disadvantage that it needs long time about three minutes in the measurement.

We injected the main bunch first, and injected the test bunch into a selected bucket. The beam current of each bunch is 20 mA and 1 mA, respectively. To avoid the coupled bunch instabilities, both bunches were dumped by a stopper whenever before the measurement of the next bucket. Because it is very time-consuming to measure all buckets in AR, we only measured the successive 20 buckets in 8 places in the ring.

IV. Results and Discussion

Figure 3 shows the peak position of the test bunches. The abscissa shows the bucket number from 1 to 610 and the ordinate represents the peak position in units of picoseconds. The peak positions vary depending on the bucket number due to the transient beam loading effect of the main bunch. The calculated difference in the synchronous phases between just after and before the main bunch was 128 ps which is consistent with the measurement.

We subtract the offset due to the beam loading and calculated the Fourier transform of the variations of the peak position. Peak positions of the unmeasured buckets were assumed to be zero. The result is shown in Fig. 4. There are sharp peaks in every 6.36 MHz. These peaks arise from the fact that we could not measure the all buckets but only eight places were measured.

Two large peaks are recognized at 180.1 MHz and 241.6 MHz. From a measurement of cavity higher order modes, several modes can be listed up as candidates. In the single bunch operation, we measured the beam spectrum of a cavity with a pickup located on its end plate. The resonant frequency of the TM020 mode is ranged from about 1200 MHz to 1211 MHz because the APS cavity has 11 cells in it. These frequency will be observed
Figure 3. Peak position of the test bunches. The measured bucket number is 0±20, 80±10, 160±10, · · · , 180±10 and 560±10.

Figure 4. Fourier transform of the peak position.

Figure 5. Longitudinal line density of two bunches measured by the streak camera. The beam current of the large peak is 15 mA and the small peak is 10 mA, and the measured bunch length was 290 ps and 375 ps in FWHM, respectively. The total RF voltage was 2.3 MV.

V. Summary

The bunch deformation in the AR during the multi-bunched beam operation was measured and explained with the higher order modes of the cavities qualitatively. We thought up the test bunch measurement method and concluded that the two modes, TM020 and TM022, are candidates for the source of the deformation. The field strength estimated from the test bunch method is consistent with the strength which produces the deformation of the two bunches, however, the calculated impedance of a cavity is ten times smaller to explain it. Further analysis and measurements are now in progress.

Acknowledgments

The authors wish to thank Dr. K. Akai and Dr. Y. Morozumi who have been kindly supporting the experiment and the calculations of the cavity HOMs.

References

Design Parameters of a Spiral Inflector for Axial Injection Project of the CYRIC Cyclotron

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Abstract

A derivation is given of the Root’s solution for the beam orbit in the spiral inflector. On the basis of this solution a survey of parameters of the inflector was made, and appropriate design parameters were proposed considering the central-region geometry of the cyclotron.

1. Introduction

A preliminary numerical study of an axial injection scheme was made on the basis of an off-axis injection and a mirror inflector. Since this scheme requires rather complex deflection electrodes within the central plug through the yoke, we abandoned this and turned to using a spiral inflector together with an on-axis injection.

In the following we give a derivation of the Root’s solution and then apply this to our CYRIC cyclotron, assuming an on-axis injection, which, however, requires a change of the tips of the central plugs as well as minor changes of the central electrodes.

2. Derivation of the Root’s solution

We take a coordinate system of Fig.1. In the absence of the magnetic field the central trajectory of the injected beam at \( t = 0 \) is easily seen to be (we take \( v, R_E, E \geq 0 \))

\[
X(t) = \begin{pmatrix} z(t) \\ z'(t) \end{pmatrix} = \begin{pmatrix} R_E (1 - \cos(kt)) \\ \frac{v}{\sin \theta} \end{pmatrix}, \text{ and } \theta = k t, \tag{1}
\]

where \( R_E \) is the radius of curvature under an electric field \( E, k \equiv v/R_E \) and \( v \) is the velocity. Since \( E \cdot v = E \cdot \dot{z} = 0 \) the magnitude of the velocity \( v \) is a constant of the motion.

When a uniform magnetic field \(-eB\hat{z}\) is applied, \( z(t) \) and \( E_z \) are not affected, but \( z_H \) changes and \( E_H \) must be changed accordingly for conserving \( E \cdot v = 0 \); the suffix \( H \) denotes the horizontal component. For the sake of simplicity we use the following abbreviation.

\[
c_n \equiv \cos(nkt) \equiv \cos(n\theta), s_n \equiv \sin(n\theta), \text{ and } c_t n \equiv \cot(n\theta). \tag{2}
\]

We further define \( E_H^H \) and \( E_H^V \), the former being parallel and the latter perpendicular to \( v_H \), respectively. For simplicity we assume \( E_H^V = 0 \), then

\[
E_H \propto v_H \equiv \dot{z}_H, \text{ hence } E_x = E_H \frac{\dot{z}}{v_H} \text{ and } E_y = E_H \frac{\dot{y}}{v_H}. \tag{3}
\]

From \( E_x = E_s_1 \), we have \( E_H = E c_1 \) and hence

\[
E_x = E c_1 \frac{v}{v_H} \quad E_H = \frac{E c_1}{\sin \theta}, \quad \text{ and } \quad E_y = \left( \frac{E}{v} \right) \frac{v_H}{v_H} c_1 \dot{y}. \tag{4}
\]

On the other hand the magnetic field \(-Be_z \) gives a horizontal force on the particle

\[
F_x^B = -eB \dot{y} \quad \text{ and } \quad F_y^B = eB \dot{x}, \tag{5}
\]

giving the equations of motion for \( x \) and \( y \) under the presence of \( E \) and \(-Be_z\);

\[
m \ddot{x} = (eE/v) c_1 \ddot{z} - eB \dot{y}, \quad m \ddot{y} = (eE/v) c_1 \dot{y} + eB \dot{z}. \tag{6}
\]

Fig.1. Deflection of central beam in the absence of \( B \).
Defining the radius of curvature \( R_M \) under the presence of only \( B_R \),
\[
R_M \equiv \frac{mv}{eB}, \quad \text{hence } eB/m = v/R_M = \frac{vR_E}{R_M} \equiv 2k'k,
\]
where \( k \equiv v/R_E \) and \( K \equiv R_E/(2R_M) \). From eqs.(6) and (7) we finally obtain the equations of motion for \( x \) and \( y \);
\[
\begin{pmatrix}
\dot{x} \\
\dot{y}
\end{pmatrix}
= k
\begin{pmatrix}
ct_1 & -2K \\
2K & ct_1
\end{pmatrix}
\begin{pmatrix}
x \\
y
\end{pmatrix}
\equiv kM(t)
\begin{pmatrix}
x \\
y
\end{pmatrix}.
\]
(8)

In eq.(8) the matrix \( M(t) \) can be diagonalized by a unitary transformation;
\[
U(T) = \begin{pmatrix}
1 & -i \\
i & 1
\end{pmatrix}
\]
with \( U \equiv \sqrt{2} \). Eq.(8) then becomes
\[
\begin{pmatrix}
\dot{X} \\
\dot{Y}
\end{pmatrix}
= kU^+M(t)U
\begin{pmatrix}
X \\
Y
\end{pmatrix},
\]
(9)
i.e., decoupled equations for \( X \) and \( Y \). Eq.(10) can be integrated as follows.
\[
\ln|X(t)| = \int_0^t k(ct_1 + 2iK)dt = \ln|s_1| + 2ikKt,
\]
(11)
giving
\[
X = C_xe^{2ikKt(e^{ikt} - e^{-ikt})/2i}.
\]
(12)

We take from inspection \( \dot{Y} = 0 \) and from eq.(9) obtain
\[
\begin{pmatrix}
\dot{Z} \\
\dot{Y}
\end{pmatrix}
= k
\begin{pmatrix}
ct_1 + 2iK & 0 \\
0 & ct_1 - 2iK
\end{pmatrix}
\begin{pmatrix}
Z \\
Y
\end{pmatrix}.
\]
(10)

Taking the real part of eq.(13) and considering the initial and final conditions, \( x(0) = \ddot{x}(0) = y(0) = \ddot{y}(0) = 0 \) and \( (z^2 + y^2)(kt = \theta = \pi/2) = v^2 \), we arrive finally at the required solution;
\[
\begin{pmatrix}
\dot{x} \\
\dot{y}
\end{pmatrix}
= \frac{v}{2}
\begin{pmatrix}
S_{2K+1} - S_{2K-1} \\
-2K_{2K+1} + 2K_{2K-1}
\end{pmatrix}
\begin{pmatrix}
x \\
y
\end{pmatrix},
\]
(13)
and
\[
\begin{pmatrix}
\dot{x} \\
\dot{y}
\end{pmatrix}
= \frac{R_E}{2}
\begin{pmatrix}
-\frac{C_{2K+1} + C_{2K-1}}{2K+1} - \frac{4K^2-1}{2K+1} \\
\frac{S_{2K+1} + S_{2K-1}}{2K+1} + \frac{4K^2-1}{2K+1}
\end{pmatrix}
\begin{pmatrix}
x \\
y
\end{pmatrix},
\]
(14)
which exactly coincides with the previous results \(^2,\), \(^3\), considering that we take \( B_2 = -B \). Before going further, we give complete forms of solution;
\[
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
= \frac{R_E}{2}
\begin{pmatrix}
\frac{C_{2K+1} + C_{2K-1}}{2K+1} - \frac{4K^2-1}{2K+1} \\
\frac{S_{2K+1} + S_{2K-1}}{2K+1} + \frac{4K^2-1}{2K+1} \\
-2S_{2K+1} + 2S_{2K-1}
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix},
\]
(15)

We note that \((E_x, E_y) \propto (\dot{z}, \dot{y})\) and that \( E \cdot v = 0 \).

3. Application to the CYRIC cyclotron

Before applying eq.(15) to our cyclotron, it is noted that the injected beam comes down along the mechanical axis of the cyclotron so that the entrance point is at \((x,y,z) = (0,0,0)\) and the exit point is at \((\rho, \phi, z) = (R_0, \Phi, -R_E)\) where the beam comes out horizontally in the median plane of the cyclotron, \((\rho, \phi, z)\) being the cylindrical coordinates; \( \rho \equiv (x^2 + y^2)^{1/2} \) and \( \Phi \equiv \phi_x \) is the total rotation angle of the beam orbit in the \( x-y \) plane.

From eq.(15) we note that we have two free parameters out of, e.g., \( R_M, K, \) and \( R_E \) because of the relation of \( K = R_E/(2R_M) \); we take \( R_M \) and \( K \) as independent parameters. As shown in Fig. 2, as a crucial condition we require that the beam leaving the inflector electrodes smoothly travel along a circle of radius \( R_M \) and passes perpendicularly through the slit in the radial part of the grounded housing of the inflector electrodes; the slit at a distance \( R_d \) faces the puller at \( R_e \) from the origin so that \( R_d = R_e = 2.2 \) cm for our cyclotron. For a smooth connection of the beam at the electrode exit we require
\[
\gamma_{in} = \gamma_{out},
\]
(16)
where \( \gamma_{in} \) is the angle between \( v_H \) and \( e_x \) at the exit point, i.e.,
\[
\gamma_{in} = \tan^{-1}\left( \frac{z + y\bar{y}}{z - y\bar{x}} \right)_{\theta = \pi/2}.
\]
(17)

On the other hand, from the geometry of Fig. 2 we have at the exit point
\[
\gamma_{out} = \cos^{-1}\left( \frac{\rho_x^2 - R_e^2 + 2R_MR_0}{2R_MR_0\rho_x} \right).
\]
(18)

Satisfying this condition (eqs.(16)-(18)) leaves one free parameter, e.g., \( R_M \). We calculated numerically under the condition of eq.(16) various parameters as functions of \( R_M \) as shown in Fig. 3. Considering the central-region electrodes and the results given in Fig. 3, we chose \( R_M = 1.3 \) cm corresponding to \( K = 1.1135 \) as shown in Table
Fig. 2. Orbit projected to the $x$-$y$ plane and definition of various parameters ($B \neq 0$); $R_a = 2.2$ cm and $K = 1.1135$.

Fig. 3. Dependence of various parameters on $R_M$ for $R_a = 2.2$ cm. Note that $\beta = \alpha + \gamma$ and $R_E = 2KR_M$, and the arrows indicate the scale to refer.

4. Conclusion

For the sake of understanding we gave a rather detailed derivation of the equation of the central trajectory of an axially injected ion beam (eq.(15)), and applied it to the CYRIC cyclotron, and proposed a set of design parameters compatible to the central-region structure of the cyclotron at the cost of least change of it; see Fig. 4. We would like to stress that the results of the survey calculation (Fig. 3) should be applicable to other cyclotrons with an appropriate scaling, i.e., a normalization with respect to $R_a = R_p$.

The above discussion deals with only the central trajectory of the beam. Before manufacturing more elaborate studies are needed resorting to a higher-order optical method or a numerical one.

Table 1. Design parameters of the spiral inflector

<table>
<thead>
<tr>
<th>Parameters$^a)$</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a = R_p$</td>
<td>2.200 cm</td>
</tr>
<tr>
<td>$R_M$</td>
<td>1.300 cm</td>
</tr>
<tr>
<td>$K \equiv R_E/2R_M$</td>
<td>1.1135</td>
</tr>
<tr>
<td>$R_E$</td>
<td>2.895 cm</td>
</tr>
<tr>
<td>$\rho_{ex}$</td>
<td>2.004 cm</td>
</tr>
<tr>
<td>$\Phi \equiv \phi_{ex}$</td>
<td>130.42$^\circ$</td>
</tr>
<tr>
<td>$\gamma_{in} = \gamma_{out}$</td>
<td>19.99$^\circ$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>29.59$^\circ$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>49.58$^\circ$</td>
</tr>
<tr>
<td>$D$</td>
<td>0.99 cm</td>
</tr>
</tbody>
</table>

a) See Fig. 3 and the text.
b) $R_E$ essentially defines the height of the inflector electrodes.

Fig. 4. Spiral inflector in the central region of the cyclotron.

References

HOLLOW BEAM FORMATION IN THE EXTRACTION REGION OF ECRIS

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Abstract

Beam optics in the extraction system of an ECR ion source (ECRIS) are examined both analytically and numerically, by taking nonlinear effect due to aberrations of einzellens into account. It is shown that this effect can cause hollow beam formation. Simple analytical criteria to keep the good beam quality in the focusing system are given.

1. Introduction

Beam quality of a high-intensity heavy-ion accelerator is mostly defined by the extraction region of the ion source where nonlinearity due to space charge and focusing field are significant. At the RIKEN Accelerator Research Facility an 18-GHz ECR ion source (ECRIS) is under construction for the heavy-ion line. This new ECRIS is expected to produce higher-charge states of heavy-ions so that the acceleration performance of the linac can be further upgraded. The extraction system of this ECRIS consists of an extraction gap and an einzellens as shown in Figs. 1 and 2. After passing the einzellens, the extracted beam has to be focused onto a spot with a diameter of 10 mm to be matched with the following beam transport system. The purpose of this study is to examine nonlinear beam-optics effects of the einzellens which can influence the beam profile and emittance shape of the extracted beam.

2. Beam Emittance

In an ECRIS charged particles are born in a strong longitudinal magnetic field \( B_z \) fulfilling the ECR resonance condition \( 2\omega_0 = \omega_B \) where \( \omega_0 \) is the laser frequency and \( \omega_B \) is a microwave frequency. The effective phase space area occupied by the ensemble of particles is described by the value of root-mean-square (RMS) phase space area occupied by the ensemble of particles is given by

\[
\varepsilon = \frac{1}{\text{RMS}} = \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle + \langle y^2 \rangle \langle p_y^2 \rangle}.
\]  

where \( x, p_x \) and \( p_y \) are a mass, a transversal Cartesian coordinate and a canonical conjugate momentum of a particle, respectively, and \( c \) is the speed of light. For particles in the ECRIS one can put \( \langle p_x \rangle = 0 \). Canonical momentum of a particle \( p_x = p_x - qA_x y / 2 \) in the longitudinal magnetic field is a combination of mechanical momentum \( p_x \) and \( qA_x y / 2 \) where \( q \) is an ion charge and \( A_x \) is an \( x \)-component of vector potential of the magnetic field. The RMS value of canonical momentum is given by

\[
\varepsilon = \frac{1}{c} \sqrt{\langle p_x^2 \rangle - qB_z x}.
\]  

The first integral in eq. (2) describes the thermal spread of mechanical momentum of charged particles in the ECR plasma. Therefore, the RMS value of mechanical momentum is given by \( \varepsilon = \langle p_B^2 \rangle = \frac{1}{2} < p_B^2 > = mkT_i \) where \( T_i \) is the ion temperature and \( k \) is Boltzmann's constant. The middle integral equals zero because there is no correlation of \( p_x \) and \( y \). The last integral is proportional to the RMS value of transverse coordinate \( \langle y^2 \rangle \). For most of the beam distributions \( \sqrt{\langle y^2 \rangle} = R/2 \) where \( R \) is a beam radius comprising around 90\% of particles. Finally the RMS value of canonical momentum is given by \( \langle p_x^2 \rangle = \langle p_B^2 \rangle + \langle qB_z R^2 \rangle / 4 \). Combining the obtained value of \( \varepsilon \) with equation (1) the normalized beam emittance \( \varepsilon \) is given by

\[
\varepsilon = 2R \sqrt{\frac{kT_i}{mc^2} + \left( \frac{\theta_1 R}{2c^2} \right)^2}.
\]  

The formula (3) is usually used for estimation of the emittance of the beam with an ambient magnetic field on the cathode [1]. In the case of the 18-GHz ECRIS the resonant value of magnetic field is \( B_z = 0.637 \) T. The normalized beam emittance of, for example, an \( {\text{Ar}}^{5+} \) beam with the ion temperature \( kT_i = 3eV \) is \( \varepsilon = 2.5 \times 10^{-3} \) \( \sqrt{0.8 \times 10^{-10} + 10^{-9}} \approx 3.3 \times 10^{-7} \) \( \text{m} \text{rad} \).

3. Numerical Study of Beam Optics

Numerical calculation of particle trajectories in the extraction region was performed with the computer program BEAMPATH [2]. Particle trajectories obey the equations of motion derived from a single particle Hamiltonian in Cartesian coordinates:

\[
H = \frac{1}{2m} \left[ \left( p_x - q \phi_x \right)^2 + \left( p_y - q \phi_y \right)^2 \right] + q \left( U_x + \frac{1}{12} \right). \]  

where \( U_x \) is a space charge potential of the beam and \( U_x \) is a potential of the focusing field. The space charge potential is calculated from 2D Poisson's equation in Cartesian coordinates on the mesh \( 256 \times 256 \). The 2D electrostatic potentials in the extraction gap and in the einzellens are calculated by using the program POISSON.

Numerical study was performed for \( {\text{Ar}}^{5+} \) ion beam with current of 100 e\( \mu \)A. The following parameters were varied so as to find the optimal matching conditions for the extracted beam with the beam transport system downstream: the extraction gap was varied from 3 cm to 4 cm; the distance of einzellens from the extraction hole from 25 cm to 35 cm; and the voltage at the central electrode of einzellens from 10 kV to 14 kV. The results are presented in Table 1 and in Figs. 1-4.

It is noted that in Fig. 4 the beam forms hollow structure at the waist point of beam envelope. The same phenomena were experimentally observed in the high pervance electron guns [4] and in the short solenoid electron lenses with large aberrations [5]. For understanding more details of these phenomena, let us consider the following analytical model.

4. Hollow Beam Formation

After being extracted from the ECRIS particles pass through the focusing lens and then move in a drift space.
Fig. 1. Particle trajectories in the extraction region of the ECR ion source: extraction gap 4 cm, lens voltage 14 kV, position of lens center 25 cm, coefficient $C_{zz} R^2 = 0.15$.

Fig. 2. Particle trajectories in the extraction region of the ECR ion source: extraction gap 4 cm, lens voltage 12.5 kV, position of lens center 30.4 cm, coefficient $C_{zz} R^2 = 0.3$.

Fig. 3. Cross sections of the beam (top) and phase space projections of particles (bottom) at $z=14$ cm (left column) and at $z=51$ cm (right column) for the extraction system presented in Fig. 1. RMS emittance growth is $\epsilon_x/\epsilon_{x0} = 1.15$.

Fig. 4. Cross sections of the beam (top) and phase space projections of particles (bottom) at $z=16$ cm (left column) and at $z=60$ cm (right column) for the extraction system presented in Fig. 2. RMS emittance growth is $\epsilon_x/\epsilon_{x0} = 1.3$. 
Fig. 5. Beam profile conservation in weak nonlinear field \( C_a R^2 = 0.15 \) (left) and hollow beam formation in strong nonlinear field \( C_a R^2 = 0.3 \) (right), calculated from formula (7).

For particles born in the magnetic field of ECRIS the value of azimuthal component of canonical momentum \( P_\theta = (1/2) q B z r_0^2 \) is conserved. The electric field of the einzel lens provides focusing effect which can be described by a linear term as well as higher order terms. The radial equation of motion of a particle in this region is given by

\[
d \frac{r^2}{dt^2} = \frac{p^2}{m^3 r^1 m} \left[ L \frac{dE}{dr} + \frac{r^2}{2} \frac{d^2E}{dr^2} + \ldots \right]. \tag{5}
\]

After passing through the thin lens initially parallel particles with radial displacement \( r_0 \) are converged with slope of \( r_0 = -(1 + C_a r_0^2) r_0 / f \), where \( f \) is a focal length of the lens and \( C_a \) is a spherical aberration coefficient. The equation of motion (5) can be integrated in drift space to obtain the relationship between the initial and the final radii of particle:

\[
r^2 = r_0^2 \left[ 1 - \tau (1 + C_a r_0^2) \right]^2 + \eta^2, \tag{6}
\]

where \( \tau = z / f \) is a dimensionless drift distance and \( \eta = \omega_d t \) is a dimensionless time of particle drift. To find the beam density redistribution, let us take it into account that the number of particles \( dN \) inside a thin ring \( (r, r+dr) \) is kept constant during the drift of the beam, and hence the particle density \( p(r) = dN/(2\pi r dr) \) at any \( z \) is connected with the initial density \( p(r_0) \) by the equation \( \rho(r) dr^2 = \rho(r_0) dr_0^2 \), or

\[
\rho(r) = \frac{\rho(r_0)}{\left[ 1 - \tau (1 + C_a r_0^2) \right]^2 + \eta^2 - 2\pi \left( 1 + C_a r_0^2 \right) \left[ 1 - \tau (1 + C_a r_0^2) \right]}. \tag{7}
\]

From this relationship changing of the beam profile is observed when a spherical aberration is significant. The linear focusing lens \( (C_a=0) \) conserves the beam profile and changes only sizes of the beam. Nonlinear component of electrostatic field increases focusing of particles in comparison with the linear component only [6]. It results in a beam profile with a more particle-populated boundary than the central region (see Fig. 5).

This hollow beam formation is accompanied by emittance growth of the beam. In the case considered the effective RMS emittance can increase by 1.3 times (see Fig. 4). Such effect of the nonlinearity on beam intensity redistribution can be controlled by the product of spherical aberration coefficient and square of beam radius \( C_a R^2 \).

Table 1. Parameters of 100 eM\( ^+ \) Ar\( ^{5+} \) ion beam in the extraction region of the 18-GHz ECRIS.

<table>
<thead>
<tr>
<th>Extract. gap, cm</th>
<th>Lens center, cm</th>
<th>Waist, cm</th>
<th>Waist radius, cm</th>
<th>Emittance growth, ( \epsilon_f/\epsilon_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>10</td>
<td>30.4</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>12.5</td>
<td>30.4</td>
<td>0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>30.4</td>
<td>0.6</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>30.5</td>
<td>0.4</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>35.5</td>
<td>0.5</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>25</td>
<td>0.5</td>
<td>1.1</td>
</tr>
</tbody>
</table>

5. Conclusions

Nonlinear effect associated with the hollow beam profile formation in the extraction region of ECRIS was examined through both the numerical particle tracking and the analytical treatment. Simple formula has been derived to estimate the significance of spherical aberrations on the beam profile redistribution. This study is important in the design of the low-energy part of heavy-ion accelerators.

6. References

Merging ion-ion collisions is an important feature of the proposed RIKEN Radioactive Isotope Beam Factory\(^1\). In the merging collision case, the value of luminosity \(10^{26}\) \(1/cm^2\text{-sec}\) is several orders of magnitude less than for head-on collisions because both beams have almost the same vector of velocity and merging angle is rather small (1-10°) even when the stored number of ions is close to the space charge limit of \(10^{12}\) particles. In the present paper, the beam-beam effects are studied for the coasting merging beam collisions using particle-in-cell (PIC) model in 4D phase space. Tolerable incoherent beam-beam tune shift and beam disruption effect such as emittance growth have been evaluated from high order nonlinear resonances study. Beam luminosity and beam life time due to beam-beam effects are estimated as a function of main collider parameters.

1. Introduction

Proposed Radioactive Isotope Beam Factory is aimed to be used for wide range of experiments with unstable nuclear beams. Among variety of planning experiments the ion-ion merging collisions are of the most importance. Merged beam technique is very useful method for the study of nuclear fusion processes. Merging two Rl beams deliver low energy collisions just above the Coulomb barrier threshold that is difficult to be realized in other experimental methods. The most important collider parameter is luminosity which is limited among other reasons by physics of beam-beam interaction. In this paper we analyze the luminosity constraints originating from a beam-beam interaction as a function of main parameters of storage ring.

2. Luminosity of merge beam - beam interaction

We consider two coasting merge ion beams with particle densities \(n_1, n_2\) and beam velocities \(\vec{v}_1 = \beta_1\vec{c}\), \(\vec{v}_2 = \beta_2\vec{c}\) colliding with angle \(\alpha\) (see fig. 1). Luminosity \(L\) is defined as a ratio of interaction rate to cross section for particle interaction \(L = 1/\sigma dN/dt\). Using expression for invariant cross section\(^2\) the number of collisions \(dN\) during the time \(dt\) is

\[
dN = \int \sigma \sqrt{\left(\frac{\vec{v}_1 - \vec{v}_2}{c}\right)^2 \cdot \left(\frac{\vec{v}_1 \times \vec{v}_2}{c^2}\right)^2} n_1 n_2 dV
\]

where integration is performed over the volume of interaction. It is convenient to express luminosity as a function of collision angle \(\alpha\), number of particles per beam \(N_1, N_2\), ring circumference \(2\pi R\) and effective size of the beam \(h_{\text{eff}}\) at the interaction point:

\[
L = \frac{\sqrt{\beta_1^2 + \beta_2^2 - 2\beta_1\beta_2\cos\alpha} - \beta_1^2\beta_2^2\sin^2\alpha}{(2\pi R)^2\sin\alpha h_{\text{eff}}} c N_1 N_2
\]

Let us note that for merge coasting beams the luminosity is inversely proportional to beam height and does not depend on beam width.

3. Particle-in-Cell Model of Beam-Beam Interaction

Beam-beam interaction was studied by combination of particle-in-cell treatment of space charge problem at the crossing point and transfer matrix for particle revolution in storage ring. Self-consistent consideration of the problem is based on calculation of beam-beam interaction arising from the intrinsic space charge field of the beams. Beams are represented as a collection of large number (\(10^3 - 10^4\) modeling particles. Real number of particles in the beams is much larger (\(10^{12}\)). To reduce the numerical fluctuation arisen from over evaluated particle-particle collisions, the smoothing particle-in-cell technique is used. For merging ion-ion collision we use the assumption that two beams are identical therefore we can consider behavior of only one beam (the second
beam is the same). At the point of interaction influence of one beam on another one is simulated as strong-strong interaction of two identical beams with crossing angle.

Simulation starts with random number generation of initial particle positions $x,y$ and reduced particle momentum $p_x = p_x Y$ and $p_y = p_y Y$ in four-dimensional phase space. Initial distribution of the beam in transversal phase space coordinates gives the elliptical phase space projections described by root-mean-square (RMS) beam ellipse $a_0 x^2 + 2b_0 x p_x + c_0 p_x^2 = \varepsilon$ where the RMS beam emittance $\varepsilon$ is defined as

$$\varepsilon = 4 \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle} = 4 \sqrt{\langle x^2 \rangle \langle p_x^2 \rangle}$$

(3)

analogously for $y$, $p_y$. Simulation of each turn of particle with longitudinal momentum $p_L = p_y Y$ consists of transfer mapping of one revolution of particle in storage ring of radius $R$ with betatron tunes $Q_x$, $Q_y$ and nonlinear kick $\Delta p_x, \Delta p_y$ due to beam-beam interaction:

$$x_{n+1} = x_n (\cos 2\pi Q_x + p_{xn} (\sin 2\pi Q_x)) + p_{xn} (\cos 2\pi Q_x)$$

$$y_{n+1} = y_n (\cos 2\pi Q_y + p_{yn} (\sin 2\pi Q_y)) + p_{yn} (\cos 2\pi Q_y)$$

(4)

(5)

Self-consistent beam-beam kicks $\Delta p_x, \Delta p_y$ are calculated from space charge problem with instantaneous distribution of particles:

$$\Delta p_x = \frac{q}{mc^2} \frac{h_x}{\sin \beta_y r} \sum_{i=1}^{NX} E_x (y)$$

$$\Delta p_y = \frac{q}{mc^2} \frac{h_y}{\sin \beta_y r} \sum_{i=1}^{NX} E_y (y)$$

(6)

(7)

where $mc^2/q$ is a rest energy divided by charge of particle, $E_x (y)$, $E_y (y)$ are space charge field of the beam calculated at spatial grid points, $NX$ is a number of equidistant mesh points along $x$-axis located with step $hx$ (see fig.1). Space charge field of the beam is calculated from the Poisson's equation in Cartesian coordinates

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} = -\frac{\rho (x,y)}{\varepsilon_0}$$

(8)

with Dirichlet boundary conditions for potential $U$ on the surface of conducting pipe using Fast Fourier Transforms.

4. Beam-Beam Tune Shift

In coasting merge beams the interaction is not x-y symmetric. In the median plane of the beams ($x$-direction in fig. 1) particles experience much smaller kick than in the vertical plane ($y$-direction). As a result, initially round beams become prolonged in the direction perpendicular to median plane. Realistic beam-beam kick is a nonlinear function of transverse coordinate due to nonlinear space charge field of the beam. Gaussian beam with $N$ particles and transverse RMS size $\sigma$ delivers space charge field:

$$E_x = \frac{N q r}{4 \pi^2 R \varepsilon_0 r} (1 - \exp(-r^2/2\sigma^2)) = \frac{N q r}{8 \pi^2 \varepsilon_0 r^3}$$

(9)

From eqs. (7), (9) the linear approximation to beam-beam kick is as follows:

$$\Delta p_y = \frac{N q r}{2 \pi^2 mc^2 \varepsilon_0 \beta_y^2 \sin \alpha R \sigma_y} y$$

(10)

Multiplication of matrix of one turn and linear beam-beam kick gives the value of linear betatron tune shift for merge beam-beam collisions:

$$\xi_y = \frac{N r_0}{2 \pi^2 \sigma_y \sin \alpha \beta_y^2 \gamma Q_y}$$

(11)

where $r_0 = q^2/4\pi mc^2$ being the value of classical radius of particle.

5. Results of simulation

RI beam factory is supposed to have 2 colliding points, therefore the values of tune are half of betatron tunes in the ring: $Q_x/2 = 2.8815; Q_y/2 = 3.175$. For two coasting merge beams (see fig. 1) only $y$ - direction is responsible for degradation of beam luminosity due to compensation of beam-beam kick in $x$-direction. The closest resonance value $mQ_y = n$ to betatron tune value $3.175$ is $6Q_y = 19$, i.e. 6th order resonance is achieved for $Q_y = 19/6 = 3.1666$. Max tune shift from working point to resonance is $\xi = 3.175 - 3.1666 = 0.00833$. At fig. 2, and in Table the results of calculations for $\xi = 0.005$ (non-resonance case) and $\xi = 0.027$ (resonance case) are presented. Different initial nonlinear particle distributions were treated in calculations: Gaussian distribution $\rho (r) = \rho_0 \exp (-r^2/\sigma_x^2)$ and "parabolic" distribution $\rho (r) = \rho_0 (1 - r^2/R_0^2)^2$. Evolution of RMS beam envelope

$$2\sigma_x = 2 \sqrt{\langle x^2 \rangle} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2}$$

(12)

and RMS beam emittance $\varepsilon$ (see eq.3) were controlled during the simulations as statistical averaged values over large number of modeling particles. From results of simulations it follows that below resonance threshold $\xi < 0.008$ beams are stable, i.e. no envelope and RMS emittance growth were observed. Under resonance conditions $\xi > 0.00833$ beam-beam instability was observed. The Gaussian distribution is more unstable than the parabolic distribution. Under the Gaussian distribution the phase space portrait of the beam is typical for high order resonance (see fig.2) while for parabolic distribution the phase space projections are ellipses as for non-resonance case.
Table. Results of PIC simulation of beam-beam effects (mesh NX x NY = 64 x 64).

<table>
<thead>
<tr>
<th>Beam Distribution</th>
<th>Tune</th>
<th>Number</th>
<th>Envelope Growth</th>
<th>Envelope Growth (per 10^4 turns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td>0.005</td>
<td>4 x 10^4</td>
<td>10^3</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaussian</td>
<td>0.027</td>
<td>10^4</td>
<td>5 x 10^3</td>
<td>1.03</td>
</tr>
<tr>
<td>Parabolic</td>
<td>0.027</td>
<td>2 x 10^4</td>
<td>5 x 10^3</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Max number of particles estimated from beam-beam interactions exceeds the limit defined by incoherent space charge tune shift for circulated beam. Further study is required for estimation of synchro-betatron resonances on beam parameters due to finite length of the interacted bunches.

8. References


6. Limitation of Luminosity and Beam Lifetime

The calculation performed shows the limitation in max tune shift due to beam-beam effects $\xi < 0.008$ which is typical for ion-ion collisions. Assuming $\xi_{\max} = 0.008$, $\sigma_y = 10^{-3} m$, $\alpha = 10^0$, $\beta_y = 1.7$, $r_o = 1.5 \times 10^{-18} m$ (proton) the limited number of particles due to beam-beam interaction is (see eq. 11):

$$N < 2\pi^2 \frac{\xi_{\max} Q_y \sigma_y \sin \beta^2 \gamma^2}{r_o} = 6 \times 10^{13}$$

(13)

This value is larger than the space charge limited number of particles in the ring of radius $R = 28 m$ due to incoherent space charge tune shift (Laslett tune shift) $\Delta \nu_{\max} = 0.25$:

$$N < 4\pi \frac{\Delta \nu_{\max} Q_y \beta^2 \gamma^2 \sigma_y^2}{R r_o} = 3 \times 10^{12}$$

(14)

Taking limited number of particles $N_{\max} = 3 \times 10^{12}$, $\alpha = 10^0$, $h_{\text{eff}} = 4 \times 10^{-3} m$ and assuming $\beta_1 = \beta_2 = 1$, the limitation in luminosity is (see eq. 2):

$$L < \frac{N_{\max}^2 e}{(2\pi R)^2 h_{\text{eff}}} \frac{\sqrt{\alpha}}{2} = 2 \times 10^{36} \frac{1}{\sec cm^2}$$

(15)

From results of simulation we observe the increase of transverse beam size 1-3% per 10000 turns at the resonance conditions. If we assume that for serious degradation of luminosity the beam size should expanded twice, the upper limit of beam lifetime in resonance is

$$N_{\max} = \frac{100 \%}{2 \%} \times 10000 = 5 \times 10^5 \text{ turns.}$$

(16)

If the resonances are avoided, the beam life time is limited by other reasons.

7. Conclusions

Particle-in-cell simulation shows significance of beam-beam interaction on beam parameters. Beam lifetime and luminosity constraints were studied from strong-strong model of beam-beam interaction.
EFFECT OF FIELD VARIATION ON BEAM PARAMETERS IN RIKEN RFQ LINAC

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Abstract

Beam dynamics study in an RFQ linac using 3D particle-in-cell code BEAMPATH was performed to analyze beam parameters due to variation of RFQ field. The study shows that linear approximation of RFQ parameters adopted in PARMTEQ code along every cell requires correct treatment of vane cutting in order to reproduce the original PARMTEQ design. Our RFQ layout has non-adiabatically changing region from buncher to accelerating section. For that we noticed that inappropriate treatment of PARMTEQ design can provide mismatching of the beam with the channel and particle loss. Among the linearly varied functions of aperture and electrode modulation along every cell we choose the pair of that parameters which represent the initial PARMTEQ design in the most appropriate way. Final selection of RFQ structure is characterized by stable values of beam transmission efficiency (around 90%) both for zero-current mode and for space charge dominated regime. Effect of vane errors on beam parameters was studied as well to define the engineering tolerance for RFQ vane machining and alignment.

1. Introduction

In many experimental RFQ tests the observed values of beam transmission efficiency in RFQ linac is smaller than it is expected from theoretical predictions. Possible sources for it were found to be higher order terms in RFQ potential and image charges. However, our study of beam dynamics indicates that transmission efficiency and other beam parameters can be affected even in the case of two lowest order RFQ potential terms

\[ U(r, \theta, z) = \frac{U_o}{2} \left[ X (k z)^{2} \cos \theta + A I_o(k r) \sin \theta \right] \quad (1) \]

due to different treatment of PARMTEQ vane tip design. It comes from the fact that in PARMTEQ design the quadrupole gradient \( XU_0/a^2 \) and the axial voltage \( AU_0 \) vary linearly over each cell and the final listing of RFQ parameters contains the geometry design values (aperture \( a \) and electrode modulation \( m \)) at the end of each cell. Different interpretation of output list parameters results in systematic deviation from original design. We examined this effect as well as effect of vane tip manufacturing errors on beam transmission efficiency for RFQ structure designed for upgrading the RIKEN Linear Accelerator (RILAC).

2. Beam Transmission Efficiency

Initial design of the RFQ linac was made with standard approach using PARMTEQ code. In PARMTEQ code every cell is generated with interpolation of input parameters: normalized quadrupole gradient \( B \), synchronous phase \( \varphi_0 \), vane modulation \( m \) and intervane voltage \( U_o \). Those initial dependencies are transformed in geometry parameters (cell length \( L \), aperture \( a \) and electrode modulation \( m \)) by iterative procedure to adjust cell length with local electric field and required phase shift of synchronous particle per cell.

Output listing of PARMTEQ contains cell lengths \( L \) as well as aperture \( a \) and electrode modulation \( m \) at the end of each cell. During the vane tip machinery the monotonic functions \( m(z), a(z) \) could be approximated in different ways which result in deviation of parameters \( A(z), X(z) \) from original design. Additional reason for deviation from original design is that coefficients \( X \) and \( A \) should be considered as \( z \)-independent values at every cell due to their definition as Fourier-Bessel coefficients:

\[ X = \frac{1}{U_o \pi^2} \int_0^{2\pi} \int_0^{2\pi} U(a, \theta, z) \cos \theta \, d\theta \, d(kz) \]

\[ A = \frac{2}{\pi^2 U_o \tan(ka)} \int_0^{2\pi} \int_0^{2\pi} U(a, \theta, z) \sin \theta \, d\theta \, d(kz) \quad (2) \]

In order to verify the effect of different representation of \( X(z), A(z), a(z) \) and \( m(z) \) we checked the following approximations of original PARMTEQ design:

1) linear variation of acceleration efficiency \( A \) and focusing efficiency \( X \) along each cell (PARMTEQ - type field);
2) a step-wise function of above parameters assuming that the values of \( <X_i> = 0.5 (X_{i-1} + X_i) \) and \( <A_i> = 0.5 (A_{i-1} + A_i) \) equal to mean values of that parameters over each cell;
3) a step-wise function of \( A,X \) assuming that at every cell aperture \( a \) and electrode modulation \( m \) are equal to their average values \( <a_i> = 0.5 (a_{i-1} + a_i), <m_i> = 0.5 (m_{i-1} + m_{i+1}) \);
4) a step-wise function of \( A,X \) assuming that parameters equal to the PARMTEQ designed values at the end of each cell \( a_i, X_i \).

Calculations were done using general-purpose particle-in-cell code BEAMPATH. Beam was represented as a collection of \( 10^4 \) model particles. Trajectories were...
calculated using 20 steps per cell in the field which is a combination of RFQ potential (1) and self field of the train of bunches. Space charge field was found at each time step from the 3-dimensional Poisson's equation on the NX x NY x NZ = 64 x 64 x 256 mesh with the Dirichlet boundary conditions for potential on the surface of square pipe and periodic conditions in longitudinal direction.

Results of calculations for the beam with mass/charge ratio A/Z = 5 are presented at Figs. 1-3 and in Table 1. For linear - varied field at every cell (PARMTEQ - type field) the beam transmission efficiency calculated from BEAMPATH code is close to PARMTEQ predictions (see results 1,2 in Table 2). Almost the same values of beam transmission efficiency were observed with step-wise field representation of RFQ field where parameters were supposed to be equal to the average values <Xj>,<Aj> at each cell (result 3 in Table 1). Smaller value of beam transmission efficiency for I = 1mA can be explained by different technique in space charge calculations: in BEAMPATH the 3D space charge field is renewed every time step while in PARMTEQ 2D space charge field appear as a kick once per cell.

The other approximations of original design (results 4,5 in Table 1) show decreasing of originally expected beam transmission efficiencies, especially for the case where a,m at each cell were supposed to be equal to the designed values at the end of the cell (result 5 in Table 1). Systematic changes of parameters A, X at every cell due to different representation of RFQ field have the effect of permanent error in vane geometry design which results in deviation in synchronous phase of the bunch and mismatch of the beam with the channel. This deviation is most serious in the region between buncher and accelerating section. This region is characterized by a sharp increase of electrode modulation which results in a quick change of acceleration gradient along the structure. Most of the particle losses are observed in this area. Beam losses in the longitudinal direction are much smaller (typically 2% for zero beam current and 4% for beam current I = 1 mA).

Table 1. Beam transmission efficiency in RFQ structure (A/Z = 5, f = 40 MHz).

<table>
<thead>
<tr>
<th>Code</th>
<th>Field Variation over each cell</th>
<th>I = 0</th>
<th>I = 1 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PARMTEQ</td>
<td>Linear</td>
<td>0.94</td>
<td>0.90</td>
</tr>
<tr>
<td>2. BEAMPATH</td>
<td>Linear (PARMTEQ-type)</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td>3. BEAMPATH</td>
<td>Step-wise (&lt;Xj&gt;,&lt;Aj&gt;)</td>
<td>0.94</td>
<td>0.86</td>
</tr>
<tr>
<td>4. BEAMPATH</td>
<td>Step-wise (&lt;aj&gt;,&lt;mj&gt;)</td>
<td>0.92</td>
<td>0.78</td>
</tr>
<tr>
<td>5. BEAMPATH</td>
<td>Step-wise (Xj,Ai)</td>
<td>0.86</td>
<td>0.70</td>
</tr>
</tbody>
</table>

3. Vane Manufacturing Errors

Random errors in vane tips manufacturing result in amplitude growth of transverse and longitudinal oscillation. Analytical treatment shows monotonous enlargement of transverse oscillation amplitude r_{max} after passing through the RFQ section with N cells:

\[
<\delta r_{max}^2> = 2N \frac{<\delta r_0^2> + 4r_{max}^2}{R_0} <\delta R_0^2> ,
\]

where \( \delta r_0 \) is an axis displacement and \( \delta R_0 \) is an error in average radius of the structure: \( R_0 = a / \sqrt{X} \). To study this effect via computer simulation the following parameters were randomly distributed at every cell within the max error \( \pm \delta \): cell lengths \( L \), aperture radius \( a \), max distance from axis to electrodes \( m \) and axis displacement \( \delta q \). Results of simulation (see Table 2 and Fig. 3) demonstrate that the error of 50 microns does not create any serious degradation of the beam parameters while error of 100 microns could cause noticeable decreasing of beam transmission efficiency. The engineering tolerance of 50 microns was thus adopted for vane tips fabrications.

Table 2. Beam transmission efficiency due to errors in vane fabrication.

<table>
<thead>
<tr>
<th>( \delta ), microns</th>
<th>I = 0</th>
<th>I = 1 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td>50</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td>100</td>
<td>0.80</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Disturbance of quadrupole RFQ symmetry result in appearance of dipole field component. This effect was studied for the case when one of the RFQ electrodes is shifted from its ideal position at the distance \( \Delta \). It means that extra terms containing \( \cos \theta \), \( \cos 2\theta \), \( \cos 3\theta \),... appear in the potential expansion. We restrict our consideration by adding two lowest order terms in RFQ potential:

\[
U(r,\theta,z) = \frac{L_x}{2} [X \left( \frac{L}{a} \right)^2 + \text{Ai}(kz) \sin(kz)] + A_{01} \frac{L}{a} \cos \theta + A_{11} \frac{L}{a} (kr) \cos \theta \sin(kz) .
\]

Coefficients \( A_{01}, A_{11} \) are defined by new boundary conditions where potential is kept constant at the surface of electrodes \( U(r,\theta,z) = -U_0/2 \):

\[
U(r,\theta,z) = -\frac{U_0}{2} \quad x = -a(z) ,
\]

\[
U(r,\theta,z) = -\frac{U_0}{2} \quad x = a(z) + \Delta ,
\]

where \( a(z) \) is the vane-tip profile of the modulated electrodes defined by equation:
From boundary conditions (5) the expression for RFQ potential with dipole component is given by:

$$V(r,0,z) = -\frac{U_0}{2} \left[ \frac{X}{a^2} (X^2 \cos 2\theta + A \theta_0(kr) \sin(kz)) + \frac{X + a(z)}{a^2} \frac{A}{4} (X + A \theta_0(k^2 \sin k z)) \right] + a(z).$$

Dipole component decreases the focusing strength of pure RFQ field if electrode is shifted outside the channel $\Delta > 0$ (and vice versa if $\Delta < 0$):

$$E_{\text{dipole}} = -\frac{U_0}{2} \frac{A}{a^2} \frac{\Delta}{4} (X + A \theta_0(k^2 \sin k z)).$$

Dipole component results in shifting of stable oscillation point from the axis. From equation (7) the new stability point $E_x(x_0) = 0$ is defined as $x_0 = \Delta/2$. Beam dynamics calculation performed for electrode displacement of $\Delta = 50$ microns shows that center mass of the beam oscillates around the new stability point $x_0 = 25$ microns. In this case no significant changes of beam parameters were observed.

4. Conclusions

In summary performed study showed the significant sensitivity of beam dynamics on different representation of RFQ field even in the case of two lower terms in RFQ potential. The vanes of our RFQ were designed in the way to adopt values $X$ and $A$ as average values from original linear function in PARMTEQ design. Final version of RFQ structure is characterized by the initially expected value of beam transmission efficiency. Dipole component originating from shifting of the RFQ electrode results in displacement of stability oscillation point and does not influence beam dynamics when the value of electrode shift is much smaller than aperture radius of the channel.

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COMPARISON OF CALCULATED SHIELDING EFFECTS FOR 8 MATERIALS

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Abstract

The depth dependence of neutron and secondary photon dose equivalents in the inside of 4 meter thick materials of iron, lead, ordinary concrete, heavy concrete, graphite, marble, water and paraffin were calculated for monoenergetic source neutrons of energies less than 400 MeV. Their shielding characteristics are compared and discussed phenomenologically. Calculations were carried out by using the one-dimensional discrete ordinates code ANISN-JR and the cross section library DLC-87/HILO. Systematic knowledge concerning the shielding materials was successfully obtained.

1. Introduction

In recent years, the radiation shielding of high energy accelerators has become one of the important problems as the particle energy and/or the beam intensity get higher. In order to achieve effective shielding, it is necessary to know about the shielding characteristics of various materials for radiation, especially neutrons. So far, iron, lead, ordinary concrete and water are some of the most widely used shielding materials, and their shielding characteristics have been studied extensively for source neutrons in the wide energy range. Recently, comparison of shielding characteristics between 8 materials was given for dose equivalents at the exit surfaces of shields of varying thickness (1). (Hereafter the ordinary concrete is abbreviated simply as concrete.) In this paper, iron, lead, concrete with 5.5% water by weight, heavy concrete with 5.5% water by weight, graphite, marble, water and paraffin are taken as typical shielding materials. The depth dependence of dose equivalents in the inside of these materials is estimated for monoenergetic neutrons in the energy range less than 400 MeV. Calculations were carried out by using the one-dimensional discrete ordinates code ANISN-JR (2) and the cross section library DLC-87/HILO (3). The calculation procedure and the results are given in section 2 and 3, respectively. Details for them are described elsewhere (4).

2. Calculation Procedure

The ANISN-JR is a refined version of the ANISN (4) which was developed to solve the one-dimensional Boltzmann transport equation for neutrons and photons in materials by using multigroup cross section data, and is used to solve penetration problems under the condition of anisotropic scattering.

The DLC-87/HILO is one of several neutron-photon multigroup coupled cross section libraries which have been offered from the Radiation Shielding Information Center. In this library the cross section data are given in the structure of the 66 neutron energy groups from the thermal energy to 400 MeV and the 21 photon energy groups from 10 keV to 14 MeV. The transport calculations were made for neutrons and secondary photons with scatterings of an S16 angular quadrature and a P3 Legendre cross section expansion. The primary neutron in a group of a specified energy range is normally incident on a shielding material with a slab geometry, and its transitions to elastic and nonelastic channels are evaluated numerically. The attenuation of the secondary photons produced by neutron nonelastic reactions in materials is also obtained. Energy-to-dose conversion factors are quoted from ICRP Publication 21, and then the unit of the dose equivalent was converted from rem to Sv using the relationship $1 \text{Sv} = 100 \text{rem}$.

3. Results AND Discussion

3.1. Attenuation of Neutron Dose Equivalent

The depth dependence of the neutron and secondary photon dose equivalents is shown in Fig.1 for iron, lead, concrete with 5.5% water by weight, heavy concrete with 5.5% water by weight, graphite, marble, water and paraffin. Here, marble is regarded as pure calcium carbonate, CaCO3. In Fig. 1, solid and broken lines show the variation of neutron and secondary photon dose equivalents, respectively. Numbers on the right of each curve refer to the group number of source neutron energies, and those underlined represent the group numbers for the source neutrons producing the secondary photons. (See Table 1)

* deceased
accompanied by neutron penetration in shielding process and de-excitation of reaction products. The photons.

group consisting of lead, marble and graphite, however, efficient for shielding low energy neutrons but not so efficient for shielding secondary photons. The last group consisting of lead, marble and graphite, however, is not efficient for shielding neutrons and secondary photons.

Iron is a very effective shielding material for neutrons at energies above 30 MeV and below 100 keV. For the neutrons of around 1 MeV, however, iron is rather inferior to concrete and heavy concrete. Heavy concrete is also one of the most effective shielding materials, i.e. it is superior to iron for neutrons below 10 MeV. Although heavy concrete is more efficient than concrete in the whole energy region, concrete is widely used because of its lower cost. Water and paraffin are excellent shielding materials for neutrons below a few tens of MeV. Lead and graphite do not seem to be effective shielding materials in the whole energy region. Marble, as a whole, does not have special features. It has a similar attenuation pattern to that of concrete without water as can be supposed easily.

The dose equivalents are reduced steeply at the end of the slabs, which is due to the lack of back scattering from the outside of shielding materials.

3.2. Attenuation of Dose Equivalent by Secondary Photons

Source neutrons incident on shielding materials induce secondary photons by way of a radiative capture process and de-excitation of reaction products. The photon dose equivalents caused by monoenergetic incident source neutrons are shown as a function of material depth in Fig.1 together with neutron dose equivalents. As the secondary photons are inevitably accompanied by neutron penetration in shielding materials, both neutrons and secondary photons should be considered inclusively in shielding problems, i.e. a summed dose equivalent will be important practically. Although photon fluxes are of nearly the same order as neutron ones for all materials and in whole source energy regions, the photon dose equivalents in shielding materials are less than the corresponding neutron ones by 2 orders of magnitude. This is due to the fact that the secondary photon energy is almost independent of the incident source neutron energy and that the flux-to-dose conversion factor of photons is smaller than that of neutrons.

The attenuation characteristics of photon dose equivalents should be considered by combining the attenuation of primary and secondary photons.

Secondary photon dose equivalents of source neutrons above 90 MeV also increase near the vicinity of the surface of shielding materials. However, these have little contribution to summed dose equivalents in this energy region.

4. Conclusions

Quantitative depth dependence of dose equivalents inside each shielding material is almost same as that at its exit surface of varying thickness. Iron, heavy concrete and concrete have excellent shielding effects for neutrons of energies more than a few tens of MeV, and water, paraffin, iron and heavy concrete are efficient shielding materials for neutrons of lower energies. For neutrons in the thermal energy region, iron and heavy concrete are especially efficient.

The shielding materials studied can be classified into the three groups, i.e. heavy elements, hydrogenous materials and others, according to the difference of degradation mechanism of neutron energies.

The attenuation pattern of photon dose equivalents in shielding materials will be considered to result in competing processes between the attenuation of photons due to the density and the supply of secondary photons due to inelastic photon emission processes of neutrons.

In application to practical shielding, we should understand characteristics of each dose equivalent attenuation of incident neutrons, primary and secondary photons in shielding materials.

References

Nonlinear Resonances in a Multi-Stage Free-Electron Laser Amplifier

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Abstract
Nonlinear resonances in the longitudinal phase-space of a multi-stage Free-Electron Laser for the Two-Beam Accelerator have been studied. We have developed a new analytic theory based on the macroparticle model and the perturbation method. A resonance-structure observed in simulations is found to be modeled by the nonlinear pendulum equation and to depend on a waveguide dimension.

1. Introduction
A Two-Beam Accelerator (TBA) is a possible candidate for future linear colliders, in which rf power required for a high-gradient linac is provided from a Multi-stage Free-Electron Laser (MFEL) [1,2] as shown in Fig. 1. The MFEL has some unique features. First a bunched beam drives each FEL. Second it has a periodicity: after amplification of input seed-power in each FEL, the driving beam is re-accelerated with an induction unit for energy replenishment to go to the succeeding stage. This fact means that rf and beam characters vary periodically and a bucket evolves rapidly in each FEL.

![Fig. 1 Schematic picture of TBA/FEL](image)

One of the interesting issues in the MFEL is the resonances between the synchrotron motion in a bucket and the periodicity of the MFEL [3]. The resonances lead to a formation of islands within a rf bucket in longitudinal phase-space, and degrade the performance of the MFEL as an rf source. We suppose that the resonances should be serious when the power-density of the amplified rf is strong.

This paper presents the nonlinear resonance in the MFEL for the recent version of TBA [4,5], not for the early one [3]. Section 2 briefly shows the simulation results which show the existence of the resonance. We show in section 3 that by use of the macroparticle model [6-8], the motion of electron in the phase space of the MFEL can be described by the nonlinear pendulum equation with periodically and rapidly time-varying “mass” and “length”. Section 4 shows how the resonance can be theoretically analyzed with the perturbative calculation.

2. Simulation
The well-known one dimensional FEL simulations [9,10] have been performed. We have assumed a rectangular waveguide TE_{01} mode as a signal wave. Typical parameters of the MFEL of interest are listed in Table 1. The high rf power-density with a rapidly increasing ponderomotive force would give rise to strong resonances. In order to evaluate effects of the rf power-density on the resonances, only the waveguide width \( a' \) is varied while the other parameters are fixed. For a relatively wide waveguide (\( a' \geq 10 \) cm), our previous simulation shows that the beam propagates from the first to the 300-th stage without detrapping, and maintains the original bunch shape [7]. For cases of smaller waveguide \( a' = 8, 4 \) cm, meanwhile, the fourth and third-integer resonances are observed as shown in Fig. 2. These resonances are considered to be caused by the strong rf power-density resulting from the reduced waveguide width. When these resonances occur, the beam continues to lose its population, the rf power decreases, and the
signal phase changes [4]. These are significant problems for the multi-stage rf-source where transport of a high current beam over a long distance is indispensable to maintain a constant amount of amplified rf power.

### Table 1. FEL parameters for TBA/FEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current $I_\text{b}$</td>
<td>2 kA</td>
</tr>
<tr>
<td>Beam energy $\gamma$</td>
<td>23</td>
</tr>
<tr>
<td>Energy gain per period $\Delta \gamma$</td>
<td>1</td>
</tr>
<tr>
<td>Wiggler wave length $\lambda_\text{w}$</td>
<td>26 cm</td>
</tr>
<tr>
<td>Wiggler length per period $L_\text{w}$</td>
<td>52 cm</td>
</tr>
<tr>
<td>Wiggler peak field $B_\text{w}$</td>
<td>3.85 - 3.6 kG</td>
</tr>
<tr>
<td>Signal frequency $f_s$</td>
<td>17.1 GHz</td>
</tr>
<tr>
<td>Input rf power $P_\text{in}$</td>
<td>10 MW</td>
</tr>
<tr>
<td>Waveguide width $a^*$</td>
<td>20 - 4 cm</td>
</tr>
<tr>
<td>Waveguide height $b^*$</td>
<td>3 cm</td>
</tr>
<tr>
<td>Number of FEL stage</td>
<td>300</td>
</tr>
</tbody>
</table>

![FIG. 2 Longitudinal phase-space structure by FEL simulations. (a) the fourth-integer resonance (waveguide width $a^* = 8$ cm), (b) the third-integer resonance ($a^* = 4$ cm).](image)

#### 3. Nonlinear pendulum equation

Following the Ref. 3 and using the definition of the macroparticle [6-8], the Hamiltonian for the MFEL can be written as

$$H(e, \xi, E, X; z) \equiv \sum_i \left\{ k_i - \delta k_i \right\} (\gamma_* + e) + \omega_i \left(1 + a_i^2\right)$$

$$-a_c \left( \frac{e Z J_\text{r}}{m c^2} \right)^{1/2} \left( \frac{E - N \gamma_*^2}{N^{1/2}} \cos(\psi_* + \xi) + \frac{d \gamma_*}{dz} \right)^{1/2},$$

where $\gamma_*$, $\psi_*$ are the Lorentz factor and ponderomotive phase of the macroparticle, $e$, $\xi$ are deviations from the energy and phase of the macroparticle, $N$ the number of particles, $a_c = e B_r/\sqrt{2\pi a_c k_0}$ the normalized wiggler amplitude, $\delta k_i = \omega_i/c - k_i$ the shift of longitudinal wavenumber from its value in vacuum, $\omega_i$ rf angular frequency, $k_i = \sqrt{\omega/c^2} - (\pi/a_i^2)$ the wavenumber for TE$_{01}$ mode, $J_\text{r}$ beam current density, $e_0$ normalized signal-field, $k_0$ the wavenumber of wiggler, $\psi_*$ the signal phase, $e$ and $m_e$ are the charge and rest mass of electron, $c$ the speed of light, $z$ longitudinal coordinate, $Z_\Omega = 377\Omega$, $E = N m_e e_0^2/c Z J_\text{r}$, and $\chi = -\varphi_\text{w}$. Expanding the Hamiltonian (1) in powers of $e/\gamma_*$ and retaining the dominant terms, we have

$$H(e, \xi, z) \equiv G(z)e^2/2 - F(z)\cos\psi_* \cos\xi$$

$$+ F(z)\sin\psi_* (\sin\xi - \hat{\xi}).$$

Neglecting friction terms which are proportional to $\xi'$ because of their smallness, we obtain a nonlinear pendulum equation

$$\xi'' + GF\{ \sin\psi_* (\cos\xi - 1) + \cos\psi_* \sin\xi\} = 0,$$

from the Eq. (2), where primes denote differentiation with respect to $z$. The macroparticle model assumes $\gamma_* \approx a_c$; hence $GF$ in Eq. (3) is determined mainly by $e$, which is written in a term of the trigonometric function [8], $e(z) = (a k/ab) \sin(b/2 z)$. Figure 3, which was established in Refs. 6, 7.

Figure 3 shows the results of numerical integration of Eq. (3) for $a^* = 4$ cm. We observe that Eq. (3) can well reproduce the results of the FEL simulations seen in Fig. 2. Thus, we consider the Hamiltonian (1) with $E \propto e^2$, $\chi = -\varphi_\text{w}$ determined by the macroparticle model as a theoretical base to analytically assess the nonlinear resonances in the MFEL.

![FIG. 3 Phase-space plots of the nonlinear- pendulum's solution for (a) $a^* = 8$ cm and (b) $a^* = 4$ cm.](image)

#### 4. Isolated resonance theory

Using the isolated resonance theory [11] which has been established in beam dynamics of circular
accelerators, we can calculate the size and position of the primary resonance islands [4]. Expanding the Hamiltonian (1) in powers of $\xi$ and $e/\gamma_v$:

$$H(\xi, \xi', z) = G\xi'^2/2 + F_c\xi^2/2 + \text{(perturbations)}$$

(4)

where $F_c = F \cos \psi$. The expression can be regarded as the non-autonomous one degree of freedom Hamiltonian for a pendulum with time-varying "mass" $G$ and "length" $F_c$, affected by nonlinear perturbations.

Using the generating functions $F_l(\xi, \psi; z) = \xi e^{\gamma(z)}$ and $F_r(\xi, \psi) = -(\alpha + \tan \theta)\xi^2/2\beta$, where $\alpha, \beta$ satisfy

$$2\beta' - \beta'' + 4GF_\beta = 4,$$

(5a)

$$\alpha = -\beta'/2,$$

(5b)

the Hamiltonian (4) is transformed to

$$H(J, \beta; z) = \left(\gamma J(z)\right)^{1/2} + \text{(perturbations)}.$$

(6)

Here $\beta$ is referred to as a longitudinal amplitude function in the MFEL, which is a quantity analogous to a transverse amplitude function in circular accelerators. This function represents the orbital evolution of the bunch envelope in the MFEL. Instead of $z$, we use a new independent variable $\sigma$ defined by

$$\sigma = \left(1/\gamma_v\right)\left[1/\beta(z')dz'\right],$$

where $\gamma_v = (1/2\pi)\int_0^\sigma 1/\beta(z')dz'$ is referred to as the longitudinal tune and $2\pi \gamma_v$ is the phase advance per FEL period. Retaining only the dominant terms after some straightforward mathematical manipulation and according to the isolated resonance theory [11], we have the "time"-independent Hamiltonian for the isolated third-integer resonance:

$$H(J, \beta; z) = \left(\gamma J(z)\right)^{1/2} + \text{(perturbations)}.$$

(7)

where $\delta_{j, k}$, $\delta_{j, k}$, and $\Theta_j$ are all constants which depend on FEL parameters [4]. The Hamiltonian for the fourth-integer resonance also can be calculated in a similar way [4]. Eventually we arrive at the exact mathematical formula necessary to theoretically assess the primary resonance observed in the simulations. Fig. 4 shows lines of the equi-Hamiltonian in the phase-space for $a' = 8, 4 \text{ cm}$ in the rectangular coordinates $P = \sqrt{27} \sin \theta$, $Q = \sqrt{27} \cos \theta$ to compare with Figs. 2, 3. The calculated position and size of the islands are in agreement with simulations [4]. The transition of phase-space structures in Figs. 2, 3 also can be explained with the above theory [4]. The longitudinal tune $\gamma_v$ increases with a decrease of the waveguide width $a'$. When $\gamma_v$ is more than $1/4$ (1/3), the fourth (third)-integer resonance can occur.

This theory is able to give a crucial suggestion in choosing practical MFEL parameters.

**Acknowledgments**

The authors would like to thank Dr. H. P. Freund of Science Applications International Corporation and Prof. T. C. Marshall of Colombia University for helpful remarks and suggestions. One of the authors (S.H.) thanks Prof. S. Hiramatsu of KEK for his hospitality. The numerical calculations were performed on DEC 3000 AXP-500.

**References**

Abstract

We have designed and constructed a prebunched free-electron laser (FEL) amplifier consisting of a prebuncher and a standard FEL. Microwave power saturation with a short wiggler length was realized by the prebunched beam. We also examined the microwave phase evolution. It was found the adjustable range of the output microwave phase by changing the input microwave phase was restricted within a narrow band due to spontaneous emission radiated by the prebunched beam.

1. Introduction

We developed the X-band FEL [1-3], which is a candidate for possible high power microwave sources (~1GW) for future linear colliders and other applications. We tried a new sort of FEL experiment in which the FEL is driven by a prebunched beam [4-7]. The experimental configuration is that of a standard FEL accompanied by a prebuncher. Hereafter we call this a prebunched FEL. In this paper we describe the prebuncher FEL experiment which has two important purposes. The first is to realize a compact / efficient FEL with a large gain per wiggler length. By attaining the power saturation with a short wiggler length, we can enhance the power through the remaining length by tapering the wiggler field. The second purpose is to experimentally control the output microwave phase by changing the phase of the seed microwave to the wigglcr. Achieving the latter purpose is a crucial issue in FEL physics in a multi-stage FEL which is driven by a bunched beam in the FEL-TBA linear collider [8].

2. Prebuncher

A schematic view of the prebunched FEL amplifier is shown in Fig.1. The prebuncher is placed between the downstream induction unit (IDU) and the wiggler. An electron beam of 1.5MeV/850A generated by the induction gun is prebunched at the same frequency as that of the FEL (9.4GHz) before entering the wiggler. An input microwave signal is amplified through the wiggler due to the FEL interaction (stimulated operation regime). Even if no microwave signal is inputted, the strong spontaneous emission radiated by the prebunched beam should be amplified in the same way (superradiant operation regime).

Concerning the limited magnitude of the available microwave power, we have adopted a prebunching section with a two-cavity configuration as illustrated in Fig.2. It is similar to the bunching section of a conventional klystron. The input cavity is excited in the TM010 mode with a fraction of the power introduced from the external magnetron, leading to modulation in the beam-velocity to some degree. Velocity-modulation gradually becomes current-modulation. The gain cavity, placed 9cm downstream the input cavity, is excited by induced current-modulation and can give the driving beam further velocity-modulation. To get the current-modulation of 30% at the wiggler entrance, the cavity gap voltage of 170kV is required according to a theoretical estimation. In the two-cavity configuration, the input cavity requires a microwave power of 15kW to achieve the gap voltage of 170kV in the gain cavity. The maximum surface electric field can be reduced to 13MV/m in the gain cavity when beam-loaded, which should be sufficiently low enough to avoid surface breakdown. The same sized pill-box cavities without nose cones are employed for the input and gain cavities.

3. Prebunching Experiment

A magnitude of current-modulation attained at the entrance of the wiggler was measured in the first step of the prebunched FEL experiment to optimize and evaluate the prebuncher system. A bunch-monitoring cavity...
immerged in an axial magnetic field was installed at the location corresponding to the wiggler entrance. The magnitude of current-modulation was determined from the microwave power extracted from this cavity. Its external-Q \( Q_{\text{ext}} \) is designed to be much smaller than the unloaded-Q \( Q_u \) and the beam-Q. Under this approximation, the AC beam current \( I_{ac} \) is estimated from the extracted power \( P_{\text{out,mon}} \) by the following relation

\[
I_{ac} = \frac{2}{\mathrm{TTF}(0)} \sqrt{\frac{Q_u}{R_{sh}}} \frac{P_{\text{out,mon}}}{Q_{\text{ext}}}
\]

where \( R_{sh} \) is the shunt impedance and \( \mathrm{TTF}(0) \) is the transit time factor for a particle passing through the cavity center. This method is not so precise, but it is sufficient to estimate the fundamental component of modulation.

Figure 3 shows the experimental results in which the maximum current-modulation of 45% was achieved with an input power of 35kW and the dependence of the current-modulation on the input power seemed to be fairly consistent with the design calculation. Current-modulation beyond 45% was limited in practice by pulse-shortening phenomena at the gain cavity.

![Fig.3 Current-modulation attained at the wiggler entrance.](image)

4. FEL Experiment

4.1 Superradiant Operation Regime

In this regime, a prebunched beam of 1.5MeV/DC750A was introduced into the wiggler and the transmission efficiency through the wiggler was 70%. Figure 4 shows the power evolution measured at the wiggler field of 1.25kG for two cases of current-modulations of 45% and 10%. Both results indicated stagnation in power-growth at the wiggler length of 0.4m. They had different saturation levels and saturation distances: 120MW/1.1m and 150MW/1.5m, respectively. These features could be well-reproduced by simulations. The field growth stagnation was caused by debunching. The prebunched beam is debunched once and again bunched due to space-charge oscillation and partially trapped in the pondermotive potential. Without the space-charge effect, a significant part of the prebunched beam would be trapped in the pondermotive potential without any serious debunching.

To increase the output power beyond the saturation level, we carried out tapered FEL experiments. Simulations told us that an output power over 350MW can be achieved with appropriate tapered wiggler fields. However, an enhanced output power has not been observed yet, probably due to poor beam transport in the wiggler. The beam loss was rather severe around the resonant field (-1.4kG), where the beam should be well-bunched and trapped in the pondermotive potential ideally. Although the saturation power was a maximum for the wiggler field of 1.25kG, at which the beam loss was mitigated, the bunch structure in the pondermotive potential becomes rather elongated due to mismatching in the longitudinal phase space, resulting in poor efficiency of the wiggler field taperings.

![Fig.4 Microwave power evolutions in the case of superradiant operation.](image)

4.2 Stimulated Operation Regime

(a) Power evolution

A seed power of 60kW was introduced into the wiggler through a microwave input coupler with beam-passing metal-mesh which reduced the transmitted beam-current to DC500A. Figure 5 shows the power evolution for current-modulation of 40%. Its initial growth was very sensitive to the phase relation between the seed microwave and the current-modulation. When both were in-phase, the field evolution was quite similar to that in the superradiant operation regime. When both were in anti-phase, a rapid damping in power was observed at the initial stage of the wiggler and beyond that the power grew quickly. The current-modulation being larger, the field recovery became quicker and the power-evolution curve in the case of the anti-phase approached that of the in-phase after the quick recovery. This is quite clear from the fact that the microwave power \( P_{RF} \) at the initial stage of the wiggler may be approximated as

\[
P_{RF} \approx A_R^2 = A_{R,\text{IN}}^2 + A_{R,\text{PB}}^2 + 2 A_{R,\text{IN}} A_{R,\text{PB}} \cos \delta,
\]

where \( \delta \) is the phase difference between the seed microwave field \( A_{R,\text{IN}} \) and the prebunched superradiant emission \( A_{R,\text{PB}} \). The prebunched superradiant emission \( A_{R,\text{PB}} \) grows rapidly and surpasses the seed microwave field \( A_{R,\text{IN}} \) after a few wiggler periods for our beam parameters in the (high-gain) Raman regime. If \( \cos \delta \) is negative, the microwave power \( P_{RF} \) drops rapidly from the seed power due to the last term and soon increases again due to the second term. These features can be well-reproduced by simulations and are quite different from those of
prebunched FELs operating in the low-gain regime [5][7]. In the case of low-gain prebunched FELs including an optical klystron, the second term is negligible, because $A_{PB} < A_{IN}$. If $\cos \theta$ is negative, the power gain is negative namely $P_{RF} < P_{RF,IN}$.

![Simulation result](image)

Fig.5 Microwave power evolutions in the case of stimulated operation.

(b) Phase evolution

Microwave phase was measured with a double balanced mixer using a magic tee. The phases of input and output microwaves of the wiggler were measured with reference to the magnetron's output microwave phase. Figure 6 shows the experimental results of phase evolution for current-modulation of 15%. Initial phase variations are caused by a complicated mechanism, because intense FEL interaction starts in the matching section where a non-resonant up-tapering field is present for beam-orbit matching. However, we note that the initial phase difference of 180° decreased to 80° due to FEL interaction with the prebunched beam.

![Simulation result](image)

Fig.6 Microwave phase evolutions for different initial phases of the input microwave. The zero phase is when the beam bunch-center is located at the maximum decelerating field of the input microwave.

The response of the output microwave phase was examined for the change of the input microwave phase of the wiggler. Figure 7 plots the experimental results of the adjustable range of the output microwave phase when we changed the input microwave phase from 0° to 360° every 30°. We can say that the current-modulation being higher, the output microwave phase was determined by the superradiant emission of the prebunched beam. The adjustable range of the output microwave phase became restricted within a narrow band. When the current-modulation became higher than 30%, the adjustable range was limited to less than 40° for the input microwave power of only 60kW. These phenomena were expected based on the simulations.

![Simulation result](image)

Fig.7 Adjustable range of the output microwave phase by changing the input microwave phase.

5. Conclusion

The saturation power of 120MW was attained at the wiggler length of 1.1m by a 1.5MeV prebunched beam with a 45%-modulated DC750A current. However, FEL performances were deteriorated by beam losses in the wiggler.

The controllability of the output microwave phase was examined by changing the phase of the input seed microwave to the wiggler. When the current-modulation of the injection beam (1.5MeV-DC500A) was higher than 30%, the adjustable range was limited to less than 40° by the input microwave power of only 60kW.

References

Development of Infrared Free Electron Laser System Using Compact Linac

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Abstract

The present status of infrared free-electron laser (FEL) system using compact linac in Sumitomo Electric Industries Ltd. (SEI) is reported. Characteristics of the beam transport system was studied through numerical simulations. For precise simulating, initial condition of the beam at the end of the linac was examined in details. As a result, beam transport condition to realize well-focused beam in undulator was obtained. Spontaneous emission of peak power of 0.4mW was observed in recent experiment.

1. Introduction

We have developed a compact 100MeV linac in Harima Research Laboratories. This linac not only provides electron beam for compact superconducting SR ring NIJI-III, but is utilized for infrared FEL experiments.

Table I Main design parameters of the linac.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Frequency</th>
<th>Input Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron gun</td>
<td>Cathode</td>
<td>EIMAC Y646B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Voltage</td>
<td>200 kV - DC</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emission current</td>
<td>1.5 A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normalized emittance</td>
<td>7 π mm mrad</td>
<td></td>
</tr>
<tr>
<td>SHPB</td>
<td>Type</td>
<td>Standing wave</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>476 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Input power</td>
<td>4.6 kW</td>
<td></td>
</tr>
<tr>
<td>Prebuncher</td>
<td>Type</td>
<td>Standing wave</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>2,856 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Input power</td>
<td>5 kW</td>
<td></td>
</tr>
<tr>
<td>Buncher</td>
<td>Type</td>
<td>Traveling wave</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>2,856 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Input power</td>
<td>8 kW</td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>Type</td>
<td>Traveling wave</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mode</td>
<td>2π/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>2,856 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam energy</td>
<td>100 MeV( short pulse )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macropulse current</td>
<td>100 mA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy spread</td>
<td>0.5 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normalized emittance</td>
<td>60 π mm mrad</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repetition rate</td>
<td>2pps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accelerating gradient</td>
<td>22 MeV/m</td>
<td></td>
</tr>
</tbody>
</table>

width of 1μs for injection into NIJI-III, 10μs for FEL experiments. Accelerating rf power is supplied by klystron (Thomson-CSF TH214G). Pulse length depends on the connections in pulse forming network (PFN) in the klystron modulator.

Since the long-pulse operation mode has been designed to marking FEL oscillation in target, which includes some of the essential elements to obtain high quality electron beam suitable for FEL.

First of all, emittance of the beam should be reduced for FEL experiments. We have accomplished normalized emittance of 7 π mm mrad in the electron gun, where small-size thermionic dispenser cathode (EIMAC Y646B) is assembled and high DC voltage of 200kV is applied to anode-cathode gap. The gun container is filled with SF6 insulation gas, and the structure around the gun is determined by numerical simulation to avoid electric field concentration.

Secondary, energy spread of the electron beam from linac should be narrow. Fluctuation of resonant frequency of the accelerating tube causes energy shift of the beam. To avoid that, temperature of accelerating tubes are precisely controlled within ±0.002°C by water cooling system. Beam energy spread is also strongly influenced by the stability of pulses generated by klystron modulator. To obtain flatness and stability of output pulses, PFN is composed of two parallel 21 stages, each using the capacitors with low self inductance less than 0.1μH.

Next, subharmonic prebuncher system (SHPB) is installed. Accelerating rf frequency is selected to be 476MHz, that is one-sixth of the dominant frequency of 2,856MHz. Power supply system for SHPB is constructed by full solid-state circuits for its maintainability. Also inner surface of the stainless-steel cavity is partially coated with OFHC to optimize the Q-value, intending to reduce filling time and wake-field effect.

3. FEL experiment system

Figure 1 shows the schematic view of our FEL experiment system. The FEL beam transport system (FEL-BTS) contains two bending magnets and five quadrupoles, showing S-shape with bending angle of 25 degrees. Beam slit installed at down-stream of BM1 is expected to cut the tail of energy distribution. Equipments for beam diagnostics; two current monitors and five position monitors, also installed to observe focusing property in the undulator. To realize efficient and precise adjustment of beam trajectory, 1mm-thick aluminum OTR position monitors in the undulator section have 3mm-radius pin-hole in the center.
Fig. 1. FEL experimental system.

Table II Parameters of the undulator.

<table>
<thead>
<tr>
<th>Type</th>
<th>Halbach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet material</td>
<td>Nd-Fe-B</td>
</tr>
<tr>
<td>Period length</td>
<td>4.0 cm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>50</td>
</tr>
<tr>
<td>Total length</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Gap width</td>
<td>16~32 mm</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.62~0.18 T</td>
</tr>
<tr>
<td>K parameter</td>
<td>2.4~0.7</td>
</tr>
</tbody>
</table>

aligned to designed orbit using He-Ne laser.

Table II shows main parameters of our horizontal polarized Halbach type undulator with Nd-Fe-B permanent magnet. Magnetic field was accurately measured with BELL-9900 Gauss meter. Dispersion of peak value (∆B / B) was less than 1.0%, and second-order integral was less than 5.4 x 10⁻⁵ Gauss mm².

Optical resonators consists of two concave Au coated OFHC mirrors with the curvature of 4.42m and 4.14m. Resonator length between up- and down-stream mirrors was designed to be 7.5576m. Up-stream mirror has reflectance of more than 99.2%, and down-stream mirror has 1mm-radius pinhole to extract FEL.

Down-stream mirror can be adjusted manually with precision of 0.01mm, and remote-controllable driver unit with stepping motors and piezoelectric actuator enables fine position adjustment of up-stream mirror. In particular, piezoelectric actuator gives the precision of 10nm to the adjustment along the z-axis.

4. Beam transport experiments

Lattice structure of FEL-BTS was designed through the numerical simulation with evaluation of (i) achromaticity, (ii) quasi-isochronism and (iii) focusing property of the beam in the undulator section.

In FEL experiments the electron beam envelope should be well-focused and finely matched to the optical beam envelope in the undulator section to increase their interaction. To simulate characteristics of the beam in the FEL-BTS, particularly in the undulator section, we studied initial condition in details: not only the size and divergence

Fig. 2. Calculated beam size in FEL-BTS. Characters σₓ and σᵧ stand for half-width of the beam envelope in the x- and y-plane respectively; result of parametric fitting to observed beam size (dashed line), and well-focused beam with initial condition estimated at the exit of linac (solid line).

Fig. 3. Electron beam and optical envelope in the undulator.
but also focusing or defocusing character of the beam at the exit of the linac was taken into account.

As the first step, we injected the beam into actual FEL-BTS to collect the experimental parameters such as beam energy and energy spread, beam size at the position monitors and magnetic fields applied to Q-magnets. Setting these parameters as input values, we simulated beam transportation to search for initial condition that satisfies characters of the beam observed in the experiment. Calculated Twiss parameters $\alpha$, $\beta$, and $\gamma$ of the beam at the exit of linac are listed in Table III. We can see the parameter $\alpha$ has negative value, which means the beam initially has focusing character at the exit of the linac.

### Table III

<table>
<thead>
<tr>
<th>Plane</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-plane</td>
<td>-22.3</td>
<td>41.7</td>
<td>119.9</td>
</tr>
<tr>
<td>y-plane</td>
<td>-59</td>
<td>26.7</td>
<td>37.6</td>
</tr>
</tbody>
</table>

In the next step calculation with the initial condition of the beam obtained above, we changed the combination of fields of Q-magnets to produce well-focused beam matched to optical envelope, as shown in Fig.2. Envelope of optical beam and electron beam in the undulator are shown in Fig.3, where the optical envelope of the wavelength of 2.78 $\mu$m is assumed to be Gaussian beam that has beam waist of 1.84 mm at the center of the undulator. Through the study of initial condition of the beam at the end of the linac, we can precisely predict the beam characteristics in the FEL-BTS by the numerical simulation, and it is helpful to arrange the operating parameters.

### 5. FEL experiments

Referring the result of transport experiments, we carried out spontaneous emission experiment. Figure 4 shows observed spontaneous emission under the conditions listed in Table IV. With the assumption the micropulse is 10ps-long, the peak power is estimated to be 0.4 mW.

### Table IV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>50 MeV</td>
</tr>
<tr>
<td>Peak current</td>
<td>25 A</td>
</tr>
<tr>
<td>K parameter</td>
<td>0.84</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.23 T</td>
</tr>
<tr>
<td>FEL wavelength</td>
<td>2.8 $\mu$m</td>
</tr>
<tr>
<td>Gain</td>
<td>10%</td>
</tr>
</tbody>
</table>

We also roughly estimated the small-signal gain to be 10% through the calculation method used in the FELIX facility[2]. Though energy spread is known to eliminate gain, it is hard to make it narrower only by adjusting the operational parameters of linac. Subharmonic prebuncher system (SHPB) can increase the micropulse current and it will lead to increase of the gain. Recently we observed desirable bunching effect throughout the macropulse.

### 6. Summary

Characteristic behavior of the beam in our FEL experiment system can be well predicted through the numerical simulation with the initial condition at the end of the linac. The calculation result indicates the experimental condition of the next stage that we can produce the beam well-focused and matched to optical envelope in the undulator.

Spontaneous emission was observed as the primary stage of our FEL experiments using the compact linac. Also we intend to achieve FEL oscillation through the increase of micropulse current by SHPB system and fine adjustment of the optical resonator.

### References

[1] T. Haga et al., on this proceedings.
Experiments of Beam-Induced-Plasma for Basic Study of HIF by RFQ-Linac

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Abstract

An intense heavy ion linear accelerator system is being constructed for basic researches on HIF and heavy ion pumped laser at TIT. This accelerator system consists of an RFQ-Linac, an ECR ion source, a fine-focusing beam transport system and a fast beam pulsing system. At present, the obtained maximum beam current from the TIT-RFQ is 1.6 mA for 4He+. By using this system, An ion beam of 4He+ with an energy of 220 keV/amu was focused onto a small spot area of about 1mm². This beam deposited a specific deposition power of about 0.14 GW/g to the target. The overall status of this linac system and preliminary experiments with beams of 4He+ are discussed.

1. Introduction

Heavy ion beams are one of the favorable drivers for Inertial confinement fusion because of their good efficiency and effective energy deposition in the target. It is important for Heavy Ion Inertial Confinement Fusion (HIF) to make researches on a heavy ion accelerator and a beam-target interaction. At Tokyo Institute of Technology (TIT), a heavy-ion-induced plasma has been studied for basic researches on HIF and heavy ion pumped laser. For these experiments, an energy driver is required to create a high intensity and brightness beam. An intense heavy ion linear accelerator system is being constructed to meet the requirements. Fig 1 shows the layout of the intense heavy ion linac system. This system consists of a four vane type 81 MHz Radio-Frequency Quadrupole Linac (TIT-RFQ), a 2.45 GHz Electron Cyclotron Resonance (ECR) ion source, a fine-heavy ion linac system. The first experiments have been carrying out with 4He+ beams.

2. Intense ion beams from an RFQ-Linac

The TIT-RFQ was designed to accelerate particles with a charge to mass ratio (q/A) greater than 1/16 from 5 keV/amu up to 220 keV/amu. The calculated beam transmission is 68.4% for 10 mA with a beam of 16O+. The main parameters of the TIT-RFQ are shown in Table 1 [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge-to-mass ratio</td>
<td>1/16</td>
</tr>
<tr>
<td>Operating frequency (MHz)</td>
<td>80.9</td>
</tr>
<tr>
<td>Input energy (keV/amu)</td>
<td>5</td>
</tr>
<tr>
<td>Output energy (keV/amu)</td>
<td>220</td>
</tr>
<tr>
<td>Duty factor (%)</td>
<td>10</td>
</tr>
<tr>
<td>Q factor</td>
<td>10635</td>
</tr>
<tr>
<td>Cavity diameter (cm)</td>
<td>72.5</td>
</tr>
<tr>
<td>Cavity length (cm)</td>
<td>425</td>
</tr>
<tr>
<td>Expected beam transmission (%)</td>
<td>91.8</td>
</tr>
<tr>
<td>0 mA input</td>
<td>68.4</td>
</tr>
<tr>
<td>10 mA input</td>
<td></td>
</tr>
</tbody>
</table>

At present, the beam experiments are being performed with intense 4He+ beams by using a 2.45 GHz Electron Cyclotron Resonance (ECR) ion source. This ECR ion source can produce a beam current of 2.5 mA for 4He+. The maximum productive ratio of 4He+ is more than 99%. The 4He+ beam is extracted by a voltage of 20 kV from the plasma chamber and focused with an einzel lens, and injected into the RFQ. The maximum obtained beam current was 1.6 mA for 4He+ after the acceleration by the RFQ-Linac [2]. By considering the beam acceptance, a transmission efficiency is estimated to be 70%. This result is in good agreement with the calculated beam transmission.

Fig.1. Layout of the intense heavy ion linac system at TIT
3. Fine-focusing system

The fine-focusing system after the RFQ should be designed to obtain minimum beam spot size in order to increase a specific deposition power \( P \) (W g). Because if the beam can deposit enough energy to be evaporated in the target, then the specific deposition power \( P \) is the appropriate parameter to estimate the temperature of the beam-induced plasma.

We designed the fine-focusing system that consists of a faraday cup, a gate valve, three magnetic quadrupole lenses, and an electrostatic beam kicker. The magnetic quadrupole lenses were made with a bore diameter and a maximum field gradient to be 60 mm and 3 kG/cm respectively. The parameters of RFQ output beams were analyzed by using the computer code PARMTEQ-H. The momentum dispersion is about 0.8 %. The initial phase space occupied by the ion beam is 24.5 mm mrad in the \( x \) - and \( y \) -directions for the maximum intensity of the RFQ-beams. The beam envelope for the fine-focusing system was calculated by using the computer code MS-TRANSPORT (M. Sekiguchi at INS). The calculated beam envelope is shown in Figure 2. By the result of the simulation, the heavy ion beam of \(^{16}\)O\(^{+}\) with a current of 7 mA and an energy of 3.5 MeV can be focused onto a spot size of 1.0 mm\(^2\). From this spot size, the beam power density of 2.5 MW/cm\(^2\) - during the macropulse of the RFQ Linac - is expected to be transferred to the target.

At present the ECR ion source for the TIT-RFQ can produce only \(^4\)He\(^+\) beam. After conditioning the magnetic lenses, we focused \(^4\)He\(^+\) with a beam current in the macropulse of about 1.6 mA. In this case the beam current corresponds to the ion beam of \(^{16}\)O\(^{+}\) with a current of 6.4 mA. To measure the size of the spot, we stopped the \(^4\)He\(^+\) beam in an aluminum target (0.8 mm in thickness), where the \(^4\)He\(^+\) beam marked the geometric structures (Fig 3). Table 2 shows the comparison of calculated and experimental spot size. The area of experimental spot size is 1.06 mm\(^2\). This value is in good agreement with the calculated value. A power of 1.4 kW was transferred to the aluminum target. This corresponds to a specific deposition power of 0.17 GW/g.

![Fig 2. Calculated beam envelope for the fine-focusing system by the computer code MS-TRANSPORT. \([16O^{+}:7mA]\)](image)

![Fig 3. Marked spot size structure by focused \(^4\)He\(^+\) beam in an aluminum target](image)

| Table 2. Comparison of calculated and experimental spot size for \(^4\)He\(^+\) beam with a current of 1.6 mA. |
|-------------|--------|--------|
| Calculated value | x (mm) | y (mm) | S (mm\(^2\)) |
| 0.26 | 1.22 | 1.00 |
| Experimental value | 0.30 | 1.12 | 1.06 |
4. Expected Parameters of beam-induced plasmas By Simple Scaling Laws

At the first, the beam-target interaction experiments to study the heavy-ion-induced plasma are planned by using a solid target, and then a gas puff target. The gas target is a cylindrical tube of 25 mm length and 10 mm diameter. Table 3 shows the expected parameters of ion-induced plasma for various solid targets. Table 4 shows the expected specific deposition power for various ion beams in H2 gas target (1 atm). The deposition power P (GW/g) is given

$$P = \frac{I \times E}{\rho \times \pi r^2 \times R}$$

(1)

with the total particle energy E (keV), the particle intensity I (mA), the density of matter (g/cm3), the initial radius of the target r (cm) and the range of the ion beam in matter R (cm). The maximum temperature is expressed

$$T_{\text{max}}[eV] = 50 \times \left(\frac{3 \rho \times r}{2}\right)^{\frac{1}{2}}$$

(2)

for solid targets [3-4].

By the simulations of simple scaling laws, the beam power amounts to 24.6 kW, and a specific deposition power can be obtained 11.5 GW/g to focus a heavy ion beam of 160+ with currents of 7 mA and an energy of 3.5 MeV in H2 gas target.

The parameters of ion-induced plasma such as the electron density and temperature are measured with a CCD camera coupled to a streak camera.

Table 3. Expected parameters of ion-induced plasma for the TIT-RFQ Beam

<table>
<thead>
<tr>
<th>Target (solid)</th>
<th>R (10-4cm)</th>
<th>P (GW/g)</th>
<th>T_{\text{max}} (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>2.96</td>
<td>2.93</td>
<td>0.98</td>
</tr>
<tr>
<td>Ti</td>
<td>2.54</td>
<td>2.02</td>
<td>0.66</td>
</tr>
<tr>
<td>Ag</td>
<td>1.73</td>
<td>1.28</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Table 4. Expected specific deposition power for various ion beams in H2 gas target (1 atm).

<table>
<thead>
<tr>
<th>ION BEAM</th>
<th>CURRENT (mA)</th>
<th>BEAM POWER (kW)</th>
<th>P(GW/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4He+</td>
<td>2.0</td>
<td>1.76</td>
<td>0.76</td>
</tr>
<tr>
<td>14N+</td>
<td>6.1</td>
<td>18.9</td>
<td>9.00</td>
</tr>
<tr>
<td>16O+</td>
<td>7.0</td>
<td>24.6</td>
<td>11.5</td>
</tr>
</tbody>
</table>

5. Conclusion

The intense heavy ion linac system for plasma experiments is currently set-up. By using this focusing system, we succeeded that the 4He+ beam with a current of 1.6 mA from the TIT-RFQ focused onto a small spot area of about 1 mm². Due to the short range of the ion beams of about 1 mg/cm², the beam power of 1.4 kW amounts to a specific deposition power of 0.14 GW/g to be transferred into the target. The first experiment of 4He+ beam-induced plasma will soon be carried out by using a gas puff target.

REFERENCES

PARTICLE ORBIT SIMULATION OF DECELERATOR CYCLOTRON FOR RI PRODUCTION

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Abstract

We are studying an IH type linear accelerator for the application as the international cooperative research (Japan, Germany and Romania). Acceleration of deuteron and triton by the IH linac were planned for the production of useful radio-isotopes which is for practical use in medical science. Cyclotron type decelerator with a gas target room is developed. Short life radio-isotope for PET (Positron Emission Tomography) is produced in the decelerator by irradiating deuteron beam to gas target.

This paper will present the conceptual design of the decelerator and report a part of particle orbit simulation.

Introduction

The IH linac has successfully accelerated proton beam. The shunt impedance was estimated to be about 370 M Ω/m by experiment. So we are engaged in the next stage of the project.

Generally, the life of radio-isotope for medical diagnostic is short. Half-life of 150 is in particular only about two minutes. That is, we should do acceleration in hospital, production and refining in hospital, and administration to a patient in hospital. It is necessary that the conceptual design of decelerator be compact, speediness and high efficiency.

Conceptual design

Fig. 1 shows conceptual design of the gas target room. Output beam from the IH linac will be deprived of energy by irradiating to gas target. Gradually, a rotation radius will be small in the magnet field. And we get the radio-isotope by pumping.

Calculation

Fig. 2 shows calculation of the equilibrium orbit. Input energy of proton beam is 1.6 MeV and the first stage of magnet field is 1 T. And now, we take emittance growth into consideration and compute again.

Fig. 1 Conceptual design of the gas target room.

Fig. 2 Calculation of the equilibrium orbit.

References

3) T. Hattori et al., Proc. 18th Linear Acc., Meeting in Japan 18(1993)38
A NOVEL TECHNIQUE FOR CONSTRUCTING
A PLASMA MICRO-UNDULATOR
AND A COMPACT SOFT X-RAY SOURCE

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Abstract

The plasma micro-undulator is a compact light source in which a relativistic electron beam radiates in an oscillating electric field of the rippled ion-space-charge instead of an oscillating magnetic field of conventional undulators. In the present paper, we propose a new method of creating the plasma micro-undulator: a combined technique of laser interference and resonant photoionization, where the pitch and density of plasma ripples have been controlled separately by a laser alone. A preliminary design of the undulator with the pitch of 10–100 µm, the number of ripples of 100–1000 and the undulator constant of 0.1–1.0 has been discussed.

1. Introduction

There has been a considerable attention to develop a compact free electron laser (FEL) since it has many advantages over conventional lasers, such as high output power and brightness, high conversion efficiency, tunability over wide range of wavelength and long life, all of which are quite important for applications. In general, FEL consists of a magnetic undulator and a Fabry-Perot optical resonator. In the magnetic undulator, permanent magnets whose polarity changes alternately are aligned periodically. When a relativistic electron beam is injected into the undulator along the axis, it experiences a transversely oscillating force and emits an intense electromagnetic radiation along the beam path.

The wavelength of the undulator radiation \( /l \) is given by

\[
\lambda = \frac{\lambda_0}{2\gamma^2} \left(1 + \frac{K^2}{2}\right)
\]

where \( \lambda \) is the wavelength of radiation, \( \lambda_0 \) is the wavelength of undulator (pitch of magnets), \( \gamma = (1 - \frac{v^2}{c^2})^{-1/2} \) is the relativistic factor and \( K \) is the undulator constant defined as

\[
K = \frac{eE_0 \lambda_0}{2\pi \mu_0 c^2} = 93.4 \lambda_0 (\text{in}) E_0 (\text{T})
\]

It is to be noted that \( \lambda \) is proportional to the pitch of magnets and inversely proportional to the beam energy. Since it has been difficult to make \( \lambda_0 \) much shorter than 10µm due to demagnetization of permanent magnets, a large accelerator has been required inevitably to obtain shorter-wavelength radiations extending to visible or uv region.

Recently, an alternative concept, a plasma micro-undulator has been reported /2,3/, where a relativistic electron beam has been injected obliquely into one-dimensional, plasma-density ripples. The electrons then experience a transversely oscillating electrostatic force (induced by the periodic ion-space-charge distribution) during propagation in the ripples and emit undulation radiation. The plasma micro-undulator has a potential of an extremely compact and short-wavelength FEL which is rather difficult by conventional magnetic undulators. This paper proposes a new scheme for the formation of the plasma micro-undulator: a laser-interference, resonant-photoionization scheme using a coherent, tunable laser. In particular, we discuss a preliminary design of the undulator with \( \lambda_0 = 10–100 \mu m \), the number of ripples, \( N = 100–1000 \), \( K = 0.1–1.0 \).

2. Principle

Figure 1 explains the principle /4/. A well-collimated laser beam at wavelength \( \lambda_L \) (wavenumber \( k = 2\pi/\lambda_L \)) and intensity \( I_0 \) is divided into two half-intensity beams by a half mirror \( A \) and a full mirror \( B \). These beams interfere at the intersection with angle \( \phi \) and create optical fringes. As is well known, the total intensity becomes

\[
I = I_0 \left[ 1 + \cos \left(2kx \sin \frac{\phi}{2}ight) \right],
\]

and the pitch of fringes is given by the formula:

\[
d = \frac{\lambda_L}{2 \sin \frac{\phi}{2}}.
\]

When a plume of neutral gas is introduced into this region, a plasma will be created by photoionization. Since optical fringes correspond to a spatial modulation in the laser intensity and the plasma density should increase in proportion to the laser intensity (without saturation), we can obtain plasma density
ripples which are quite regular reflecting the coherence of laser. It is worth emphasizing that the pitch of ripples is controlled only by optical parameters, \( \lambda_d \), and \( \phi \).

We have considered two photoionization schemes: resonant ionization and tunnel ionization /5/. In resonant ionization, the laser wavelength has been tuned to the energy level of a neutral atom. However, elements of interest have the ionization energy \( U_i \), of at least 5-10 eV (the minimum energy is 3.9 eV of Cs). So, the ionization occurs by absorbing two or more photons. Shibata et al. /6,7/ have developed one-wavelength multi-step resonant photoionization schemes:

\[
\text{Nd}(U_i = 5.52\text{eV}): \quad 441.96\text{nm} \quad \text{two step,}
\]

\[
\text{Gd}(U_i = 6.15\text{eV}): \quad 575.19\text{nm} \quad \text{three step,}
\]

which use resonant metastable states. These schemes should be most suitable for our purpose. Two-wavelength schemes developed for laser isotope separation are also considered to be applicable. The plasma created by resonant photoionization has quite low temperature (< 0.1 eV). This is an important feature because the life time of plasma ripples is predominantly limited by thermal expansion.

When a neutral atom is irradiated by an intense laser beam of greater than 10^14 W/cm^2, its coulomb potential barrier is strongly deformed and a bound electron is liberated by tunnel effect. Tunnel ionization requires strong compression (focusing and bunching) of the laser pulse to achieve a high power density above threshold. However, this leads to degradation in the periodicity of interference fringes. Therefore, we conclude that resonant-photoionization scheme is more appropriate for our purpose.

3. A preliminary design

Here, we consider design parameters of the plasma micro-undulator for a compact FEL. When plasma density ripples are of the form:

\[
n = n_0 \left( 1 + \sin \frac{2\pi x}{d} \right),
\]

an alternating force acting on a relativistic electron beam injected at an angle \( \theta \) is given by

\[
F = e^2 n_0 k_u s \cdot \sin \theta \cos \theta / k_u c_0 \propto \frac{n_0}{k_u},
\]

where \( k_u = k \cos \theta = 2\pi / \lambda_u, \lambda_u = d / \cos \theta, \cos \theta = s \cdot x / s \) and \( s \) is the coordinate along the beam axis. For typical \( \theta = 45 \text{deg} \), it becomes \( \lambda_u = \sqrt{2d} = 1.41d \). The performance of undulators is well characterized by \( K \) of eq.(2). Since brightness of the undulator radiation is proportional to \( K^2 \), small \( K \) leads to an inefficient device, while too large \( K \) \( (K \gg 1) \) wiggler mode causes quite large broadening in the radiation spectrum and increase in the emittance. So it is reasonable to assume \( K = 0.1 \cdot 1.0 \). In addition, we employed the following parameters: \( d = 10 \cdot 100 \text{nm}; N = 100 \cdot 1000 \text{;} \) the length of undulator, \( L = N d = 1 \text{cm}; \) Nd plasma (two-step photoionization, \( \lambda_d = 441.96 \text{nm} \)). Since \( L \) is comparable to the diameter of laser beam, \( D \), the effective volume of undulator, \( V \) becomes \( V \approx L^3 = 1 \text{cm}^3 \). From eq.(4), the interference angle \( \phi \) required for \( d = 10 \mu \text{m} \) and \( 100 \mu \text{m} \) are 2.5 deg and 0.25 deg, respectively (see also Fig. 2). When a cost-effective 10 MeV (\( \gamma = 21 \)) linac is used, we can cover wavelengths of 20-200 nm.

Finally, we examine the requirement for the plasma density and laser energy. Suzuki /8/ calculated \( K \) for three types of electron beams: short bunch (radius \( r_0 \), length \( l_b \ll \lambda_u \) ), long bunch (\( r_0 \ll \lambda_u \sim l_b \) ) and uniform bunch (\( r_0, l_b < \lambda_u \) ). He showed that the plasma density was proportional to \( K/\lambda_u^2 \) and was about \( 2 \times 10^{16} \text{cm}^{-3} \) for \( \lambda_u = 10 \mu \text{m} \) and \( 2 \times 10^{14} \text{cm}^{-3} \) for \( \lambda_u = 100 \mu \text{m} \) under \( K = 1.0 \). A rough estimate of the laser energy should be given by \( n_p V U / n_i \), where \( n_p \) is the plasma density and \( n_i \) is the efficiency of photoionization. When typical values, \( n_p = 10^{15} \text{cm}^{-3}, \lambda' = 1 \text{cm}^3, U = 5.52 \text{eV} \) and \( n_i = 0.1 \), we obtain 9 mJ. The latest pulse-dye-lasers and solid-state-lasers will cover this energy without difficulty. A schematic view of the system is shown in Fig. 3.

There remain items to be further examined.

- Laser pulse length

The laser pulse length \( \tau_L \) must satisfy the condition:

\[
\frac{L}{c} < \tau_L < \tau_r,
\]

where \( L/c = 30 \text{ ps} \). The life time of ripples, \( \tau_r \) is predominantly determined by thermal expansion as

\[
\tau_r \approx \frac{0.5d}{\sqrt{\frac{T_r + T_v}{k_B}}},
\]

For Nd plasma, \( T_r < T_v \approx T_0 \) (vaportemperature) \( \approx 500 \text{K} \) has been reported. This yields \( \tau_r = 30 \text{ ns} \) for \( d = 10 \mu \text{m} \), so that eq. (7) is easily satisfied.

- Beam attenuation due to neutral collisions

Rutherford scattering is dominant. The attenuation rate, \( \Delta n_e / n_e \) is estimated using the cross section of Rutherford scattering, \( \sigma_R \) to be:

\[
\frac{\Delta n_e}{n_e} = \sigma_R n_0 L < 0.1,
\]

where \( \gamma = 21(10 \text{ MeV}) \), the neutral density \( n_0 = 3 \times 10^{16} \text{cm}^{-3} \) (1 Torr), \( L = 1 \text{ cm} \), and scattering angle of \( 10^{-2} \text{ rad} \) are assumed.

- Repetition

Once the electron beam interacts with the plasma undulator, the plasma will break up. So, the repetition rate, \( f \) will be limited by the time for a plasma with a flow velocity \( u_0 \) to traverse a distance \( D \) as
4. Application to a compact soft X-ray source

We showed above that a combination of a 10-MeV linac and a 10-μm plasma undulator can generate soft X-ray radiation. However, the conventional linac is too large to realize a table-top device. Recently, there has been a rapid progress in the development of plasma-based accelerators in which the interaction between a dense plasma and a ultra-short-pulse driver beam (laser beam or electron beam) generates strong accelerating fields of order of GeV/m. For example, a LWA (laser-wake-field accelerator) experiment at KEK /9/ has demonstrated acceleration of electrons up to 18 MeV over a distance of 0.6 mm. However, there has been a problem that diffraction limits the laser-plasma-interaction distance to \( \approx \pi Z_R \) (\( Z_R \) : Rayleigh length) and optical guiding /10/ using a parabolic plasma-density profile (plasma channel) has been proposed. Our laser-interference, resonant-photoionization scheme will be useful to create plasma channel too. Two sets of plasma density ripples created with intersection at 90 deg by four laser beams form a bundle of square plasma channels /11/. It is clear that the density and diameter of plasma channel can be easily controlled by the laser intensity, laser wavelength and interference angle. A combined system of LWA and the plasma micro-undulator is quite attractive because it has a possibility of making a table-top x-ray FEL. In the beginning, proof-of-principle experiments will be needed.

References

Study of Differential Pumping System for Beam-Pumped Laser by TIT Heavy-Ion RFQ Linac

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Abstract

3.1MeV $^4$He$^+$ beam from V.d.G. was used to pump He-Ar gas Laser with a differential pumping system. In our experiments, Laser action of the 1.27 nm line could not have been observed above the threshold of 33W beam power input. One of the reasons is that the differential pumping system does not have the orifices aligned. For the experiments of Beam-Pumped Laser by using 0.88MeV $^4$He$^+$ beam from TIT Heavy-Ion RFQ Linac, I designed a differential pumping system with the orifices which are able to be aligned easily.

1. Introduction

Heavy ion beam-pumping is a method to produce the population inversion of a medium through projecting heavy ions into the medium. Experiments to study lasers pumped by heavy-ion beams in Munich were initiated by P. Kienle in 1979, and optical gain and laser effect were first observed in 1982-1983. A low threshold pumping power of 33 W was found in rare gas mixtures lasing in the near infrared in experiments performed at the Munich Tandem van de Graaff accelerator (Ulrich et al. 1983). This work had been stimulated by results of nuclear-pumped laser experiments in the Soviet Union and the United States that had been published in the 1970s, and most of the laser lines observed by ion beam pumping appear also on the list of nuclear-pumped lasers (Fitaire 1978). This immediately indicated that ion beam-pumped lasers can be used as model systems for nuclear-pumped lasers. A practical advantage of working with accelerators is that there is access to the target area, often also during operation of the laser. Continuous or quasistatic operation allows experimental parameters such as gas mixtures and the alignment of the optical cavity to be optimized rapidly.

Heavy-ion accelerators are widely used in atomic physics, especially to study few-electron atoms and inner-shell excitation process. The possibility of obtaining well-focused beams of particles with a high energy loss -dE/dx in the target material has stimulated the idea of using heavy-ion accelerators as drivers for inertial confinement fusion experiments. On the basis of similar arguments we have started a program to explore the possibility of short-wavelength lasers pumped by heavy-ion beams.

Fig. 1 The Experimental setup for Heavy-ion Pumped Laser by V.d.G.
2. Experiment

In our research program, at first we make experiment for 1.27\(\mu\)m (Ar I) laser action of He-Ar gas mixture with 50\(\mu\)A, 3.1MeV \(^4\text{He}\) beam by TIT Van de Graaff. Then we are going to make experiment for 1.79\(\mu\)m laser action with 0.88MeV \(^4\text{He}\) beam by TIT Heavy-Ion RFQ Linac. The program of the experiments with V.d.G. (Fig.1) is as follows:

(1) Designing for the experiment setup
(2) Detecting the spontaneous emission from He-Ar gas target with spectroscope to examine the population inversion
(3) Testing infrared laser action
(4) In the case of no laser action, improving the systems

In this paper, I report the result of the experiments and some improvements of this setup.

Laser action is a phenomenon which has a threshold. Therefore, on the development of laser systems, it is hard to make clear what is going on in the whole system. For the method to check the possibility on the laser action, I used plasma spectroscopy to measure the population inversion.

3. Experimental Result and Improvement

We could not observe He-Ar, 1.27\(\mu\)m laser action in our experimental setup.

The cause of unsuccessful result of the laser action is probably as follows:

(1) The laser resonator is not aligned, or the laser gain is less than laser resonator loss.

(2) This experimental setup needs a differential pumping system to keep the pressure difference between the accelerator and the gas cell. It consists of 4 stages which are pumped independently. In this system fine alignments of the beam axis obtained by means of orifice-shaft nuts shimming. Thus the orifices are not stable on the wall between the stages. It makes hard to align the optic axis. Moreover it is almost impossible to develop the study with it, because this system can not have any reproducibility.

For the improvement of such a system, I made a compact differential pumping system (Fig.2) which is machined from one brass block. As the loss of beam power was great in the differential pumping system, the distance along beam axis of the new compact differential pumping system is made five times shorter than that of the ex-differential pumping system. I prepared 4 kinds of diameters of the orifices. They are 1.6mm, 2.0mm, 2.5mm, and 3.0mm. Every orifice is screwed to be self-aligned, when they are screwed directly into walls of the main body of compact differential system.

References

OPERATION OF LINAC BASED FELs IN IR- AND VISIBLE-RANGE AT THE FELI


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Abstract
Two infrared free electron lasers (FELs) facilities covering the wavelength range of 1-20μm are opened for FEL users in this October. We are also challenging 0.3μm-FEL oscillations using a 2.68m undulator (λu=4cm) installed at the 160-MeV beam line of the FELI linac with a thermionic gun. A 0.52-μm spontaneous radiation of 0.1W has been observed using a 145-MeV electron beam and the undulator.

INTRODUCTION
The Free Electron Laser Research Institute, Inc. (FELI) has been established in March 1991 and has achieved first lasings at infrared- and visible-range using an S-band 80-MeV electron linac with a thermionic gun driven by a 500-ps, 22.3125-MHz grid pulser in Oct. 31, 1994 and Feb. 28, 1995, respectively, in a year from the start of the machine installation [1]. At the FELI there are three free electron laser (FEL) facilities installed along by the beam line of an S-band 160-MeV linac, as shown in Fig. 1. The linac and these FEL facilities are located in the accelerator room on the ground floor.

The FEL beam becomes rather thick and round due to hole coupling and is delivered to the diagnostics room and eight user's stations on the third floor through the evacuated pipeline, and is further delivered through a simultaneous FEL beam sharing system [2] from the diagnostics room to eight user's stations.

The FELI 160-MeV linac, the S-type BT line 3 [3] and the FEL facility 3 (covering from 0.3 μm to 1.2 μm) are in the commissioning stage.

We are trying to achieve UV-range FEL oscillations using the FELI linac with the thermionic gun, taking the advantage of the thermionic gun's superior performances such as long-life, easy operation, and low-cost, in addition to some attempts on low emittance beam acceleration of the order of 10 π mm·mrad in the 6-MeV injector [4].

IR- AND VISIBLE-FELs AT THE FELI
First lasing at 5.5 μm was achieved using the FEL facility 1 composed of a 2-m long planar undulator (λu=3.4cm) [5] and a 6.72-m optical cavity [6] installed at the 30-MeV BT line of the FELI linac in Oct. 31, 1994. The FEL beam can be delivered from a 0.5-mm aperture in the upstream mirror of the optical cavity to the diagnostic room through a 50-m long evacuated pipeline as shown in Fig. 1.

First lasings at 1.88 μm and 0.63 μm was achieved using the FEL facility 2 composed of a 3-m long planar undulator (λu=3.8cm) and a 6.72-m optical cavity installed at the 80-MeV BT line of the FELI linac in Feb. 27 and 28, 1995. The FEL beam can be delivered from a 0.5-mm aperture in the upstream mirror of the optical cavity to the diagnostics room through a 40-m long evacuated pipeline.

The characteristics of the linac beams, the undulators used in these oscillations and lasing are shown in ref. [1].

Fig. 2 shows average FEL powers as a function of wavelength at a 0.5-mm aperture in the upstream mirror of the optical cavity. A spectral range of the facility 1, between 5 and 22 μm, is covered using three electron energy values: 32, 26 and 20 MeV. A spectral range of the facility 2, between 1 and 6 μm, is also covered using four electron energy values: 78, 62, 50 and 40 MeV. The present maximum average power is...
0.14W at 7.5 μm at the 0.5-mm aperture in the upstream mirror of the FEL facility 1 for 4000 micropulses/s. The FEL micropulse duration is not measured yet but estimated to be 10 ps from the electron bunch measurement with a streak camera. The peak power is calculated from an average power, the micropulse duration and the number of micropulses in the FEL macropulses. The peak powers of the FEL facility 2 are about 2MW and 0.45MW at 1.88 μm and 0.63 μm, respectively, at the 0.5-mm aperture in the upstream mirror.

The peak power of the facility 1 reaches up to 707% of the theoretical limit E_{f}P/(4eN), where E is the electron energy (MeV), I_{p} is peak current (A), e the electron charge, and N is the number of periods of the undulator. The present intracavity peak power is about 0.7GW at 7.5 μm. Therefore, the average power of 0.5W will be obtained by using the mirror aperture of 1mm and should be 4W at a high micropulse repetition rate of 178.5MHz of the 500-ps grid pulser. Considering the fact that the electron beam diameter is 1mm and the optical beam waist is 2.5-5.4mm for the wavelength λ_{FEL}=4.8-22.7 μm, the peak power as well as the average power will be improved at wavelengths longer than 10 μm by changing the mirror curvature. Furthermore, both will be improved at these wavelengths by changing the aperture from 0.5mm to 1mm, since the transparency of FELs declines at these wavelengths.

On the other hand, a 2-MW peak power of the facility 2 is a seventh of the expected value but this is due to a small filling factor between the low emittance beam whose diameter is less than 0.5mm and a 1.5-mm waist of the stored FEL beam at 1.88 μm. Color red beam were observed on the third harmonics at 1.88 μm oscillation and on the fifth harmonics at 3.1-μm oscillation.

CHALLENGE AT ULTRAVIOLET-RANGE FEL

The 160–MeV linac consists of the 6–MeV injector [4] and seven ETL type accelerating waveguides [7] as shown in Fig. 1. These accelerating waveguides are of linearly narrowed iris type to prevent beam blow up (BBU) effects at high peak current acceleration. The length of the linac including bending sections of two S-type BT systems for two IR–FEL facilities is 46m.

An rf system for linac based FELs requires rf sources with long pulse duration and high stability. Our rf sources are a klystron (IVA88R) for the 714-MHz prebuncher and two klystrons (E3729, 24MW for 24-μs flat top pulses per each) for the buncher and seven accelerating waveguides. The latter klystrons are modified for a 24-μs pulse operation [8]. A modulator for the klystron IVA88R uses MOS–FET modules [9]. However, a modulator for the klystron E3729 consists 4 parallel networks of 24 capacitors and 24 variable reactors, and it has a line–switch of an optical thyristor stack. The flatness of our klystron modulator for E3729 is 0.067% at 24-μs duration [10]. An rf–ageing for new four accelerating waveguides of the high energy section was started in June.

The FEL facility 3 including a 2.68-m undulator (λ_{s}=4.0cm, N=67, K_{nx}=1.9, gap length ≥18mm) and an optical cavity (L_{c}=6.72m) was installed in July. The optical cavity 3 is the Fabry–Perot cavity which consists of two mirror vacuum chambers. Each chamber has a rotating type mirror holder accommodating eight mirrors. One mirror position is empty and used for alignments of the optical cavity line and the five OTR beam profile monitors. The cavity mirror is controlled with a resolution of 0.1 μm or 10 μrad. To cover wide wavelength range from 0.3 μm to 1.2μm, seven dielectric multilayer mirrors for IR–, visible–, and ultraviolet–range are installed.

A calculated small signal gain of this undulator is 7.8% per pass for a 0.3-μm spontaneous radiation using a 160–MeV, 50–A electron beam when the K parameter is 0.95 [12,13]. The net gain is estimated to be larger than 7.3%, considering that an extraction factor of a dielectric multilayer mirror is 0.4% and the mirror loss per roundtrip of the spontaneous radiation is 0.1%. Figure 3 shows a 0.52-μm spontaneous macropulse shape measured with a Si–photodetector (Si–APD C5331–04, HAMAMATSU PHOTONICS Inc.) and an electron current pulse measured with a button monitor [14]. The peak power of the spontaneous radiation is about 0.1W on August 18, 1995.

CONCLUSIONS

IR– and visible–range FELs are delivered to the diagnostic room and eight user’s stations through the evacuated pipelines and simultaneous beam sharing systems. The FEL 160–MeV linac and the FEL facility 3 including the 2.68-m undulator and the 6.72-m optical cavity are in the commissioning stage.

References

Fig. 1 Bird's eye view of three FEL facilities at the FELI

Fig. 2 Average FEL powers as a function of wavelength

Fig. 3 0.52-\mu m spontaneous macropulse and current pulse
Novel X-ray Source Using Collisions of Circulating Relativistic Electrons and a Wire Target

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Abstract

The novel method for generating brilliant x-ray beams is proposed, in which inelastic collisions of circulating relativistic electrons and a thin wire target are used. High brilliance of this new photon source stands on narrow angular divergence due to the kinematics of relativistic electrons, and repeated use of electron beams. The estimated brilliance of this source based on a 50 MeV electron storage ring is comparable to that of compact synchrotron light sources.

1. Introduction

X-ray emissions are generated when electrons are decelerated by either an electric or a magnetic force. Classical x-ray tubes and rotating anode sources use atomic electric forces, and synchrotron radiation (SR) uses bending magnets or wigglers. All of these sources generate continuous and incoherent spectra. The SR emissions are brighter than x-ray tube emissions only because SR emissions have a narrower angular divergence, but the integrated total radiated power is almost the same for both methods. Note that the divergence is determined by the kinematics of the electron beam regardless of what the decelerating force is. Using relativistic electron beams is the key issue for achieving the narrow angular divergence of x-ray beams.

The bremsstrahlung spectrum extends up to the incident electron energy. This implies that 100 keV electron beam is enough to produce 100 keV x-rays. X-rays are therefore produced more efficiently with conventional x-ray tubes than with SR.

The above consideration leads to a simple idea for a novel x-ray source that uses collisions of circulating high-energy electrons and solid targets in a storage ring. The narrow angular divergence is secured by the high electron energy. High energy x-rays can be easily generated by the bremsstrahlung due to the inelastic collisions inherent with this kind of source.

Using a thin target is also the key issue for present x-ray source in order to avoid increasing angular divergence of x-ray beam due to multiple scatterings. The electron beam passing through the thin target is utilized repeatedly so that the x-ray productivity will be significantly enhanced in comparison with the case using a thick target. A thin target is useful to minimize absorption of x-rays and electrons which cause heating problem of the target. The continuous injection of an electron beam into the storage ring at full energy is a way to compensate for the lost beam and to keep a high, constant beam current. We gain yet another advantage when a thin wire target is used, because effective x-ray source size is determined by the width of this wire.

2. Bremsstrahlung yield

As well known the differential cross section of bremsstrahlung has been quantum-mechanically calculated by Bethe and Heitler\(^1\), Schiff\(^2\), and others in the 1950’s. A summary of theories and experiments is given by Koch and Motz\(^3\). In order to evaluate the bremsstrahlung yield in comparison with synchrotron light, we define here the brilliance of the bremsstrahlung as:

\[
\frac{d^2 \sigma}{dk dm} = \frac{t}{16E^2 - 19y^2} \frac{\pi}{\sigma} \frac{4\pi}{\sin \theta} \left( \frac{\theta}{2} \right)  
\]

where \(k\) is the beam current, \(n_t\) and \(\tau\) are the target density and thickness, \(E_o\) and \(E\) are the x-ray energy, the incident electron energy, and the scattered electron energy measured in the electron rest of mass energy units, respectively. The \(\theta\) is defined as \(\theta = \theta \cdot E_o\), where \(\theta\) is the angle between the directions of photons and incident electrons. The integral in eq.(1) is carried out over \(\cos \theta\). We assume \(\theta = \pi/2\) which covers the peak in the angular distribution around \(\pi/2\). Thus, this definition gives averaged brilliance, but not the peak value. The brilliance is a normalized value with the source size \(\chi \cdot \chi\), where \(\chi\) is the horizontal and vertical target size or beam size, whichever is smaller. While the target size is smaller than the beam size, the
brilliance is determined by the target size. Please note that in eq. (1) we take the effective beam current \( I_e \), where \( I_e \) is the x-ray source area which is determined by the target size, and \( S_0 \) the beam size.

3. Beam current

In the next we estimate the obtainable ring beam current resulting from collisions of the beam and the target material with a continuous beam injection. The time evolution of the stored beam current \( \frac{dI}{dt} \) may be expressed by the following equation:

\[
\frac{dI}{dt} = R_i \cdot e_i \cdot I \cdot \delta t \cdot f - \mu I - \eta I^2.
\]

The first term of the right hand side is the beam growth rate by injection, which is given by multiples of the injection rate, \( R_i \), the total injection efficiency, \( e_i \), peak current, \( I_0 \), the duration in which the beam is accepted by the storage ring, \( \delta t \), and the frequency of the circulating beam, \( f \). The current decay rate can be represented by first- and second-order terms of \( I \) with the coefficients \( \mu \) and \( \eta \). The meanings of these rate coefficients will be clarified in the following.

The stored beam decays by two principal effects. One effect is Touschek scattering which is large-angle scattering caused by Coulomb repulsion between electrons in a bunch. The other effect is electron-target scattering as the formula is known by the problem of gas scattering in a storage ring. In electron-target scattering both inelastic and elastic scattering on target nuclei occur, with inelastic scattering causing bremsstrahlung.

Elastic scattering on nuclei of the target leads to angular kick for the betatron motion of the electron beam. If the induced betatron amplitude exceeds the transverse acceptance of the ring, \( A_c \), the beam will be lost. The total cross section for this process is expressed by:

\[
\sigma_{el} = \frac{2\pi r_e^2 Z^2 \langle \beta \rangle}{\gamma^2} A_c
\]

where \( Z \) is the atomic number, \( r_e \) is the classical electron radius, and \( \langle \beta \rangle \) is either the horizontal or vertical betatron amplitude, whichever limits the beam circulation. The transverse acceptance is actually limited by either the half-chamber aperture or the dynamic aperture, \( A_c \), at the place where the betatron amplitude is \( \beta \). The acceptance is then given as \( A_c = A_{\beta \gamma} \beta r_e \) and \( \langle \beta \rangle = \beta \). Note that this cross section decreases quadratically with increasing electron energy.

Bremsstrahlung is an inelastic scattering process that leads to an energy loss for the circulating electron. The electron will be lost if the energy loss exceeds the limiting longitudinal momentum half-aperture, \( (\Delta p / p)_{\text{max}} \) of the ring that is proportional to the radio-frequency bucket height. The total cross section for this inelastic process leading to the beam loss is given by:

\[
\sigma_{n} = \frac{4Z^2 r_e^2}{137} \left\{ \ln \left( \frac{183}{Z^2} \right) - \ln \left( \frac{1}{(\Delta p / p)_{\text{max}}} - \frac{1}{5} \right) \right\}.
\]

Note that this cross section is independent of the electron energy.

The total beam loss rate, \( \mu \), due to the above elastic and inelastic scattering can be expressed as:

<table>
<thead>
<tr>
<th>Machine parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy [MeV]</td>
<td>50</td>
</tr>
<tr>
<td>Orbit radius [m]</td>
<td>0.15</td>
</tr>
<tr>
<td>SR boost voltage [kV]</td>
<td>360</td>
</tr>
<tr>
<td>Power [W]</td>
<td>0.11</td>
</tr>
<tr>
<td>RF voltage [kV]</td>
<td>1200</td>
</tr>
<tr>
<td>Harmonics</td>
<td>8</td>
</tr>
<tr>
<td>RF frequency</td>
<td>2.451 GHz</td>
</tr>
<tr>
<td>Horizontal damping rate</td>
<td>50</td>
</tr>
<tr>
<td>[As]</td>
<td>0.1</td>
</tr>
<tr>
<td>Touschek half-life [sec]</td>
<td>0.1</td>
</tr>
<tr>
<td>IBA</td>
<td>0.5</td>
</tr>
<tr>
<td>Vertical beam width [mm]</td>
<td>0.1</td>
</tr>
<tr>
<td>Beam loss rate by elastic</td>
<td>1.291</td>
</tr>
<tr>
<td>[As]</td>
<td>1.291</td>
</tr>
<tr>
<td>Beam loss rate by inelastic</td>
<td>1.291</td>
</tr>
<tr>
<td>[As]</td>
<td>1.291</td>
</tr>
<tr>
<td>Electron flux for 100 keV x-ray</td>
<td>5.011 × 10^11</td>
</tr>
<tr>
<td>Photon flux for 100 keV x-ray</td>
<td>5.011 × 10^11</td>
</tr>
<tr>
<td>Brilliance for 100 keV x-ray</td>
<td>5.011 × 10^11</td>
</tr>
</tbody>
</table>
\[ \mu = -\frac{1}{t} \frac{dl}{dh} = (\sigma_t + \sigma_{tr}) \cdot n_t \cdot \lambda_t \cdot \frac{j_{\text{HF}}}{S_b} \]

where \( n_t \) and \( \lambda_t \) is the target density and thickness, respectively.

The \( \alpha_t \) is the x-ray source area which is determined by the target size when it is smaller than the beam size, \( S_b \). If the target size is larger than the beam size, \( \alpha_t \) is equal to the beam size. The calculated beam loss rates for a 50 MeV ring with various target materials and shapes are shown in Table 1. A half-momentum aperture of \( a_{\text{max}} \) = 0.06 and the vertical half-chamber aperture of \( b = 3 \) cm is assumed in these calculations. A 10 \( \mu \)m-thick carbon foil gives beam loss rate of 7640/sec for the inelastic and 26300/sec for the elastic scattering. In the case of 10 \( \mu \)m tungsten wire, these are 1250/sec and 5160/sec, respectively on assumption of RMS beam size of 9 \( \times \) 0.5mm. Increasing beam size simply leads to reducing beam loss rate, and consequently increasing ring current according to eq. (2) and (5). The maximum beam current is reached when the beam injection and the beam loss are balanced. Then the maximum beam current is obtained by solving eq. (2) for \( dI/dt = 0 \).

We summarize the resulting maximum beam current and the machine parameters of a 50 MeV electron storage ring in Table 1. In this calculation we assumed 50A peak current and 10 Hz injection rate. We assumed an injection efficiency of \( \varepsilon = 0.6 \) which is conservative for a resonant injection method. We assumed a 10 \( \mu \)m thick carbon foil, 100 \( \mu \)m carbon wire, and 10 \( \mu \)m tungsten wire target, but the thickness is unimportant for estimating the maximum x-ray yield, because the effect of the target thickness and density are canceled out in this calculation. The x-ray cross section is proportional to the target thickness and density, but the maximum beam current is inversely proportional to these target parameters. The x-ray yield is the multiple of the cross section and the beam current. The width is important for higher brilliance. The beam size is unimportant for the total x-ray yield. It may grow due to the scattering, but the total x-ray yield will be unchanged.

Consequently, the maximum obtainable x-ray production is determined by the maximum output power of the injector.

4. Conclusion

In summary, we believe that the use of inelastic collisions of relativistic electron and of solid targets is a promising new way to generate brilliant photon beams ranging from soft x-ray to beyond 100 keV x-ray. The size of this novel source must be very attractive compared with compact SR sources.

It is worth to point out that if the size of the ring is not a problem, the higher energy electron storage ring is advantageous. For instance a 300MeV ring generates thousands times brighter x-ray beam, since the angular distribution is less than 1/3, the beam loss rate by elastic scattering is reduced 10 times, and the beam size is reduced 100 times.

In this paper we didn’t include other radiation mechanisms like transition and Cerenkov radiations. It is known that the strength of transition radiation may reach the same level as bremsstrahlung, and that photon energy from 50 MeV electrons is available up to a few keV. It is also known that stacked foils generate coherent x-ray beam. We therefore expect that the new x-ray source will produce much more power than we have described above.

References

Abstract

The performances of a free electron laser oscillator based on Tohoku Linac are numerically analyzed with a one-dimensional nonlinear theory. It is shown that the FEL can operate in wavelengths of infrared range and a radiation power of several megawatts can be obtained. Some design parameters are discussed. The FEL based on Linac has various applications for its advantages of broad spectral range, picosecond pulses and high peak power.

1. Introduction

Since the first free electron laser (FEL) experiment was achieved, the FEL has developed rapidly in last two decades due to its advantageous characteristics of high power, high efficiency and tunability of frequency. In FEL, a simple relationship of the radiation wavelength with the undulator period and electron energy factor is

\[ \lambda = \frac{\lambda_0}{2 \gamma^2} \]

Thus the wavelength can be tunable by changing the electron energy or undulator period, and the FEL, in principle, can operate in wavelength region of millimeters to X-ray. The FEL based on a linac, therefore, have attracted considerable interest in researches and applications of biology, medical, material and industry because it would be the only source capable of providing picosecond pulses of coherent radiation in the infrared wavelengths. In this paper, a one-dimensional nonlinear simulation mode is used to analyzed the performances of a free electron laser oscillator with the Tohoku Linac. It is shown that the FEL can operate in wavelengths of infrared range and a radiation power of several megawatts can be obtained. Some design parameters are also discussed.

2. FEL Equations

We consider that an electron beam transforms in a planar undulator with constant parameter and exchanges its energy with the radiation fields. For simplifying, we consider one-dimensional case and use the approximate condition of the slowly-varying field amplitude and phase. The longitudinal motion of electrons (averaged over the undulator period) is described by the Lorentz factor and the electron phase \( \gamma \) as

\[
\gamma = \frac{eK}{\gamma_{\text{mc}}} E_z [J_0(x) - J_1(x)] \sin(\psi + \phi),
\]

\[
\frac{d\gamma}{d\xi} = - \frac{eK}{\gamma_{\text{mc}}} E_z [J_0(x) - J_1(x)] \sin(\psi + \phi),
\]

\[
\frac{d\psi}{d\xi} = 2\pi k u \gamma - \gamma_s \gamma_r,
\]

where \( \xi = \frac{x}{2 \lambda_0} \), \( k_u = 2\pi / \lambda_u \) is the undulator wavenumber, \( K = \frac{eB_0 \lambda_u}{\gamma_{\text{mc}}} \) undulator parameter and \( \gamma_r \) the resonant energy factor given by the relation of

\[ \gamma_r = \frac{1 + K^2}{2 \lambda_r} \]

\( E_0 \) and \( \phi \) describe, respectively, the field amplitude and initial phase with respect to the electron. \( J_0 \) and \( J_1 \) are the Bessel functions of first kind.

The evolution equation for the radiation field with the electron is described by Maxwell equations, where the moving electrons is used as transverse current density. Assuming the condition of the slowly varying field amplitude and phase approximation, the evolution of radiation field amplitude is governed by the following complex partial differential equation,

\[
\left( \frac{\partial}{\partial z} + \frac{i}{c} \frac{\partial}{\partial t} \right) E_0 \exp(i\psi) = \frac{J_0(x) - J_1(x)}{2\pi \gamma_r} E_0 \exp(i\psi),
\]

where \( E_0 \exp(i\phi) \) is the complex field. The bracket \( \langle \cdot \rangle \) indicates the average over all the electrons in a volume \( V \). \( J_0 \) describes current density of moving electrons.

The Eqs.(1) and (2) describe the evolution of the electron energy and phase. The Eq. (3) describes the evolution of radiation field amplitude, in space and time, due to the interaction with electron beam. These equations are a set of self-consistent FEL equations from which the general time-dependent, saturated behavior of the radiation field can be described by numerically integrating these motion equations of the electrons and the radiation field.

3. Numerical simulation

We focus our interest in the important case of an free electron laser oscillator with a linac. Because of the limitation of electron beam current in linac, the gain in the FEL is small for single pass of electron pulse and it usually operates as an oscillator. The radiation
electromagnetic wave, reflected by the two mirrors, then back to the entrance of the undulator, can be repeatedly amplified. The length of the cavity must be taken to keep the electron bunch and radiation pulse synchronizing when they enter the undulator field. Using the self-consistent one-dimensional FEL theory, the performances of the infrared FEL oscillator with Tohoku Linac are analyzed numerically.

The initial distribution of electrons in a bunch is assumed to have parabolic form in space and random form in energy. According to the operation conditions of Tohoku Linac, an electron beam with energy of 32 MeV, energy spread of 0.5% are taken. The bunch length of 1.2 mm, beam cross area of 2x2 mm$^2$ and peak bunch current of 10 A are supposed, corresponding to current density of $2.5 \times 10^6$ A/m$^2$. The period and field amplitude of undulator is 4.0 cm and 0.268 T, respectively, so the undulator parameter K approximately equates to unit. The total length of undulator is 240 cm with respect to 60 periods. The cavity length $L_c$ must be chosen to satisfy the synchronization condition $nL_b=2L_\alpha$, where $L_\alpha$ is the distance between two electron bunches. The total reflectance of the cavity is assumed as 98%. The FEL parameters are summarized in Table 1.

Table 1. The parameters of FEL oscillator with Tohoku Linac.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td></td>
</tr>
<tr>
<td>Macropulse length</td>
<td>3 µs</td>
</tr>
<tr>
<td>Macropulse repetition rate</td>
<td>300 Hz</td>
</tr>
<tr>
<td>Micropulse length</td>
<td>3-4 ps</td>
</tr>
<tr>
<td>Macropulse repetition rate</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Beam energy</td>
<td>20-60 MeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.5%</td>
</tr>
<tr>
<td>Emittance</td>
<td>45 mm mrad</td>
</tr>
<tr>
<td>Macropulse current</td>
<td>100-200 mA</td>
</tr>
<tr>
<td>Average current</td>
<td>150 µA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wiggler</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Planar permanent</td>
</tr>
<tr>
<td>Period</td>
<td>4 cm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>60</td>
</tr>
<tr>
<td>Wiggler parameter</td>
<td>1 - 2</td>
</tr>
<tr>
<td>Wiggler field</td>
<td>0.268 T</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cavity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>3 m</td>
</tr>
<tr>
<td>Mirror reflectance, M1</td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>M2 98.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coherent Radiation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>10 µm</td>
</tr>
<tr>
<td>Power</td>
<td>- 5 MW</td>
</tr>
</tbody>
</table>

Fig.1 The Efficiency vs. pass number.

Fig.2 The gain vs. pass number.

Fig.3 Optical intensity vs. normalized frequency.

Fig.4 Optical intensity vs. normalized distance.
Some typical numerical simulation results are shown from figure 1 to 3. Figs. 1 and 2 show the relationship of efficiency and gain of radiation field with the oscillation numbers of radiation pulse between the cavities. As shown in Fig.1, the efficiency of FEL oscillator increases exponentially from noise under the pass number of 100. After that it gradually reaches to saturation with a value of one percent. In the case of electron energy of 32 MeV, peak current of 10 A and assuming that the energies loss in electrons are transferred totally to the radiation field, the laser output peak power of several megawatt can be obtained, corresponding to average radiation power of several ten kilowatt. The gain of the FEL oscillator decreases approximately to the total loss of the cavity at saturation, shown in Fig.2.

Fig.3 shows the dependence of optical pulse intensity with the distance of \((z-c t)/N_{\lambda_0}\), where the distance is measured as a relative point in the moving optical field and normalized the slip length \(N_{\lambda_0}\). From Fig.4 we can see that the optical gain in the front part of the laser pulse are relatively low, where is in the absence of electrons due to the effective of slippage. Thus, in practically, the electron pulses should be put enter the undulator slightly earlier than laser pulses in FEL experiments.

The optical spectrum at saturated regimes is shown in Fig.4, where the frequency, or more precisely wavenumber, is normalized as \(N_{\lambda_0}(k-k_0)\). We can see from this figure that the optical pulse gains in a relatively wide spectrum and shifted down far from its resonance value because of the low-energy electrons.

4. Conclusions

Based on above discussion and the operating parameters of Tohoku Linac, it is possible to realize an infrared free electron laser oscillator with this accelerator. The parameters of the FEL are summarized in Table 1. The FEL may be operating in the wavelength of infrared regime and reach to the peak power of several megawatt.

References

A Design Study of an FEL-SR at the FELI
Yasuyuki MIYAUCHI, Tohru TAKII and Takio TOMIMASU
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Abstract

A compact, low emittance SR dedicated to both of FEL and SOR is studied. The FEL wave length and small signal gain are estimated using the emittance of the designed lattice. Designing problem of the FEL-SR was also shown, and a 45° bending, modified DBA lattice was adopted. The FEL wavelength, small signal gain, and output power are estimated.

1. Introduction

Considering the practical application of the short wave length FEL, two types of facilities are promising: Linac type and SR type. Linac can have high power FEL, and SR can make cw FELs with narrow spectrum bands. Considering the application of high peak power FEL, the FELI has adopted an S-band linac for its main accelerator system, and succeeded in the lasing at two lasing sections (30 MeV and 70 MeV) for middle and near infrared FEL longer than 1 μm, and has begun the application study in the regions of solid state physics and bio-sciences. In addition, we have constructed a high energy (160 MeV) beam line for the lasing of visible and UV FELs, and obtained spontaneous emission of 0.5 Jm. On the other hand, aiming as a research and application center of FEL in Japan, the FELI has also considered the possibility of the construction of an SR for FEL and has prepared its space. This paper reports a preliminary design study of an SR FEL apparatus suitable for the FELI.

In the design of SRs, the selection of the lattice from various candidates is most important. Most of SR FEL experiments made use of existing machines such as ACO, VEPP-3, Teras, UV-SOR, and few SRs such as super-ACO, Duke-SR, and NHU-IW which were designed for FEL lasing. Hence, we compared several achromatic, low emittance lattices for a compact FEL SR suitable for the FELI, and chose a modified DBA lattice with eight 45° bending magnets. We applied this lattice to the designed of a 1 GeV SR for the application of SOR to say nothing of FEL.

2. Comparison of lattices

Considering the limit of the available space, we were interested in so called compact rings. In these rings, bending angles are large and corresponding changes of machine functions are also large. Therefore, making of dispersion-free straight sections is inevitable for the reduction of beam diameter in the undulator section. For this reason, we concentrated on achromatic lattice as DBA, TBA, and QBA.

As the small signal gain of FEL rapidly decreases below the diffraction limited wave length, the lasing wave length depends on the bending angle, respectively. In addition, the lattice of FEL SRs also needs long straight sections for the installations of undulators. Putting these conditions in mind, we compared five achromatic lattices shown in Fig. 1 using MAGIC, and obtained machine functions shown in Fig. 2.

Parameters including the emittance of 1 GeV of these lattices are listed in Table 1. We chose the betatron numbers so as to make the emittance to be minimum, and adopted edge angles so as to reduce the maximum values of vertical betatron functions βν. The variation of the edge angle does not affect the emittance. Table 1 shows that, there is no remarkable difference between three typical achromatic lattices of DBA, TBA, and QBA.

Considering the diffraction limit of the lasing wave length of eq.(1), we adopted the 2-fold modified DBA lattice shown by Fig.1(c).

Table 1 Comparison of typical compact lattices

<table>
<thead>
<tr>
<th>Lattice type</th>
<th>DBA</th>
<th>TBA</th>
<th>QBA</th>
<th>DBA*</th>
<th>DBA*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending angle θ (deg)</td>
<td>90</td>
<td>60</td>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Bending radius ρ (m)</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Edge angle ε (deg)</td>
<td>0</td>
<td>22.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Circumference C(m)</td>
<td>41.95</td>
<td>43.46</td>
<td>45.75</td>
<td>68.05</td>
<td>52.46</td>
</tr>
<tr>
<td>Long straight sec. L(m)</td>
<td>9.8</td>
<td>9.8</td>
<td>9.8</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td>Periodicity N</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Field gradient K (X/km)</td>
<td>0.662</td>
<td>0.866</td>
<td>0.734</td>
<td>1.01</td>
<td>0.899</td>
</tr>
<tr>
<td>(b)Length</td>
<td>0.662</td>
<td>0.111</td>
<td>1.04</td>
<td>0.938</td>
<td>1.18</td>
</tr>
<tr>
<td>(OD)</td>
<td>-1.08</td>
<td>-0.990</td>
<td>-0.990</td>
<td>-0.995</td>
<td>-1.14</td>
</tr>
<tr>
<td>(OF)</td>
<td>0.752</td>
<td>0.752</td>
<td>0.752</td>
<td>0.752</td>
<td>0.752</td>
</tr>
<tr>
<td>Betatron number ν</td>
<td>2.75</td>
<td>2.75</td>
<td>2.75</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Emittance ε (mm • mrad)</td>
<td>0.90π</td>
<td>0.65π</td>
<td>0.76π</td>
<td>0.29π</td>
<td>0.37π</td>
</tr>
<tr>
<td>(1 GeV, MAGIC)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>Betatron function βν (cm)</td>
<td>1.06</td>
<td>2.54</td>
<td>2.51</td>
<td>11.8</td>
<td>1.76</td>
</tr>
<tr>
<td>(straight sec. center)</td>
<td>23.6</td>
<td>12.0</td>
<td>12.1</td>
<td>13.8</td>
<td>15.4</td>
</tr>
<tr>
<td>βν (cm)</td>
<td>2.75</td>
<td>0.770</td>
<td>1.32</td>
<td>9.65</td>
<td>2.72</td>
</tr>
<tr>
<td>βν (cm)</td>
<td>27.1</td>
<td>77.2</td>
<td>45.8</td>
<td>23.0</td>
<td>27.5</td>
</tr>
</tbody>
</table>

Fig. 1 Achromatic lattices for compact rings
Fig. 2 Machine functions of achromatic lattices

3. Design estimation of an FEL SR

Considering the limit of available space, we modified the lattice of Fig. 1(c) to resemble a race track shape and designed a ring shown in Fig. 3.

Its parameters are listed in Table 2, and the machine functions are shown in Fig. 4. The maximum energy is set to be 1 GeV considering the application of SOR not only FEL. The RF frequency is set to 915 MHz, and its power source is supposed to be Toshiba cw klystron with highest output power of 200 kW. Using this high frequency, we can make short micropulse FELs which are convenient for the basic research of materials. In addition, as the length of optical beam packet is proportional to the square root of the length of electron bunches [5], the time fluency of FEL increases according to the square root of the RF frequency.

Table 2 SR ring parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice type</td>
<td>Modified DBA</td>
</tr>
<tr>
<td>Beam energy</td>
<td>1 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>160 MeV</td>
</tr>
<tr>
<td>Average current</td>
<td>0.5 A (0.3 A' )</td>
</tr>
<tr>
<td>Circumference</td>
<td>47.21 m</td>
</tr>
<tr>
<td>Long straight section</td>
<td>8.78 m</td>
</tr>
<tr>
<td>Periodicity</td>
<td>2</td>
</tr>
<tr>
<td>Bending angle</td>
<td>45 deg</td>
</tr>
<tr>
<td>Bending radius</td>
<td>2.3 m</td>
</tr>
<tr>
<td>Bending field</td>
<td>1.45 T</td>
</tr>
<tr>
<td>Field index</td>
<td>0</td>
</tr>
<tr>
<td>Edge angle</td>
<td>0 deg</td>
</tr>
<tr>
<td>Focusing field gradient</td>
<td>5.628 m^2 (QF1)</td>
</tr>
<tr>
<td>(Length 0.2 m)</td>
<td>-5.369 m^2 (QD1)</td>
</tr>
<tr>
<td></td>
<td>4.000 m^2 (QC)</td>
</tr>
<tr>
<td></td>
<td>-4.000 m^2 (QD1)</td>
</tr>
<tr>
<td></td>
<td>7.344 m^2 (QF1)</td>
</tr>
<tr>
<td>RF parameters</td>
<td></td>
</tr>
<tr>
<td>Harmonic number</td>
<td>144</td>
</tr>
<tr>
<td>Frequency</td>
<td>915 MHz</td>
</tr>
<tr>
<td>Tube type</td>
<td>CW Klystron</td>
</tr>
<tr>
<td>Acc. Gap Voltage</td>
<td>100 kV</td>
</tr>
<tr>
<td>Machine parameters</td>
<td></td>
</tr>
<tr>
<td>Betatron number</td>
<td>3.25</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>0.0804</td>
</tr>
<tr>
<td>Limittance</td>
<td>3.60x10^{-7} e m^2 rad(1 GeV)</td>
</tr>
<tr>
<td>Betatron function</td>
<td>1.52 m (straight section center)</td>
</tr>
<tr>
<td></td>
<td>14.2 m</td>
</tr>
<tr>
<td></td>
<td>4.33 m (straight section center)</td>
</tr>
<tr>
<td></td>
<td>21.4 m</td>
</tr>
<tr>
<td>Energy spread</td>
<td>5.3x10^{-7} (1 GeV)</td>
</tr>
<tr>
<td>Bunch size</td>
<td>0.71(0.46) mm (1 GeV,10% coupling)</td>
</tr>
<tr>
<td></td>
<td>0.38(0.46) mm (1 GeV,10% coupling)</td>
</tr>
<tr>
<td></td>
<td>24.7 mm (1 GeV)</td>
</tr>
<tr>
<td>Damping time</td>
<td>2.2 mm</td>
</tr>
<tr>
<td></td>
<td>11.1 ms</td>
</tr>
<tr>
<td></td>
<td>8.2 ms</td>
</tr>
<tr>
<td></td>
<td>3.6 ms</td>
</tr>
<tr>
<td>Touschek life time x Beam current</td>
<td>3.2x10^5 A s</td>
</tr>
</tbody>
</table>

Table used for FEL gain estimation
The FEL wave length is given by eq.(2).

$$\lambda = \frac{1}{1 + \frac{2\gamma}{K}} \lambda_u$$

(2)

Here, $\lambda_u [m]$ is the period length of the undulator, $K=93.4B\lambda_u [m]$, where $B[T]$ is the peak value of the undulator magnetic field. The FEL wave length according to the electron beam energy is shown in Fig. 5 with the diffraction limit of eq.(1). Here $K$ is fixed to be $\sqrt{2}$ for simplicity. This value of $K$ makes the small signal gain almost maximum in many cases. Considering that the maximum average FEL output power is proportional to the synchrotron radiation (so called Renieri's limit) which is proportional to the fourth power of the electron beam energy as eq.(3), the combination of a long period undulator and high energy electron beam is the answer to the demands of high power FEL.

$$P_{\text{max}} = \frac{(\Delta E/E)_{\text{max}}}{\rho} \times 10^{-4} \frac{\text{T} \cdot \text{m}}{\rho}$$

(3)

Here, $\Delta E/E$ is the energy spread of the ring, $I[a]$ the average current, and $\rho [m]$ the bending radius, respectively. Figure 5 shows that the diffraction limit of $2\pi \varepsilon$ is a very severe restriction to high energy i.e. high output power operation of FEL rings. In this figure, a moderate experimental limit such as $\varepsilon=0.1$ is also plotted.

The small signal gain of compton regime FEL can be estimated by eq.(4) which uses a trivial arithmetic deformation of the equation presented by Dattoli [7].

$$G_s = \frac{4.6 \times 10^{-3} (\frac{K^2}{2}) \gamma^{-2} (L \lambda_u \lambda_u) \cdot \frac{c}{(2\pi)^2 (2\pi \sigma_z \sigma_z \sigma_z) \cdot \Phi}}{I_F}$$

(4)

Here, $N_u$ is the period number of undulator, $L_u [m]=N_u \lambda_u [m]$ is the undulator length, $[H]=\{A \sigma + \sigma \sigma \sigma \sigma \}$, $\sigma = \sigma_z \sigma_z \sigma_z$ are horizontal and vertical bunch radius and the half of the bunch length, respectively. The factor $\Phi=\frac{1}{\sqrt{(1+w/2\sigma_z)^2+(1+w/2\sigma_z)^2}}$ is the filling factor [8]. In addition, maximum small signal gain using optical klystron (OK) can be estimated by the following equation [8,9].

$$G_{\text{OK, max}} = 0.045 \frac{\text{Ge}}{\{N_u (\Delta E/E)\}}$$

(5)

Using the parameters listed in Table 2, we obtain the small signal gain with various period length according to the electron energy shown in Fig. 6. Here, the undulator length $L_u$ is fixed to be 7 m considering the long straight section of our lattice, and the filling factor is set to be 0.5 which corresponds that the optical waist size coincides with the electron beam diameter, and $K$ is $\sqrt{2}$. This figure shows that the small signal gain is large enough for the small period length of 4 cm, but, for larger period length, the gain decreases due to the decrease of period number. In this case, the use of OK is necessary.

Figures 5 and 6 show that the combination of a small undulator period length and the low electron energy is suitable for the lasing of short wavelength FEL, and the combination of a large period length and the higher electron energy is necessary for high power FELs.

4. Conclusions and discussions

We compared several achromatic lattices and adopted a 45 deg bending, modified DBA lattice as the lattice of a compact, low emittance SR for FEL. We estimated the relations between the electron beam energy, the period length of undulator, FEL wave length, and the small signal gain. Our design needs further revising considering the available space, estimated cost, and application plans.

References


— 394 —
Time-of-Flight Measurements of Positron-Annihilation Induced Auger Electrons

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ABSTRACT

We have developed an apparatus for positron-annihilation induced Auger electron spectroscopy (PAES) with a time-of-flight (TOF) technique. We report the details of the experimental set up and an example of the TOF-PAES analysis for a MoS$_2$(0001) surface.

I. INTRODUCTION

Auger electron spectroscopy (AES) is widely used for elemental analysis of solid surfaces. In the conventional AES measurements, the core-hole excitations are formed by the bombardment of electrons or photons with energies larger than the core-electron binding energies. The observation depth is determined by the inelastic mean free path of Auger electrons, and is about 10-30 Å. The positron-annihilation induced Auger electron spectroscopy which was developed by Weiss et al. [1], uses the annihilations of positrons with core electrons for creating core holes. PAES has the following advantages over the conventional AES. Firstly, the core-holes are created mainly by the positrons trapped in the image-potential well outside the surface, so that the PAES signal originates preferentially from the surface top-layer. For this reason, PAES can easily identify the elements at the surface top-layer. Secondly, the use of primary positron beams with energies less than the core-electron binding energies eliminates the large secondary-electron background around the Auger signals. Thirdly, the high signal-to-background ratio reduces radiation damages.

At the Electrotechnical Laboratory (ETL), a high-intensity slow positron beam is generated with an electron linac. Using this beam, we have developed an apparatus for PAES with a time-of-flight technique, which enables high energy-resolution and high count-rate measurements. In this paper, we show the experimental set up and the performance of the TOF-PAES apparatus, and an example of the analysis for a MoS$_2$(0001) surface.

II. EXPERIMENTAL SET UP

A slow positron beam ($\sim 10^8$ e$^+$/s) was generated with the electron linac [2]. A 70 MeV electron beam from the linac was incident onto a Ta converter where the bremsstrahlung $\gamma$ rays generate high-energy (keV-MeV) positrons through pair productions. The positrons were then moderated with a set of thin W foils to form a slow ($\sim 6$ eV) positron beam. The slow positron beam was guided to the sample chamber in an axial magnetic field ($\sim 0.01$ T) with a series of solenoid coils. The positron beam generated with the linac was pulsed since the electron beam from the linac was pulsed at a pulse width of 1 $\mu$s and a repetition rate of 100 pulse/s. However, this pulsed beam cannot be used for the TOF-PAES measurements, because the pulse width is too wide and the repetition rate is too low. Thus, the $\sim \mu$s positron pulse was stretched to $\sim 10$ ms with a linear storage section [2]. The quasi-continuous beam was used in the TOF-PAES measurements.

Figure 1 shows a schematic of the TOF-PAES apparatus. The apparatus consists of a pulsing system, an ExB plates deflector, a magnetic field electron paralleliser, and a time-of-flight energy analyzer [3]. An axial magnetic field of $4 \times 10^{-3}$ T was applied to the whole apparatus for the beam guiding and for the parallelisation of the emitted electrons. The sample chamber was pumped by a cryo-pump to a base pressure of $2 \times 10^{-9}$ Torr.
The quasi-continuous positron beam was pulsed with a chopper and a buncher. The chopper consists of three mesh grids. A pulsed voltage was applied to the middle grid to make a positron pulse with a pulse width of 30 ns. The buncher consists of two cylindrical tubes, as shown in Fig. 1. A 20 MHz sine wave potential was applied to the inner tube. The positron pulse was modulated at the gaps between the inner and outer tubes, and was compressed at the sample. The compressed positron beam was deflected with an \( \mathbf{E} \times \mathbf{B} \) plates, and then incident onto the sample. The pulse width at the sample was monitored with a BaF\(_2\) scintillator and photomultiplier (PMT) detector, and was 5 ns for the present set up.

An incident energy of 75 eV was used in the present measurements. At this energy, the implantation depth is shorter than the diffusion length of the thermalized positrons. Therefore, a large fraction of the positrons diffuse back to the surface, and are trapped into the image potential outside the surface. Some fraction (less than a few \%) of the surface-state positrons annihilate with core electrons of the surface top-layer atoms [4], resulting in the Auger electron emission.

A Nd-Fe-B permanent magnet (0.2 T) was mounted behind the sample to reduce the angular spread of the emitted electrons and to improve the energy resolution. The electrons emitted over 2\( \pi \) steradians from the sample in the high (0.2 T) magnetic field are parallelised in the weaker (10^{-3} T) uniform field [5]. The parallelised electrons were separated from the incident positron beam with the \( \mathbf{E} \times \mathbf{B} \) plates, and were detected with a micro-channel-plate (MCP) detector which was placed 8 cm away from the sample. The energy distributions of the electrons were determined by measuring the time interval between the trigger signal from the pulsing system and the detector signal with a time-to-amplitude converter.

### III. RESULTS

To demonstrate the ability of the apparatus, we chose a layered material, MoS\(_2\) as the target. It is known that a basal plane (0001) surface of MoS\(_2\) is composed of S as the topmost layer and Mo as the second one [6]. The layered structure is suitable for the tests of the surface sensitivity of PAES.

Figure 2 (a) shows a time-of-flight spectrum of the positron-annihilation induced Auger electrons for MoS\(_2\) (0001). The incident positron pulse measured with the BaF\(_2\) scintillation detector is also plotted. Figure 2 (b) shows the corresponding energy spectrum. The count rate for the S-LVV Auger peak at \( \approx 150 \) eV was \( \approx 2 \) counts/s, and the duration of the measurement was \( \approx 1000 \) s. A large component at energies below 100 eV is due to the secondary electrons excited by the primary positron beam. In the PAES spectrum, the strong S-LVV Auger peak is seen, but Auger peaks from the Mo atoms that exist 1.6 Å below the top layer are absent. In contrast, the electron-induced AES showed Mo-NMM Auger peaks at \( \approx 180 \) and 220 eV [7]. This is because PAES probes preferentially the surface top-layer whereas the electron-induced AES probes a few atomic layers beneath the surface.

In the PAES spectrum, small Auger peaks from C (KLL) and O (KLL) contaminants are seen also. It should be noted that before the measurement the sample was annealed up to \( \approx 800 \) °C for surface cleaning, and that the electron-induced AES spectrum taken for the same surface showed no Auger peak from the contaminants. The result demonstrates that PAES is extremely sensitive to impurities adsorbed on the surface. The high sensitivity to impurities implies that the surface-state positrons are efficiently trapped at impurities and defects on the surface [7].

![Time-of-flight spectrum of positron annihilation induced Auger electrons for MoS\(_2\) (0001).](image-url)
It is clear from fig. 2 (a) that the energy resolution of the present apparatus is determined mainly by the pulse width of the incident positrons. For the positron pulse of 5 ns width, the energy resolutions at 150 eV and 500 eV are ~20 eV and 100 eV, respectively. The resolution of the present apparatus is better than that of the previously reported apparatus [5,8], but is not good compared with the conventional AES apparatus with the CMA. The use of a shorter pulse would improve the energy resolution. For the present apparatus, however, it was not possible to obtain the positron pulse with width less than 5 nsec. This is because the magnetically guided positron beam was not monoenergetic but had an energy spread of ~2 eV. In order to overcome this problem and improve the energy resolution, we are constructing a new TOF-PAES apparatus with a longer flight distance and a more efficient pulsing system.

In summary, we developed the apparatus for PAES with the TOF technique. We demonstrated the TOF-PAES analysis for the MoS$_2$(0001) surface, and found that PAES probes only the surface top-layer, and that PAES is very sensitive to surface impurities. Further improvements are needed to increase the energy resolution.

Heavy Ion Medical Accelerator Project
by Hyogo Prefectural Government

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Abstract

A project to construct a heavy ion medical accelerator facility for cancer therapy in five years is expected to start from 1996 by Hyogo prefectural government. The site will be located near SPring-8 synchrotron radiation facility in Harima Science Garden City, about 75 km northwest of Kobe city, Japan. Beam particles include proton, helium and carbon. Beam energy ranges are 70 - 230 MeV/u for proton and helium, and 70 - 320 MeV/u for carbon. The beam intensities are required to satisfy the dose rate of 5 Gy/min. for treatment volumes of 15 cm³ field size and of fully extended spread out Bragg peak (SOBP) over the maximum beam range. The facility will have a horizontal line, a vertical line and an oblique (45°) line for proton, helium and carbon beams, and two isocentric gantry lines for proton beam.

From the results of the basic design, some reconsideration of the requirements on beam intensities and field size may be done to bring about a simpler and more compact design of the facility. Some options for
future extensions and upgrades will be studied. Compensation of a tune shift due to the space charge effect during multi-turn injection, irradiation synchronized with patient's breathing, beam spill control to have a flat beam structure in time, energy variability during one treatment and raster scanning system are anticipated. In the next year a detailed design study of the accelerator and the buildings will start.

Clinical trials are expected to start in the year 2001. The project will be executed in close collaboration with NIRS. Medical imaging using the synchrotron radiation light from SPring-8 for the diagnosis is anticipated. Table II shows the time schedule of the construction. This schedule has one year delay from an initial one [5] because of an earthquake in Kobe area on January 1995.

Table I
Clinical Requirement and Physical Specifications of Charged Particle Beams.

<table>
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<tr>
<th>Particles</th>
<th>Proton, Helium and Carbon</th>
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<tr>
<td>Energy Range</td>
<td>70 - 230 MeV/u for p &amp; He</td>
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<tr>
<td></td>
<td>70 - 320 MeV/u for C</td>
</tr>
<tr>
<td>Beam Intensity</td>
<td>7.2 x 10^10 pps for p</td>
</tr>
<tr>
<td></td>
<td>1.8 x 10^10 pps for He</td>
</tr>
<tr>
<td></td>
<td>1.2 x 10^9 pps for C</td>
</tr>
<tr>
<td>Dose Rate</td>
<td>5 GY/min for treatment</td>
</tr>
<tr>
<td></td>
<td>volumes of 15 cm³ field</td>
</tr>
<tr>
<td></td>
<td>size and of fully extended</td>
</tr>
<tr>
<td></td>
<td>Spread Out Bragg Peak</td>
</tr>
<tr>
<td></td>
<td>(SOBP)</td>
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<tr>
<td>Beam Range</td>
<td>40 - 300 mm for p and He</td>
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<tr>
<td></td>
<td>13 - 200 mm for C</td>
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<td>Field homogeneity</td>
<td>± 2% (over treatment field)</td>
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<td>Field size</td>
<td>30 cm x 15 cm by</td>
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<td></td>
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<tr>
<td></td>
<td>15 cm x 15 cm by double</td>
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<td>scattering method</td>
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<td>15 cm x 15 cm for gantry</td>
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<td>Displacement of beam axis</td>
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<td>Irradiation rooms</td>
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<tr>
<td></td>
<td>One vertical line</td>
</tr>
<tr>
<td></td>
<td>One oblique line (45°)</td>
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<td></td>
<td>Two gantries for proton</td>
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<td>Beam spill length</td>
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<tr>
<td>Repetition rate</td>
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<td></td>
<td>1 Hz for proton</td>
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</table>

References

Table II

Construction Time Schedule of Hyogo Heavy Ion Medical Accelerator Project.

<table>
<thead>
<tr>
<th>Budget year</th>
<th>Accelerator, beam delivery and instrumentation</th>
<th>Accelerator building and conventional plants</th>
<th>Hospital</th>
<th>Service utility (hotel,dwelling)</th>
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<td>1995</td>
<td>Basic design</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1996</td>
<td>Detailed design and Construction</td>
<td>Design</td>
<td></td>
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<tr>
<td>1997</td>
<td>Construction</td>
<td>Construction</td>
<td>Design</td>
<td>Design</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td></td>
<td>Construction</td>
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</tr>
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<td>1999</td>
<td>Installation</td>
<td>Commissioning</td>
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<td>2000</td>
<td>Commissioning</td>
<td></td>
<td>Pre-test</td>
<td>Clinical trial</td>
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<tr>
<td>2001</td>
<td>Routine Beam Operation</td>
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ABSTRACT

An emittance upgrade program of the Photon Factory (PF) storage ring is in progress. The beam emittance will be reduced to 27 nm-rad by doubling the number of the quadrupoles and sextupoles in the normal cells. This will result in typically ten times higher brilliance of SR. Designs and developments of the accelerator components were finished and the fabrications are in progress. The reconstruction work of the ring will be started in Jan. '97 and will be finished in Sept..

1. INTRODUCTION

The performance of the Photon Factory (PF) storage ring has been steadily improved since the start of its operation in 1982 [1]. Now the ring stores 300 mA positron beam on average with a lifetime of more than 60 hours. The beam energy is normally 2.5 GeV and can be ramped up to 3 GeV.

The beam emittance, which had been 460 nm-rad in the early stage of the operation, was reduced to 130 nm-rad by changing the quadrupole strengths in 1986 [2]. However, the emittance is still larger than those of the third generation synchrotron light sources by one order of magnitude [3] and the brilliance of the SR beam from insertion devices is smaller by one or two orders of magnitude.

To compete with the new generation machines in the next decade, a high brilliance (low emittance) lattice was designed [4]. Designs and developments of the accelerator components for the new configuration were finished and their fabrications are in progress. The present status of the emittance upgrade program is described.

2. LATTICE

The present FODO type normal cells which occupy one third of the ring will be modified for the high brilliance configuration, as shown in Figure 1. The quadrupoles and the sextupoles are doubled in number and are reinforced in field strength. No change is required for the bendings. The optics of the whole ring was designed for three cases of the horizontal betatron phase advance, 90, 105 and 135 degree per unit cell. The emittance is 44, 33 and 27 nm-rad, respectively. The natural beam sizes for the present optics and for the high brilliance optics (135 degree lattice) are shown in Figure 2. The smaller beam size of the new optics will result in higher brilliance of SR at all existing beam lines by a factor of 5 to 10.

Because the sextupole fields become stronger for the lower emittance optics, the dynamic aperture becomes smaller and this may be a serious problem [5]. The commissioning of the new lattice will be started with the 90 degree optics which has relatively larger dynamic aperture. The lower emittance will be challenged step by step.

Figure 1. The present (upper) and the new (lower) configurations of the accelerator components in the normal cell section.
By turning off some of the magnets and changing the polarities of some of others in the normal cells, an optics almost same as the present one can be reproduced [4]. This enables us to restart the operation quickly just after the reconstruction work with our familiar optics.

3. DEVELOPMENTS OF ACCELERATOR COMPONENTS

3-1. Magnets
All the present quadrupoles and sextupoles in the normal cells will be replaced with the new ones of higher field gradients. All of them are Collins type, not to disturb the synchrotron radiation extraction to the existing beam lines. Since the spaces are very limited, they have relatively short lengths and small bore diameters. The sextupoles have auxiliary windings for vertical steering. The fabrication of all the magnets was finished and the field measurements are under way [6].

3-2. Injection
The injection kickers will be reinforced to be compatible with the optical functions around the injection point of the new lattice. A traveling-wave type kickers are developed and under fabrication[7], whose short pulse length enables a single-turn injection scheme. No change will be made for the septum magnets.
3-3. Vacuum

About a half of vacuum chambers will be replaced with new ones, which are now under fabrication, to be compatible with new configuration of the magnets. The straight sections of the chambers are newly constructed. The bending sections are remained because there is no change on the bendings. A design consideration is taken to install all the components, such as pumping port, bellows and flange, in the narrow space limited by the doubled magnets. The smaller emittance and the shorter bunch length in the new lattice are expected to result in a shorter Touscheck lifetime and a higher sensitivity to irregularities of inner wall of the vacuum chambers. To guarantee a long beam lifetime, the new chambers are required to have effective pumping speeds equal to or higher than those of present chambers. The bellows and flanges are equipped with a shielding contact to cure the irregularities.

3-4. RF

For a low emittance beam, Landau damping produced by the octupoles cannot be effective to suppress the beam instabilities. The existing four RF Cavities will be replaced with damped cavities, in which dangerous higher order modes giving rise to beam instabilities are damped. A high power model is now under testing [8].

3-5. Beam Channels

The front-ends of the existing SR beam channels in the normal cells will be modified to fit with the new configuration of the magnets and vacuum components and also to cope with the increased power density of SR [9]. The reconstruction of the beam lines has already been started in advance to that of the storage ring. All the work will be finished in 1996.

3-6. Beam Monitors and Handlings

The present beam position monitors in the normal cells, each of which consists of six electrodes, are replaced with new ones with four electrodes to fit with the new vacuum chambers. The signal processing will be improved to achieve an accuracy as good as a few micron, a speed of data taking as fast as 2 kHz. A turn-by-turn beam position measurement scheme is under developing [10], which will be useful for commissioning of the new lattice.

For the orbit stabilization, which will be more important for a lower emittance light source, a fast and precise feedback system for fluctuations lower than 50 Hz is now under developing [11], which utilizes the new fast and precise BPM system mentioned above.

A transverse feedback system to suppress the beam instabilities is under developing, which consists of one deflector and two BPM's[12]. This will be an effective tool to suppress the beam instabilities due to the RF cavities, beam-ion interactions or beam-electron interactions.

3-7. Control

The control system will be replaced with a new one which consists of UNIX work stations and VME systems[13]. Since the control of the magnets and the beam monitors are more important in the commissioning of the new lattice, their control system will be replaced, first during the shutdown in 1997.

4. SUMMARY

The developments and fabrications of the accelerator components for the emittance upgrade are in progress. All the preparations will be finished until the end of 1996. From Jan. to Sept. in 1997, the ring will be shut down. All the reconstruction work will be completed within this period. The operation of the ring will be restarted in Oct. 1997 with the present emittance optics, as mentioned in section 2. Commissioning of the new high brilliance optics will be tried in the machine study time, typically one day a week. The new optics will be introduced to users times as soon as possible.

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It is a pleasure to acknowledge all the contributions of the other Light Source Division staff of the Photon Factory.
Calculation of Electron Orbital for the Design of the X-band LINAC

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Abstract

The X-band linear accelerator, which can generate such a short pulse as 100fs, is under design at the Nuclear Engineering Research Laboratory, the University of Tokyo. The design study of the X-band linac is carried out by using PARMELA and SUPERFISH. Then it is found that 600 ps (tail-to-tail) emission from a thermionic gun can be bunched to about 1ps (FWHM) at the end of the 2nd accelerating tube and 80 % of the initial charge is transmitted.

1. Introduction

Femtosecond technology is going to become a key technology in radiation physics, chemistry and material science to investigate ultrafast and fundamental quantum phenomena. Up to now, 700 ps electron single bunch has been successfully generated at the S-band linear accelerator of the University of Tokyo by magnetic pulse compression[1]. However the X-band linac whose main RF frequency is 11.424 GHz is thought to be more effective for generation of shorter electron single pulse than the S-band linac. The X-band linac for a linear collider is already under design at Stanford[2] and KEK[3]. The X-band linac is discussed as the femtosecond accelerator in this paper. As to the design of the X-band linac, the most difficult problem is an increase of the space charge effect, which is accompanied with shortening of an electron bunch.

In order to generate a 100fs single pulse, an electron beam from the electron gun must be compressed till a pulse length is shorter than one period of the X-band RF (87.5 ps).

Taking that point into account, transport simulation of an electron beam has been carried out by using PARMELA and the feasibility of a generation of a femtosecond single pulse has been confirmed.

2. Design

The layout of the X-band linac designed here is shown in Fig. 1. It consists of a thermionic gun, a subharmonic buncher (SHB), two accelerating tubes and achromatic magnetic pulse compression system. And there are solenoid coils along the linac to generate axial magnetic field for controlling the transverse beam size. The final energy of the beam is 35MeV. Parameters of the components and calculated results are described in the following.

Thermionic Gun

The present thermionic gun Y796 has achieved 500 ps (tail-to-tail) at the voltage of 90 kV so far[4]. In this design, Gun voltage is increased up to 200 kV. This is because both an increase of emission current and a decrease of the space charge effect are expected. Other parameters are determined as follows. Rms normalized emittance is 50 x mm mrad, the pulse length (tail-to-tail) is 600 ps, peak current is 10 A, and the space distribution of an electron beam is assumed to be K-V distribution.

Fig. 1 Layout of the X-band linac
SHB Even though the pulse from the gun can be bunched to 87.5 ps by only one 476 MHz SHB, max energy gain must be more than 0.09 MV, which reduces engineering design margin. Therefore double SHB system is adopted here. In this system, the voltage required for each SHB is reduced down to 0.05 MV. Frequencies of SHB are determined 476 MHz and 2856 MHz, respectively, as the subharmonic numbers of 11.424 GHz.

Solenoid Coil In the non-relativistic region along the low energy part, the space charge effect has an large influence on a growth of emittance in the transverse direction. As the aperture of the accelerating tube is 8.4 mm in diameter, the beam must be controlled in the transverse direction by an external longitudinal magnetic field. In the calculation with PARMELA, the external magnetic field is supplied by various kinds of circular coils with different radius and current. There are 52 coils. Radius of a coil changes from 50 mm to 150 mm and supplied current to the coil changes from 200 to 6000 A turn. The longitudinal magnetic field distribution by these coils is shown Fig. 2. The magnetic field at the entrance of the former accelerating tube is about 1000 Gauss. Variation of both pulse length and beam size as a function of the distance from the anode is shown in Fig. 3. It shows that the required conditions are satisfied at the entrance of accelerator.

Accelerating tube There are two accelerating tubes in this linac. The former consists of a buncher section and a regular section and the latter consists of only regular section. This is because magnetic pulse compression is scheduled and the 2nd accelerating tube is used for energy modulation. It is designed to carry the 11.424 GHz constant-impedance travelling wave with the 2/3r mode. Input power for each accelerating tube from the X-band Klystron is about 15 MW and the field gradient at the entrance of the accelerating tube is just below 40 MV/m. In the first accelerating tube, the first 6 cavities form the buncher section and the rest 69 cells form a regular section. The second accelerating tube consists of 69 regular cells. Travelling wave inside the accelerating tubes is numerically evaluated by SUPERFISH as an input to PARMELA. The results are explained as follows. Table 1 shows the

<table>
<thead>
<tr>
<th>cell No.</th>
<th>Length of a cell L (cm)</th>
<th>Energy of the beam (MeV)</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.64</td>
<td>0.304</td>
<td>0.78c</td>
</tr>
<tr>
<td>2</td>
<td>0.71</td>
<td>0.505</td>
<td>0.86c</td>
</tr>
<tr>
<td>3</td>
<td>0.75</td>
<td>0.728</td>
<td>0.91c</td>
</tr>
<tr>
<td>4</td>
<td>0.78</td>
<td>0.832</td>
<td>0.92c</td>
</tr>
<tr>
<td>5</td>
<td>0.81</td>
<td>1.085</td>
<td>0.95c</td>
</tr>
<tr>
<td>6</td>
<td>0.83</td>
<td>1.343</td>
<td>0.96c</td>
</tr>
</tbody>
</table>

Fig.2 Manetic field distribution along the accelerator

Fig.3 Beam size and pulse length along the injector
variation of the length of each cell, the energy and velocity of an electron beam through the buncher section. Parameters of the regular section determined by SUPERFISH is shown in Table 2. Table 3 shows the final beam parameters calculated by PARMELA. In this calculation, 80% of the initial electric charge is transmitted and the resultant pulse length is 1.04 ps (FWHM). At the present S-band linac, the pulse length at the end of the 2nd accelerating tube is about 10 ps and it is compressed 1/10 by magnetic pulse compression. If we can achieve the same compression ratio, a 100 ps single pulse can be expected by this X-band linac.

### Table 2 Parameters in the regular section

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q value</td>
<td>6663</td>
</tr>
<tr>
<td>Shunt Impedance ((r_0))</td>
<td>78.034 MΩ/m</td>
</tr>
<tr>
<td>Attenuation Constant (a)</td>
<td>0.473 N/m</td>
</tr>
<tr>
<td>Group Velocity ((v_g/c))</td>
<td>3.79%</td>
</tr>
</tbody>
</table>

### Table 3 Final beam profile

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse length (ps)</td>
<td>1.04</td>
</tr>
<tr>
<td>Beam size (mm)</td>
<td>X = 0.55, Y = 0.58</td>
</tr>
<tr>
<td>Momentum (mrad)</td>
<td>Px = 7.8, Py = 7.5</td>
</tr>
</tbody>
</table>

### 3. Conclusion

Transport simulation of an electron beam is carried out by using PARMELA and SUPERFISH associated with the design of the X-band linac for generating a femtosecond single pulse. The layout of the accelerator is arranged as follows. After the thermionic gun, there are the double SHB, two accelerating tubes and achromatic magnetic pulse compression system. According to the results by PARMELA, 80% of the initial electric charge is transmitted and pulse length at the end of the 2nd accelerating tube is 1.04 ps (FWHM). Therefore, the feasibility of generating the 100 femtosecond single pulse is confirmed.

### 4. Reference

**BEAM DYNAMICS ISSUES IN THE JAPANESE HADRON PROJECT CIRCULAR ACCELERATORS**

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Abstract

Beam dynamics issues in the JHP circular accelerators are described. The booster ring, which is a 3 GeV proton synchrotron, accelerates $5 \times 10^{13}$ protons per pulse (ppp) and the main ring, which is a 50 GeV machine, accelerates $4 \times 10^{14}$ ppp. Problems associated with high intensity beams are examined, especially space charge effects and dynamic aperture.

I. Introduction

The proposed accelerator complex of the Japanese Hadron Project (JHP) [1] consists of a 3 GeV fast cycling booster and a 50 GeV slow cycling main ring. In order to obtain high average beam current, which is $200 \, \mu A$ in the booster and $10 \, \mu A$ in the main ring, with technically feasible repetition rate, the number of protons per pulse becomes quite large. That is, $5 \times 10^{13}$ for the 3 GeV booster and $4 \times 10^{14}$ for the 50 GeV main ring. In terms of circulating current, they are 7 A and 14 A, respectively [2]. Obviously, beam loading effects in the longitudinal direction would be one of main beam dynamics issues in both machines.

Beam dynamics issues associated with the large number of protons per pulse exists in both longitudinal and transverse directions. One could easily imagine that space charge effects right after the injection until beams get accelerated up to sufficient energy may cause problems such as beam emittance growth and beam loss. The machines have quite little margin for those because the machine aperture is limited by size of each lattice components which are essentially determined by the total cost of the rings. Even a small fraction of beam loss, say 1%, is no more negligible because it is almost equal to the entire beam loss of the KEK PS, for example, and radio activation of the facility becomes serious problem.

In order to keep the space charge tune shift moderate magnitude, the beam emittance is taken relatively large from the beginning. At the same time, to squeeze the beam size small, a rather strong focusing lattice is adopted. Chromaticity correction by sextupoles, therefore, introduces strong nonlinearity and dynamic aperture becomes one of primary concerns.

In this paper, we will pick up some of those beam dynamics issues in the JHP synchrotrons and describe our present understanding. For those issues which are not studied yet, we will show our future direction of the study. As for the lattice design itself, a separate paper describes the detail [3].

II. Space Charge Effects

One of figures which describes space charge effects in a circular machine is Laslett tune shift.

\[
\Delta \nu_y = - \frac{r_p \cdot n_t}{\pi \beta \gamma \epsilon_h (1 + \sqrt{\frac{\gamma}{\epsilon_v}}) B} \cdot \hat{F}
\]

where $\Delta \nu_y$ is the vertical tune shift, $r_p$ is the classical proton radius, $n_t$ is the total number of protons, $\beta$ and $\gamma$ are Lorentz factors, $\epsilon_h$ and $\epsilon_v$ are unnormalized horizontal and vertical emittance, and $B$ is the bunching factor. Laslett tune shift includes, not only direct electro-magnetic field in a free space, but the field due to image charge on vacuum chambers and magnets, which is represented by the form factor $F$. In fact, at the injection energy of the 3 GeV booster, namely 200 MeV, the tune shift mostly comes from a direct space charge field, but at that of the 50 GeV main ring, the field due to image charge accounts for not a small fraction of the total tune shift. In any case, we choose lattice parameters such that Laslett tune shift should be less than -0.25.

Since our design of machine acceptance is $320 \pi \cdot \text{mm} \cdot \text{mrad}$ (unnormalized) for the 3 GeV booster and $54 \pi \cdot \text{mm} \cdot \text{mrad}$ for the 50 GeV main ring, incoherent space charge limits are $5.6 \times 10^{13}$ for the 3 GeV booster and $4.7 \times 10^{14}$ for the 50 GeV main ring. Coherent space charge limit for the 50 GeV main ring is $4.2 \times 10^{14}$. Bunching factor is assumed to be 0.3 in all cases.

In addition to the fact that the space charge force shifts the transverse tune down, the space charge force itself creates resonances. Unless the beam distribution has a uniform shape, the space charge force has nonlinear dependence of its transverse coordinates. The Hamiltonian including space charge terms, therefore, becomes

\[
H = \frac{1}{2} p_x^2 + \frac{1}{2} p_y^2 + \frac{1}{2} \beta \frac{\partial B_x}{\partial z} (z^2 - y^2)
\]
We assumed that the beam distribution is Gaussian and $\sigma_x$ and $\sigma_y$ are horizontal and vertical rms beam size, respectively, and $\lambda$ is a line charge density. The first square bracket shows the magnetic force terms in lattice elements. They are essentially zero if the lattice is constructed in a perfect manner except a quadrupole term which provides focusing force and a sextupole one which is introduced intentionally to correct chromaticity. The second square bracket shows the space charge terms of both linear and nonlinear contributions. Those exist even if the lattice is perfectly constructed.

The driving term of one dimensional fourth integer resonance excited by space charge force ($4\nu_y = N$) is, for example,

$$\Delta\epsilon_x = \frac{2J_y}{4\pi} \int \frac{1}{\beta_y^2} \left[ \frac{2\sigma_y + \sigma_x}{12\sigma_x^2(\sigma_x + \sigma_y)^2} \epsilon^{-1/4} \right] ds,$$

where $2J_y$ is the Courant-Snyder invariant, $\beta_y$ is the vertical amplitude function and $\phi_x$ is the vertical phase of betatron oscillations. One can see that only harmonics which is integer times the number of superperiod ($N = \text{integer} \times n_i$) are non zero because the harmonics of rms beam size $\sigma_{x,y}$ follows lattice amplitude functions, $\beta_{x,y}$. In reality, there are small modulation in amplitude functions and harmonics other than the above number has small magnitude in driving term. Figure 1 shows the driving terms of space charge induced fourth integer resonances in the KEK PS. Note that the KEK PS has fourfold symmetry. Horizontal tune is fixed to 7.12.

Figure 1. Resonance width of space charge induced driving harmonics in the KEK PS. Because small amplitude function modulation is included, structure (filled box) as well as nonstructure resonance (empty box) is excited. Note that the KEK PS has fourfold symmetry. Horizontal tune is fixed to 7.12.

III. Dynamic Aperture

Botli rings are operated under transition energy with entire energy region. From collective instability point of view, such as zeroth mode of head-tail instability, beams are stable without chromaticity correction. In fact, natural chromaticity of the 3 GeV booster ring is around -7 to -6 and we plan to start commissioning of the 3 GeV ring without chromaticity correction until it is required by some reasons.

On the other hand, the natural chromaticity of the 50 GeV ring is around -30. With momentum spread of ±0.5% in a beam, transverse tune oscillates ±0.15%, that is not allowed. Chromaticity correction is essential in the 50 GeV ring.

Two families of sextupoles are installed in the missing bend regions, which are located one for every three FODO cells. Typical strength of the sextupoles to make the chromaticity zero is 29 T/m for focusing sextupoles and -59 T/m for defocusing ones. Those numbers include the sextupole length in it, that is 1 m. With those sextupoles excited, we investigated the dynamic aperture as follows.

A. Tune dependence

To obtain a rough idea of the dynamic aperture of the ring, we did tens of particle tracking runs taking transverse operating point as a parameter. The simulation code SAD [4] was used without synchrotron oscillations or momentum offset of a particle. Transverse tune area of ±1 near the nominal operating point (24.25, 20.70) was searched. A dynamic aperture turns out 380 $\pi \cdot \text{mm} \cdot \text{mrad}$ at one point as shown in Figure 2, which is much larger than the physical aperture, that is 54 $\pi \cdot \text{mm} \cdot \text{mrad}$.

B. Momentum dependence

Momentum dependence of the dynamic aperture was studied using the simulation code Simpsons [5], which tracks particles in 6D phase space with synchrotron os-
Figure 2. Dynamic aperture of the 50 GeV ring at several operating points.

Operating point was chosen at (22.75, 22.65) and sextupoles are excited such that chromaticity becomes zero for both planes. The rf voltage of 200 kV was applied so that the rf bucket high is ±0.43 % in the $\Delta p/p$ axis. The longitudinal tune at the injection energy is 0.004. As shown in Figure 3, no strong momentum dependence was observed.

C. Chromaticity dependence

The last figure (Figure 4) shows the dynamic aperture of the 50 GeV ring with different chromaticity setting. The simulation code Simpsons [5] was used. Natural chromaticity is around -30. With a small correction of chromaticity (chromaticity = -25 and -20), still large tune oscillations exist and dynamic aperture is small. When stronger correction was applied, the dynamic aperture becomes large at one point (chromaticity = -15). The further increase of the strength of sextupoles, and therefore smaller chromaticity, reduces the dynamic aperture gradually.

At this moment, we are not sure if we should correct the chromaticity to zero or not.

IV. Summary

Based on the proposed lattice of the JIP circular accelerators, we studied space charge effects and dynamic aperture. In fact, combining those two effects is necessary, namely tracking study of dynamic aperture with space charge effects included. We plan to do it in near future.

References

[4] SAD stands for “Strategic Accelerator Design” code. It is developed by K. Oide and colleagues at KEK.
The optical design of HIMAC secondary beam course

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National Institute of Radiological Sciences
4-9-1 Anagawa, Inage-ward, Chiba-city, Chiba-prefecture, 263, Japan

ABSTRACT

A new beam course is under construction in HIMAC, NIRS, in order to utilize radioactive secondary beams for medical purpose. The new course comprises a doubly achromatic spectrometer, which separates projectile fragmentations. The design and the beam optics are presented.

1. INTRODUCTION

Application of radioactive beams[1] is related to vast scientific areas, and one of the fruitful candidates is a medical use. The heavy-ion accelerator complex for medical use, HIMAC, began its operation in 1994 and continues treatment of cancer patients[2]. Great advantages of charged-particle therapy, especially by heavy ions, are the excellent dose distribution and the high biological effectiveness.

Although ranges and scattering angles in various materials can be, in principle, precisely evaluated, small ambiguities are left in evaluation of the dose distribution inside human bodies because they are complicated mosaic of soft and hard tissues. In order to fully utilize the advantage of the charged particles, precise measurements and/or confirmation of dose distribution inside bodies under practical conditions are important.

Combination of radioactive secondary beams of positron emitters and annihilation γ-ray detectors like PETs will realize these measurements with no excessive dose. Beams of $^{11}$C and $^{19}$Ne are good candidates for this purpose and are mainly quoted in the design stage of the new course. On the other hand, other types of beams, especially heavier ones, are taken into consideration in order to expand experimental fields being carried out by the new course. Therefore beam optics of three beam courses are studied in order to maintain the versatility in the future. One of the new courses is now under construction and will be completed in three years. This paper describes design and beam optics of the new course.

2. BEAM OPTICS AND LAYOUT

Layout of the new course A layout of the new course is illustrated in Fig. 1. The new beam course is a double-achromatic fragment separator, comprising two bending magnets, 11 quadrupole magnets, and an energy degrader.

The reaction products produced in the production target, are separated from the primary beam by a 20° bending magnet (BM01). The maximum magnetic rigidity is chosen to be 8.13 Tm, which corresponds to $q/A = 1/2$ ions with an energy of 600 MeV/nucleon.

![Fig. 1 Layout of HIMAC secondary beam course. The course denoted by "SBL1" is now under construction.](image-url)
Dumping locations of primary beams vary dependent on their magnetic rigidity relative to that of a secondary beam. Most of primary beams are stopped by a movable beam stopper placed between an exit of the magnet, BM01, and an entrance of a quadrupole magnet, SQ04. The exact separation of the fragments is performed at a dispersive focusing position F0 where the fragments with different magnetic rigidity are focused on the different position. The dispersion \( D \) at F0 is taken to be the value of 1.87 (cm%). With an object size \( x_0 = \pm 0.3 \text{cm} \), at the production target, and then at F0 the image size \( x = (x,x)x_0 = \pm 0.28 \text{cm} \), the momentum resolution is \( R = 2x/D = 0.30\% \). An achromatic energy degrader of a wedge in shape can be inserted at F0, which allows an additional fragment separation at the later stage.

The second magnet, BM02, with a bending angle of 26.5° and a pair of quadrupole magnets realize the double achromatic condition that two chromatic terms \((x,p)\) and \((x',p)\) vanish hereafter. Thus, the image size of the secondary beam, which is broadened owing to its own momentum spread at the dispersive focus F0, once more shrink. When an achromatic energy degrader is placed at F0, an additional isotope separation can be performed at the second focusing point F1. This second selection based on the difference of the atomic energy loss in the degrader, is essential for the separation of fragments of heavier nuclei with whose magnetic rigidity one cannot identify.

The three last quadrupole magnets gives the third focus at F2 where irradiation of the radioactive secondary beam is performed for medical purpose or for other scientific research. The flexibility of using three quadrupole magnets allow the focusing position to vary to meet various requirements.

As shown in Fig. 1., whole system is not symmetric due to constraint that three beam courses should be made within limited space. Although the optimization process to attain double achromatic condition may need a longer time than that of the symmetric case, it essentially gives the same properties. The beam optics was calculated using the code MAGIC[3]. The design parameters and values of matrix elements are summarized in Table 1 and the first order beam envelopes are shown in Fig. 2.

### Table 1

The parameters of the secondary beam course

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular acceptance</td>
<td>±13 mrad</td>
</tr>
<tr>
<td>Horizontal Acceptance</td>
<td>±13 mrad</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>±2.5%</td>
</tr>
<tr>
<td>Max. magnetic rigidity</td>
<td>8.13 Tm</td>
</tr>
<tr>
<td>Flight path length</td>
<td></td>
</tr>
<tr>
<td>F0</td>
<td>11.9m to F0</td>
</tr>
<tr>
<td>F1</td>
<td>12.6m to F1</td>
</tr>
<tr>
<td>F2</td>
<td>29.4m to F2</td>
</tr>
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</table>

The ion optical matrix elements

<table>
<thead>
<tr>
<th>Matrix element</th>
<th>F0</th>
<th>F1</th>
<th>F2</th>
</tr>
</thead>
<tbody>
<tr>
<td>((x,x)) [cm/mrad]</td>
<td>-0.93</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>((x',x')) [cm/mrad]</td>
<td>-0.26</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>((y,y)) [cm/mrad]</td>
<td>-1.75</td>
<td>0.86</td>
<td>0.010</td>
</tr>
<tr>
<td>((y',y')) [cm/mrad]</td>
<td>-2.1</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

\[ x' = (x',x')(x,x x',p)/x_0 \]

\[ p' = (p,x)(p,x')(p,p)/p_0 \]

---

### Notes

1. The matrix elements transfer initial values of \( x_0, x'_0 \) and \( p_0 \) as following.
Acceptance. In general large values of beam emittance and momentum spread are unavoidable in secondary beams. Therefore wide acceptance is needed to collect a larger amount of all the fragment. These angular and momentum spread of the secondary beam are estimated based on the statistical model of Goldhaber[4]. Consequently the acceptance values of ±13 mrad both horizontal and vertical angle, and ±2.5% in momentum are chosen. With these values, the fragment separator can transport as secondary beam, 65% of $^{11}$C and 90% of $^{19}$Ne fragments produced in the reaction that a 5cm-thick beryllium target are bombarded with 600MeV/nucleon $^{12}$C and $^{20}$Ne primary beams respectively.

Second order calculation. An optics of an ion optical system with a wide acceptance, might be affected by the higher order aberration greatly. Hence we evaluated the second order aberration for the secondary beam course using the code GIOS[5] and the following effects were found. First, the focal plane at F0 is slightly tilted relative to the perpendicular plane to the optical axis. Although this aberration deteriorates the momentum resolution at F0, it was confirmed that degrading of the ability is negligible for the separation of nuclei such as $^{11}$C or $^{19}$Ne. Second, the image size is found to increase owing to the second order aberration, especially at the focusing points. As an example, the calculated position distribution of the secondary beam of $^{11}$C at the second focus F1 is shown in Fig. 3. The secondary beam is assumed to be initially distributed of Gaussian shape in position, angle and momentum space, whose widths are determined under the condition that the secondary beam is produced by a bombardment of a primary beam of 600MeV/nucleon $^{12}$C with a 5cm thickness beryllium target. As shown in the figure, the second order aberration does not make much difference to the position distribution of the secondary beam, except for a rather long outer tail. This tail may have a harmful effect for the separation of the fragments with very small production cross section from those with large production cross section, but in most of case the effect is exptected to be of little importance.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. K. Kawachi for his encouragement and helpful advice.

REFERENCES


Fig. 3. Calculated $^{11}$C beam position distribution at F1.
Solid line : the second order calculation
Dashed line : the first order calculation
DESIGN OF A COMPACT PROTON ACCELERATOR FACILITY DEDICATED FOR CANCER THERAPY

Akira NODA, Makoto INOUE, Yoshisasa IWASITA, Toshiyuki SHIRAI
Masatoshi NISHI, Kazuo IIRAMOTO* and Jyunichi HIROTA**

Abstract

A compact proton accelerator facility dedicated for cancer therapy is designed. A combined function synchrotron with the maximum energy of 250 MeV is adopted. A ferrite-loaded untuned cavity with the frequency range of 1.6-8 MHz is utilized for beam acceleration. Combination of a horizontal beam line and a gantry in the same treatment room will realize multi-port irradiation. The beam efficiency will be improved by positioning outside the treatment room even with a single treatment room. Scanning method for beam spreading also increases beam utilization efficiency.

1. Introduction

Recently it becomes to be known that cancer therapy with use of charged particles as proton and heavy ions is very promising from the view-point of quality of life of the patient due to the merit of no erosion. As the national center for cancer therapy with heavy ions, HIMAC has been constructed at National Institute of Radiological Sciences and clinical treatments have already been started with good results1). However, the number of patients who need such treatments is overwhelmingly large compared with the curable patients at such a limited facility and it is inevitable to realize a proton therapy facility of such a size as can be operated with an area-center hospital of somewhat larger size. For this purpose, a proton accelerator facility entirely dedicated for cancer therapy has been designed. Because of the merit of variability of the output beam energy, proton synchrotron is adopted. In order to avoid the complex control of magnet power supplies, a combined function lattice is adopted2). As the RF accelerating cavity, a ferrite loaded untuned cavity with the frequency range of 1.6-8 MHz is adopted for the merit of easy operation3). For the medically dedicated machine, it should be operated with minimum possible down time without any professionals of accelerator. From this point of view, the RF power source of the injector linac is to be optimized.

2. Total Scheme

As the main accelerator, a proton synchrotron as shown in Fig. 1 is adopted because of the merit of energy variability2). The charged particle therapy is considered to orient the pin-point irradiation to the volume spread in three dimensions. In this case, the depth of the irradiation is to be controlled by the beam energy and then variable energy accelerator is inevitable. The pencil beam is to be scanned in two directions in the transverse phase spaces. In order to realize flat dose distribution by this scanning method, good time structure of the beam is required.

Fig 1. Layout of the Proton Accelerator System.
For the efficient use of the beam, positioning of the next patient is required to be performed in parallel with the present treatment. Usually, several treatment rooms are provided to make preparation in the other rooms. It, however, requires rather larger number of operators. So we propose such a system that positioning of the patients is performed outside the treatment room with use of X-ray CT and so on. After entering into the treatment room, the precise positioning of the patient to the beam is realized with mechanical alignment of the positioning stage with use of knock-pins. Thus, only one treatment room will be provided. The required beam specification by the medical use is listed up in Table 1.

### Table 1 Main Parameters of the Proton Therapy Facility

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>Proton</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>70-250 MeV</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>0.5 Hz</td>
</tr>
<tr>
<td>Dose Rate</td>
<td>5 Gy per Min.</td>
</tr>
<tr>
<td>Number of Treatment Rooms</td>
<td>1</td>
</tr>
<tr>
<td>Beam Ports</td>
<td>Horizontal and Rotatable</td>
</tr>
<tr>
<td>Method of Beam Spreading</td>
<td>Scanning</td>
</tr>
</tbody>
</table>

In order to provide the beam with long duration from the synchrotron, slow beam extraction with third order resonance is to be utilized. In the proposed system, the new method to utilize transverse RF electric field is to be utilized. The betatron amplitude of the beam which initially locates inner side of the separatrix is enlarged by this RF electric field. This method is effective to realize the small emittance extracted beam and synchronization with breathing.

In Table 2, the main parameters of the proton synchrotron are listed up.
Fig. 5 Layout of the proposed KUMPF as the example of the irradiation facility with a single treatment room.

5. Irradiation System

It is needed to enlarge the irradiation field to some size as 15 cm in diameter to cover the region of the tumor to be treated. For this purpose, we propose to utilize the scanning method. The scatterer reduces the beam utilization efficiency to ~1/4, while the present method is expected to utilize the extracted beam more than 85 %5). This reduced the necessary beam intensity from the synchrotron to 5 x 10^{10} at the needed dose rate of 5 Gy/min. Due to this reduction of the beam intensity, the space charge tune shift is under 0.01 even if the injection energy is 7 MeV, which is considered to contribute the injector system to be compact.

In order to make efficient irradiation to the tumor with smallest possible damage to the surrounding normal cells, multi-port irradiation is inevitable. For this purpose, we propose a combination of a single horizontal beam line and a rotating gantry in the same treatment room. With this configuration, concentration of the irradiated dose to the tumor is considered to be well realized.

As already mentioned, a single treatment room equipped with both a horizontal and a rotatable gantry is provided which keeps the needed operator as small as possible. The positioning of the patients will be performed outside the treatment room relying on the mechanical precision of alignment. In Fig. 5, the layout of the KUMPF is shown as an example of such medically dedicated facility.

The present authors at Kyoto University are proposing to realize such a facility at first at their university in order to make R&D research with real facility.

6. Acknowledgements

The authors would like to present their sincere thanks to the group of the HIMAC at National Institute of Radiological Sciences in Chiba for providing them a lot of valuable information based on the experience of operation of the HIMAC. They are also grateful to Prof. K. Ono at Research Reactor Institute, Kyoto University for his fruitful discussion on the KUMPF. This work is supported by Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture.

7. References

7. K. Hiroto et al., Contribution to this symposium.
X-RAY LEAKAGE
AROUND 1.7 MV TANDETRON ACCELERATOR

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Abstract
For the purpose of offering fundamental information on radiation protection of an accelerator, the dose rates around 1.7 MV tandetron accelerator were measured in various operating conditions. The dose rates except around the ion source were generally kept low enough. The peak energy of X-ray detected around the ion source was about 25 keV, which could be easily shielded by 1 mm thick iron.

1. Introduction
The installation of small accelerator is expected for the research of ion beam science. The 1.7 MV tandetron accelerator was newly installed at Research Center for Nuclear Science and Technology of the University of Tokyo in 1994. For the purpose of offering fundamental information on radiation protection of an accelerator, the dose rates around the accelerator (ion source, magnetic inflector, high voltage power supply, acceleration tube, switching magnet, and end station) were measured in various operating conditions (ion source, terminal voltage, and beam current).

2. Outline of Tandetron Accelerator System
The 1.7 MV tandetron accelerator system is mainly consisted of ion source, magnetic inflector, high voltage power supply, acceleration tube, switching magnet, and end stations. For applications, Particle induced X-ray emission (PIXE), Rutherford backscattering spectroscopy (RBS), and ion implantation system are prepared. The system was named RAPID (Rutherford backscattering spectrometry Analyzer with Particle induced X-ray emission and Ion implantation Devices). The system was supplied by HVEE (High Voltage Engineering Europe B.V.). The system layout is shown in Fig. 1.

(1) Ion source and injector: Two types of ion source are equipped for the system: one is a duoplasmatron (model 358), the other is a Cs spatter ion source (model 860A). They are mounted simultaneously on the dual leg injector system. It provides the flexibility to produce a large variety of ions and the quick changeover from heavy ions to H ions.

(2) Accelerator system: Model 4117-HC is used for an accelerator system. High voltage power supply system is a Cockroft-Walton type one. The terminal voltage range is 0.1 - 1.7 MV. The main specifications of ion source and beam current are shown in Table 1. The control of whole accelerator system is done by the computer control. It allows for unattended start-up and operation of the entire accelerator system.

(3) End station: PIXE, RBS and Ion Implantation system are prepared for the application.
- PIXE: 3 axis and 2 translations sample manipulator, Si(Li) detector with 8192 ch PHA

Fig. 1 The system layout of 1.7 MV tandetron accelerator system and dose rate measuring points.
A: ion source, B: magnetic inflector, C: low energy acceleration tube, D: center of acceleration tube, E: high energy acceleration tube, F: end of acceleration tube, G: switching magnet, H: ion implantation target
Table 1 Ion species and beam current

<table>
<thead>
<tr>
<th>ion species</th>
<th>beam current (µ A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H+</td>
<td>25</td>
</tr>
<tr>
<td>He2+</td>
<td>2.4</td>
</tr>
<tr>
<td>Si2+</td>
<td>140</td>
</tr>
<tr>
<td>Cu2+</td>
<td>20</td>
</tr>
<tr>
<td>N2+</td>
<td>20</td>
</tr>
<tr>
<td>Au2+</td>
<td>80</td>
</tr>
</tbody>
</table>

- RBS: 3 axis and 1 translation sample manipulator, silicon surface barrier detector
- Ion implantation: implantation angle 7°, 10 samples within 32 mm, heatable and coolable target holder
(4) Control cabinet

The control cabinet is situated out of the accelerator room. The door interlock system was not prepared for the convenience of access. The data transmission from the accelerator is done by the optical fiber cable for the reduction of electro-magnetic noise.

3. Method

3.1 Radiation detectors

The ionizing chamber type survey meter (AE-133L, Applied Engineering Inc.) was used for the dose rate measurement. The spectrum measurement around the ion source was done by using NaI(TI) scintillation detector with Be window (Ohyo Koken Kogyo Co.).

3.2 Measuring points

Measuring points are 8 as shown in Fig. 1 and, the measuring height was 1215 mm from the floor, which is the same height of beam line.

3.3 Measuring operation condition

The ion species of H+, He2+, N2+, Si2+, Cu2+, and Au2+ were measured. Terminal voltage was around 1.7 MV except H+ (1.5 MV). As for Si2+, terminal voltages and beam currents were changed as a standard case.

4. Results and Discussions

4.1 Dose rate

The results of dose rate measurements were shown in Table 2.

High dose rates were detected around the ion source in case of accelerating Cu2+ and Au2+ beam. In case of Si2+, the high dose appears irregularly. This X-ray generation has no reappearance. This may be caused by the difference of geometry between a sputter electrode and an ion source holder. Further measurements were done for this X-ray generation. The results was described in the paragraph 4.2.

The accelerating energy of H and He per particle is rather high because of those small mass numbers. Therefore, the dose rates around ion implantation target become rather high in case of accelerating H+ and He2+.

In spite of the almost same operating condition, the dose rates in case of accelerating N+ were slightly high as a whole. This was caused by the way of accelerating N+. Nitrogen ion source was prepared as NO+. NO+ was accelerated from ion source to stripper canal at the center of acceleration tube. Then, oxygen was stripped with a charge exchange.

Compared with the dose rate around the low energy tube and around the high energy tube, the former were generally high. There were more complex structures in the high energy tube than in

Table 2 Dose rates around 1.7 MV tandetron accelerator system (µ Sv/hr)

<table>
<thead>
<tr>
<th>ion source</th>
<th>H+</th>
<th>He2+</th>
<th>N2+</th>
<th>Si2+</th>
<th>Cu2+</th>
<th>Au2+</th>
</tr>
</thead>
<tbody>
<tr>
<td>terminal voltage (MV)</td>
<td>1.53</td>
<td>1.70</td>
<td>1.74</td>
<td>1.73</td>
<td>1.71</td>
<td>1.72</td>
</tr>
<tr>
<td>beam current*1 (µ A)</td>
<td>11</td>
<td>2.4</td>
<td>26</td>
<td>180</td>
<td>41</td>
<td>130</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ion source</th>
<th>0.06</th>
<th>0.14</th>
<th>2.7</th>
<th>0.33</th>
<th>15 (0.45)*2</th>
<th>35 (0.8)*2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ion injector</td>
<td>0.11</td>
<td>0.15</td>
<td>2.3</td>
<td>0.17</td>
<td>0.75</td>
<td>1.6</td>
</tr>
<tr>
<td>low energy acceleration tube</td>
<td>0.10</td>
<td>0.26</td>
<td>2.0</td>
<td>0.46</td>
<td>0.85</td>
<td>1.7</td>
</tr>
<tr>
<td>center of acceleration tube</td>
<td>0.09</td>
<td>0.32</td>
<td>1.2</td>
<td>0.71</td>
<td>0.62</td>
<td>1.5</td>
</tr>
<tr>
<td>high energy acceleration tube</td>
<td>0.05</td>
<td>0.15</td>
<td>1.5</td>
<td>0.22</td>
<td>0.40</td>
<td>0.7</td>
</tr>
<tr>
<td>end of acceleration tube</td>
<td>0.05</td>
<td>0.08</td>
<td>0.1</td>
<td>0.15</td>
<td>0.12</td>
<td>0.1</td>
</tr>
<tr>
<td>inflection magnet</td>
<td>0.10</td>
<td>0.31</td>
<td>0.05</td>
<td>0.07</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>ion implantation target</td>
<td>4.0</td>
<td>2.4</td>
<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*1 at faraday cup of ion implantation, *2 after shielding of 1 mm thick iron, background dose rate: 0.05 (µ Sv/hr)
the low one. Therefore, the shielding effect from this structure could be expected.

4.2 X-ray around ion source

The spectrum of X-ray around the ion source in case of accelerating Au\textsuperscript{2+} beam was shown in Fig. 2. The photopack energy was 25.8 keV. The photopack energies were almost same in case of accelerating Cu\textsuperscript{2+} and Si\textsuperscript{2+}. This low energy X-ray was easily shielded by 1 mm thick iron. The dose rates were decreased from 15 μSv/hr under no shielding condition to 0.45 μSv/hr under the 1 mm iron shield (Cu\textsuperscript{2+}), from 35 μSv/hr to 0.8 μSv/hr (Au\textsuperscript{2+}).

4.3 Relationship of voltage, current and dose rate

In the acceleration tube, the remaining air is ionized by ion beam. In this process, the produced electron is also accelerated. As a result, the bremsstrahlung X-ray is generated. Figure 3 shows the relationship of terminal voltage and dose rate per voltage-current around the acceleration tube in case of accelerating Si\textsuperscript{2+} beam.

No significant tendency was recognized below 1.4 MV. The dose rates were relatively low and the reading error of dose meter might be large. Above 1.4 MV, the X-ray production at the center tube and the high voltage tube increased drastically.

5. Conclusion

The measured dose rates around 1.7 MV tandemron accelerator were obtained, which will be useful as a fundamental data for radiation protection of this type accelerator.

Reference

Three projects for quantum beam science, an ultra fast electron pulse, a free electron laser, and a slow positron beam, has been started by using 38 MeV L-band and 150 MeV S-band linacs at ISIR in Osaka University. Both study on the production of three beams and study on quantum material science by using three beams will play an important role in the beam science.

1. Introduction

The new research system has been started since this April by the reorganization of the Institute of Scientific and Industrial Research (ISIR) at Osaka University. The Radiation Laboratory in ISIR will play an important role of studies on quantum beam science in collaboration with the division of quantum beam science and technology which is composed of two departments, department of accelerator science and department of beam material science.

Fig 1 shows a new project that three kinds of quantum beam, ultra short electron pulse, FEL, and slow positron beam, generated by using the electron linac are used for the quantum beam science.

Picosecond pulse radiolysis by using the ultra short electron pulse is very important for the elucidation of the primary process of the radiation chemistry which contributes to the material science. Infrared FEL is also important for the material analysis. The analysis of atomic and molecular structure near material surface can be achieved by using the slow positron.

In this paper, the developments of three quantum beams and its application are described.

2. Quantum Beams Generation

The ultra short pulse is produced by the 38 MeV L-band linac with the pulse compressed system which is composed of two 1/12 sub harmonic prebunchers and a 1/6 sub harmonic prebuncher. The FEL is produced by using the L-band linac. The slow positron is generated by using 150 MeV S-band linac. Fig. 2 shows the location of the linacs and the experimental ports for the quantum beams.
3. Ultra Short Electron Pulse

A 20 ps single bunched beam from the L-band linac has the maximum charge of 67 nC, which is hundred times larger than that of typical S-band linac. The highly intended beam as irradiation source has many advantages for picosecond pulse radiolysis.

A new picosecond pulse radiolysis system[1] combined with a femtosecond laser is under development. Fig. 3 shows the block diagram of the new system. The femtosecond Ti-sapphire laser is used as the analyzing light instead of the Cherenkov light produced by the electron beam[2]. The laser analyzing light can cover the wide wavelength region from ultra violet to infrared by using the technique of second harmonic generation, third harmonic generation, and optical parametric oscillation.

The important point to get the time resolution of picosecond is the timing jitters between the electron pulse and the laser pulse. The timing jitters is within 10 ps by synchronization of rf by which both the linac and the laser can be controlled.

The first experiment of the new system will start this autumn.

4. Infrared Free Electron Laser

FEL experiments in visible region by using linac have been succeeded at about 10 places in the world. For Infrared FEL, the development has been proceeded. At ISIR, the FEL lasing[3] in the region from 32 ~ 40 μm was succeeded in 1994 by using the L-band linac[4]. The estimated maximum

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Fig. 2 The Location of S&L-band linacs and experimental ports for three beams.

Fig. 3 A new picosecond pulse radiolysis combined with femtosecond laser.
peak power at 40 μm was 8.3 MW.

Fig. 4 shows the typical time profile of the FEL at 40 μm monitored by a fast response far infrared detector. The net FEL gain obtained by the raise of the time profile and the optical cavity loss obtained by the decay after the electron pulse are 58 % and 6.2 %, respectively. The results have good agreements with the calculated values based on the two-dimensional model.

In order to get more high performance of the FEL, several improvements, such as a newly designed electron gun of the linac, a variable gap system of the undulator, and an optimized optical cavity, will be required. The preparation of the experimental port for FEL application is under consideration.

5. Slow Positron Beam

Since the first image of the slow positron beam produced by the S-band linac was obtained in 1995, the measurement of numbers of positrons and extension of the slow positron beam line have been performed.[5]

The present position of the end of the slow positron beam line is point A in fig 2, where the performance of the slow positron beam is measured. The end position will be prolonged to the measurement room located over point B to avoid the interference with L-band linac.

Fig. 5 shows the space profile of the slow positron beam. The transport efficiency was improved by the optimization of the operation condition of the S-band linac, the moderator, and magnetic field. The estimated beam intensity of slow positron beam was 2 x 10^8 n/s.

The beam quality of the slow positron will improved by increasing the brightness of the beam. The dc and pulsed slow positron beam and their application will be started in near future.

references
A preliminary experimental result confirmed a possibility to study defects in silicon with an internal positron source produced by a proton beam from a cyclotron. A pulsed MeV positron beam, which can be applied for detailed bulk defect analysis of wider range of materials, is under construction. In the design study for the Positron Factory, a feasibility of simultaneous extraction of multi-channel monoenergetic positron beams was demonstrated by an experiment using an electron linac.

1. Introduction

We have been developing positron spectroscopy techniques combined with accelerator technology. Detailed bulk defect analysis using an internal positron source in silicon produced with a cyclotron is now in progress. The preliminary result is reported. We have been constructing a pulsed MeV positron beam line for the same purpose, which will be applied not only for silicon but for various materials. Outline of the design is described. We have been promoting design studies for the 'Positron Factory' [1], in which linac-based intense monoenergetic positron beams are planned to be applied for advanced materials characterization and new fields of basic research. A tentative goal of the slow (i.e. mono-energetic) positron beam intensity is $10^{10}$/sec, which is larger by two orders of magnitude than those of existing strongest beams in the world. We have proposed a concept of simultaneous extraction of multi-channel mono-energetic positron beams, on the basis of a Monte Carlo simulation, in the design study. In this report, an experimental result to confirm the feasibility of this concept is demonstrated.

2. Internal Positron Source Production with a Cyclotron

It is possible to produce a positron emitter $^{22}$Na inside silicon from a nuclear reaction $^{28}$Si(p,$^{7}$Be)$^{22}$Na with a proton bombardment. This internal positron source enables thermal defect studies by using positron lifetime measurement at high temperature where usual positron sources would be melt down. Positron lifetime spectra of a high-purity FZ-silicon irradiated by 70 MeV proton from the TIARA AVF cyclotron in JAERI Takasaki Establishment are shown in Fig.1. The fluence was $2.5 \times 10^{17}$cm$^{-2}$. The lifetime measurement was carried out at room temperature. The spectrum (a) is for the sample as irradiated. It is resolved into three components: $\tau_1=170\text{ps}(l=59.4\%), \tau_2=284\text{ps}(l=39.0\%)$ and $\tau_3=1.73\text{ns}(l=1.6\%)$, where $\tau$ and $l$ are the lifetime and the intensity, respectively. The value of $\tau_3$ is too large for that corresponding to defects in silicon. When the irradiated specimen was sandwiched between two unirradiated ones, this component disappeared as shown in the spectrum (b). Consequently, this extra component of small amount is assumed to come from positrons emitted from the vicinity of the surface of the irradiated specimen into air and/or surrounding materials like a detector. This is an important fact to which we must pay attention in use of the internal positron source technique.

The value of $\tau_2$ indicates that vacancy clusters were induced by the irradiation, which survive even at room temperature. We will further investigate the detail of the cluster with elevating the temperature and also the behavior of thermal vacancies at much higher temperatures.

3. Construction of a Pulsed MeV Positron Beam Line

The above internal positron source technique has an advantage that ion-induced defects can be studied in addition to thermal defects at higher temperatures. However, available materials are limited. A pulsed positron beam, on the other hand, makes it possible to analyze defects in a variety of materials at arbitrary temperatures. Suzuki et. al. [2] constructed a pulsed slow positron beam line connected to an electron linac and succeeded in various sorts of surface characterizations. The pulse width is about 100ps, and the beam energy range is from several tens of eV to several tens of keV.

To study defects in a 'bulk' as well as those at a surface is important. Fig.2 shows stopping probability of 1 MeV positron beam onto tungsten, which was calculated with a Monte Carlo simulation system EGS4-SPG developed by us[3]. The fraction of implanted positrons was 0.63 and the others were back-scattered. It is deduced that almost all implanted positrons annihilate in a bulk of the material. If the beam is accelerated not by an electrostatic field but by RF, only a little portion of the back-scattered positrons may reenter the material.

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3a2-3

PRESENT STATUS OF THE POSITRON FACTORY PROJECT AND DEVELOPMENT OF POSITRON BEAM TECHNIQUES

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Abstract

We have been developing positron spectroscopy techniques combined with accelerator technology. Detailed bulk defect analysis using an internal positron source in silicon produced with a cyclotron is now in progress. The preliminary result is reported. We have been constructing a pulsed MeV positron beam line for the same purpose, which will be applied not only for silicon but for various materials. Outline of the design is described. We have been promoting design studies for the 'Positron Factory' [1], in which linac-based intense monoenergetic positron beams are planned to be applied for advanced materials characterization and new fields of basic research. A tentative goal of the slow (i.e. mono-energetic) positron beam intensity is $10^{10}$/sec, which is larger by two orders of magnitude than those of existing strongest beams in the world. We have proposed a concept of simultaneous extraction of multi-channel mono-energetic positron beams, on the basis of a Monte Carlo simulation, in the design study. In this report, an experimental result to confirm the feasibility of this concept is demonstrated.

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Fig.1 Positron lifetime spectra of a high-purity FZ-silicon irradiated by 70 MeV proton, which were measured by using the internal positron source technique.
On the basis of this concept, we have been constructing a pulsed MeV positron beam line with a pulse width of 100ps, for detailed bulk defect analysis. Schematic view of the beam line is shown in Fig.3. The parts of the positron source, the slow positron beam generation and the beam transport were already installed. The subharmonic buncher (178.5 MHz) and the acceleration cavity (2856 MHz) will be installed by the end of 1996 fiscal year.

4. Design Study for the Positron Factory

We have performed design studies for the Positron Factory until 1994 as follows[4]:
1) An optimum electron beam energy for slow positron generation was estimated to be around 100 to 150 MeV.
2) It was calculated that a tentative goal of the slow positron beam intensity (10^10/sec) could be attained with a linac of 100 kW class with the above energy range.
3) A technical survey study confirmed a feasibility of manufacturing such a state-of-the-art linac.
4) Further detailed analyses were carried out concerning thermal deformation of the accelerator structures, beam instability, reliability of the components, down-sizing of the machine and a computer-aided control system.
5) A 'self-driven rotating converter' suitable for the high power beam was proposed and successfully tested.

In the design study, we have also proposed 'multi-channel moderator assemblies' to supply multiple slow positron beams simultaneously as shown in Fig.4. The slow positron yield, that is a ratio of the number of slow positrons emitted from each tungsten moderator assembly to that of incident electrons onto the tantalum converter, was estimated using the EGS4-SPG. The result is shown in Fig.5. The contribution by energetic positrons from the converter to generate slow positrons drastically decreased at the assemblies distant from the converter. It was deduced from tracking of the particles that this is caused by spatial spread of the positron beam. On the contrary, there still were sufficient slow positron yields originating in energetic photons, even at the rear assemblies. This is because the photons go almost straightforward and cause pair production reactions uniformly in every assembly. Thus produced positrons have comparatively lower energies, which results in higher probabilities to be thermalized in each moderator foil.

To demonstrate a feasibility of the simultaneous extraction of multi-channel slow positron beams, we fabricated a set of 2 channel tungsten moderator assemblies as shown in Fig.6. The set was composed of 18 tungsten foil layers of 25 μm in thickness. Slow positrons from each 9 layers were separately extracted by 2 tungsten mesh grids. Each moderator layer was divided into 3 parts, electrically separated and biased to drift emitted slow positrons by sloping the electric field toward the extraction grids. We observed the slow positron beam profile from the assemblies with a MCP (micro channel...
plate), using a 100 MeV electron beam from a S-band electron linac at Osaka University.

The result is shown in Fig. 7. Three peaks were observed in the slow positron beam intensity. The largest one was attributed to slow positrons from the first channel which was nearer to the tantalum converter. The second and third peaks were both attributed to slow positrons from the second channel. It is assumed that back-scattered positrons and pair production reactions by photons give rise to the third peak, because thick tungsten plates were placed at the end of the second moderator assembly. This means that positrons and photons passing through the first and second assemblies still have a potential to generate slow positrons, and also that it will be efficient to place a heavy metal at the end in fabrication of moderator assemblies.

The intensity of slow positrons from the second channel was smaller only by an order of magnitude than that from the first channel, which agreed well with the simulation result. It was concluded that such an extra beam will be useful for preliminary or potential researches which are promoted simultaneously with main experiments using the strongest beam.

5. Conclusion

We confirmed a possibility to study defects in silicon with an internal positron source produced by proton bombardment. In the positron lifetime spectrum, a small extra component which may originate in escaping positrons from the irradiated specimen was found. Construction of a pulsed MeV positron beam, which is applicable for defect analysis of various materials, will be completed at the end of 1996 fiscal year. In the design study for the Positron Factory, we demonstrated a feasibility of simultaneous extraction of multi-channel monoenergetic positron beams using an electron linac, by an experiment.

The experiments of the internal positron source production and the multi-channel positron beam extraction were carried out in cooperative researches with Tohoku University and Osaka University, respectively. The authors wish to thank Prof. M. Hasegawa, Prof. S. Tagawa, Dr. Y. Honda and their colleagues for their cooperation.

References


Fig. 6 Experimental setup of 2-channel moderator assemblies for the demonstrative experiment of simultaneous extraction of multi-channel monoenergetic positron beams.

Fig. 7 The intensity of slow positrons extracted from the moderator assemblies shown in Fig. 6, observed with a MCP.
I. Introduction

A third-generation VUV and soft X-ray ring (VSX ring in short) with a low emittance of several mm-rad is being designed at the Institute for Solid State Physics (ISSP) of the University of Tokyo, in close collaboration with the Photon Factory of KEK. The proposal for constructing the light source facility (VSX Light Source) is now in preparation for submission to the government. This project was previously considered as one of the whole future plans of ISSP that will move to a new site called Kashiwa Campus. However, it is now proposed that the light source facility should be constructed by a newly organized body, the Center of Accelerator Science, which directly belongs to the university: the new center is expected to be established soon, probably within a year (see Fig. 1). Following a recommendation on synchrotron radiation science made last June by the Accelerator Science Subcommittee of the Minister of Education and Science, the establishment of the new center is aimed to obtain full support for the construction of the VSX Light Source from all through the university and to make up its own firm base of the necessary manpower and budget for the facility construction, the administration and so forth. The center is also aimed to concentrate the university's efforts of other accelerator related sciences; synchrotron radiation science of X-ray region, a cyclotron facility for nuclear study and a facility for utilizing various low-energy ion beams.

Fig. 1 New organization

The SR (Synchrotron Radiation) Users Group of Tokyo University organized a few years before has set a working group in order to discuss the scientific opportunities provided by the extremely high-brilliant VSX Light Source, and to explore potential users and then got new proposals from these users as well as from the already active X-ray users. In addition, a new nationwide users group (VSX Users Group), in which several hundred people are expected to participate, will be established this September. The users group will discuss how to use VSX Light Source and what to study there, and also take part in the construction of the facility, specifically the construction of the beamlines and their operation; it is otherwise impossible for the in-house staff to construct and operate about thirty beamlines available at the facility. After the construction completed, this users group becomes a central body of the user community of VSX Light Source. Furthermore, an official committee, the Advisory Committee of VSX Project, has been established at ISSP (see Fig. 2): the committee is a decision-making body of the project, and it coordinates two Users Groups and gives advice and recommendation to the construction groups. It will be a steering committee of the facility in future. Three working groups, accelerator, beamline and research groups, which are presently the driving forces of the project, is being reorganized as three construction groups under the Advisory Committee. Meanwhile, the Positron Users Group with active researchers of Tokyo University, who have expressed much interest in utilizing slow positron beam produced by the facility, is being involved in the project.

II. Facility

Figure 3 shows a layout of the facility buildings; Light Source Building, High-voltage Power Station, Utility Center, Power Supply Station, Assembly Hall and Office Building. The large building at the center of the figure is the Light Source building that houses the injectors (Linac
and Synchrotron), Storage Ring, Control Room, Experimental Hall and so on. Storage Ring is at ground level, while Synchrotron and Linac are underground and Control Room is on a second floor. The Experimental Hall is surrounded by a large hall called Hall for Special Experiments, Experimental Preparation Rooms (first floor) and Users Offices (second floor). A general construction company and a large construction design company have been already involved in the design work of the facility buildings and their utilities. The basic design of buildings will be completed early next year.

### Table 1. Principal parameters of Storage Ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy $E$ [GeV]</td>
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</tr>
<tr>
<td>Lattice type</td>
<td>DBA</td>
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<td>Superperiod $N_s$</td>
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</tr>
<tr>
<td>Circumference $C$ [m]</td>
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</tr>
<tr>
<td>7-m straight section</td>
<td>12</td>
</tr>
<tr>
<td>12.5-m straight section</td>
<td>4</td>
</tr>
<tr>
<td>Natural emittance $\varepsilon_0$ [mm-rad]</td>
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</tr>
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<td>Energy spread $\sigma_E/E$</td>
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</tr>
<tr>
<td>Horizontal damping time $\tau_x$ [msec]</td>
<td>24.17</td>
</tr>
<tr>
<td>Vertical damping time $\tau_y$ [msec]</td>
<td>24.25</td>
</tr>
<tr>
<td>Longitudinal damping time $\tau_l$ [msec]</td>
<td>12.14</td>
</tr>
<tr>
<td>Revolution frequency $f_{rev}$ [MHz]</td>
<td>0.7718</td>
</tr>
<tr>
<td>RF voltage $V_{RF}$ [kV]</td>
<td>1.4</td>
</tr>
<tr>
<td>RF frequency $f_{RF}$ [MHz]</td>
<td>500.1</td>
</tr>
<tr>
<td>Harmonic number $h$</td>
<td>648</td>
</tr>
<tr>
<td>Synchrotron tune $\nu_s$</td>
<td>0.007</td>
</tr>
<tr>
<td>Bunch length $\sigma_z$ [mm]</td>
<td>4.0</td>
</tr>
<tr>
<td>RF-bucket height $(\Delta E/E)$</td>
<td>0.028</td>
</tr>
</tbody>
</table>

### III. Storage Ring & Injectors

The 2 GeV Storage Ring has a lattice type of DBA and four superperiods with sixteen cells. The betatron and dispersion functions in a superperiod are shown in Fig. 4. The principal parameters of Storage Ring are listed in Tables 1. The chromaticity will be corrected by six families of sextupole: two of them are put in dispersion sections (four chromatic sextupoles in a cell), and two in dispersionless semi-long straight sections, the remaining two in long straight sections (four harmonic sextupoles in a straight section). Figure 5 shows a typical example of horizontal and vertical dynamic apertures versus momentum deviation in a case without magnet errors. A wide momentum aperture is required to obtain a long Touschek lifetime.

Gas-scattering and Touschek effects are sever factors of determining the beam lifetime for a third-generation synchrotron light source. The vacuum pressure less than 1 nTorr is a design goal to be attained at a maximum beam current of 400 mA and the design value of the minimum gap of vacuum chamber is 16 mm at insertion devices. Total RF voltage is about 1.4 MV in order to increase the Touschek lifetime. This value can be easily obtained by three RF-cavities to be installed in Storage Ring. The lifetimes due to gas-scattering and Touschek effects are shown in Figs. 8 and 9 of Ref. 1.
The present ring design does not need C-type quadrupole or sextupole, so that all ring magnets would be robust for deformation caused by magnetic field or thermal load. Almost all vacuum ducts of the ring will be made of aluminum alloy, except for flanges, bellows and vacuum ducts for undulators, which will be made of stainless steel. A challenging point of the vacuum design is that in-situ baking of vacuum ducts is not made, though they are baked out before installation in the ring (see Figs. 10, 11 and 12 of Ref. 1 for the cross-sectional views of the vacuum ducts for bending and quadrupole magnets and undulators). For the control system, its conceptual design has been almost fixed. The core of control system will consist of several UNIX workstations. FDDI is adopted for the main data highway and Ethernet for the branch lines. VME and VXI is a standard of the computer interface to accelerator components. For the undulator, the basic designs of typical undulators, both planar and circular undulators, have been finished. The brilliances of synchrotron light to be obtained by some typical undulators, both planer and circular undulators, have been finished. The brilliances of synchrotron light to be obtained by some typical undulators, both planer and circular undulators, have been finished.

For Synchrotron, the lattice design has been finished. The extraction energy of the synchrotron is 2 GeV in order to meet the full-energy injection to the ring. The injection energy is, however, variable around 300 MeV; it depends on electrons or positrons and on the pulse length of the Linac beam. The principal parameters of Synchrotron arc listed in Table II.

### Table II. Principal Parameters of the Booster Synchrotron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Energy (E_{\text{in}}) [GeV]</td>
<td>0.3</td>
</tr>
<tr>
<td>Maximum Energy (E_{\text{max}}) [GeV]</td>
<td>2.0</td>
</tr>
<tr>
<td>Repetition Rate (f_{\text{rep}}) [Hz]</td>
<td>4.0</td>
</tr>
<tr>
<td>Circumference (C) [m]</td>
<td>97.11</td>
</tr>
<tr>
<td>Horizontal tune (\gamma_x)</td>
<td>5.17</td>
</tr>
<tr>
<td>Vertical tune (\gamma_y)</td>
<td>4.79</td>
</tr>
<tr>
<td>Momentum compaction (e_p) [mm-rad]</td>
<td>0.058</td>
</tr>
<tr>
<td>Natural emittance (\epsilon_0)</td>
<td>262</td>
</tr>
<tr>
<td>Energy spread (\alpha_s/E)</td>
<td>7.0x10^{-4}</td>
</tr>
<tr>
<td>Horizontal natural chromaticity (\epsilon_x)</td>
<td>-6.34</td>
</tr>
<tr>
<td>Vertical natural chromaticity (\epsilon_y)</td>
<td>-6.38</td>
</tr>
<tr>
<td>Horizontal damping time (t_x) [nsec]</td>
<td>5.48</td>
</tr>
<tr>
<td>Vertical damping time (t_y) [nsec]</td>
<td>5.50</td>
</tr>
<tr>
<td>Longitudinal damping time (t_e) [nsec]</td>
<td>2.76</td>
</tr>
<tr>
<td>RF voltage (V_{\text{RF}}) [MV]</td>
<td>0.8</td>
</tr>
<tr>
<td>RF frequency (f_{\text{RF}}) [MHz]</td>
<td>500.1</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>162</td>
</tr>
<tr>
<td>Synchrotron tune (v_s)</td>
<td>0.024</td>
</tr>
<tr>
<td>(bunch length (\alpha_z) [mm]</td>
<td>26</td>
</tr>
<tr>
<td>RF-bucket height (v_r) [(\Delta E/E)]</td>
<td>0.004</td>
</tr>
</tbody>
</table>

The parameters dependent on the beam energy are at 2 GeV.

Linac is about 60 m long including an ECS system; it can provide 300 MeV positron beam together with electron beam. This design has become only possible by adopting the SLED scheme for RF generation and also by incorporating recent results of R&D for high-gradient linac. The design parameters of Linac are listed in Table III. To realize the positron beam, a target of positron generation is put in the middle of the linac. A short pulse of 1 nsec makes possible a single-bunch operation of the ring. On the other hand, when the ring requires a multi-bunch mode of positron beam, the linac is able to deliver a semi-long positron pulse of a few tens nsec. For electron beam, the linac can provide 800 MeV short pulse (1 nsec) and about 250 MeV long pulse (2 usec). In addition, this design of linac makes possible an option, the production of slow positrons with a pulse length of 2 usec. The target for slow positron production will be located at the end of linac. When the ring is in a storage mode, the linac can provide slow positrons for material science experiments.

### Table III. Principal Parameters of the Linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron gun (200) kV (X)</td>
<td>10A</td>
</tr>
<tr>
<td>Klystron</td>
<td>80 MW (X) x 4</td>
</tr>
<tr>
<td>Number of SLED cavity</td>
<td>2</td>
</tr>
<tr>
<td>SLED output power</td>
<td>400 MW</td>
</tr>
<tr>
<td>Accelerator guide</td>
<td>3 m (x) x 10, 2 m (x) x 1</td>
</tr>
<tr>
<td>Total length</td>
<td>-about 60 m</td>
</tr>
<tr>
<td>Maximum repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Normalized emittance (electron)</td>
<td>100 (\pi) mm-rad</td>
</tr>
<tr>
<td>Normalized emittance (positron)</td>
<td>3000 (\pi) mm-rad</td>
</tr>
</tbody>
</table>

R&D's of BPM and RF-cavity are now underway. We have developed a BPM system that uses PIN diodes for switching and attenuating RF-signals from pickup electrodes. This system has already been installed in SOR-RING. The relative accuracy of the system obtained so far with a real beam of SOR-RING is horizontally 0.3 \(\mu\)m and vertically 0.4 \(\mu\)m [2]. With the BPM system developed, a global orbit feedback has been applied to SOR-RING. For the horizontal feedback the orbit is corrected by exciting the steering and by changing the RF frequency, while for the vertical feedback it is corrected only by exciting the steerings. The orbit drifts have been suppressed horizontally less than ten \(\mu\)m and vertically within a few \(\mu\)m; otherwise the orbit fluctuates around the order of 100 \(\mu\)m. The examples are shown in Figs. 14 and 15 of Ref. 1.

The R&D of RF-cavity is going well. The feature of the RF-cavity is that resistive material of SiC attached to both ends of the cavity is used for damping the HOM's. Two model cavities were made and their low power test was completed. The production process of SiC and the method of welding SiC to metal have been well studied. And further a hot model cavity that can store the same amount of RF power as the design value or more was fabricated last March. Presently about 100 kW RF power has been successfully stored in the cavity [3].

### References

3. T. Koseki et al., High Power Test of a Damped Cavity for High-Brilliant Synchrotron Radiation Source, in these proceedings.
DESIGN OF A BEAM-POSITION MONITOR CIRCUIT FOR THE KEKB INJECTOR


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Abstract

The PF linac is presently being upgraded for the KEKB project. In this project, stripline-type beam-position monitors (BPMs) are to be installed at every Q-magnet. The beam-displacement signals are to be processed by BPM circuits. The circuit must work with high stability under strong electromagnetic interference. Two types of narrow-band circuits have been investigated: one comprises a band-pass filter of 120-MHz center-frequency with a 3.2-MHz bandwidth; the other comprises one differentiating circuit and several-stage integrating circuits. The design and performance of BPM circuits as well as the design of the BPM electrode are discussed.

1. Introduction

The PF 2.5-GeV linac is being upgraded in order to meet the requirements of KEKB project. The electron-beam energy is to be increased from 2.5 GeV to 8 GeV, and that of the positron beam from 2.5 GeV to 3.5 GeV. The bunch charge of the positron beam is to be increased so as to be 20-times as intense as the present one. In order to realize this big increase of the positron beam, the primary electron beam must contain 10 nC/bunch. In order to suppress the transverse wakefield due to a high-current beam, the beam must be accelerated in the center axis of the accelerating structures.

BPM electrodes will be installed at every Q-magnet for measuring the beam displacement from the center axis. The BPM circuits are to be used near to the klystron modulators, which generate very strong electromagnetic noise, and must work stably in such an environment. Two narrow-band amplifiers have been studied for this purpose. One comprises a band-pass filter, and the other consist of an RC differentiating circuit and several-stage integrating circuits. In this paper, the latter one is mainly discussed as well as the performance of the BPM electrodes.

2. BPM electrode

The BPM electrode is made of stainless steel with four-fold symmetry; its dimensions are shown in fig. 1. All of the BPM electrodes are calibrated using a precise test bench. A 0.5-mm wire is used to simulate the beam line, and the BPM electrode on a movable stage is scanned in the plane of ±5-mm square around the beam line. The beam position is calibrated using the following formula:

\[ X = A_0 + A_1x + A_2y + A_3x^2 + A_4xy + A_5y^2 + A_6x^3 + A_7x^2y + A_8xy^2 + A_9y^3 \]

where \( x = \frac{V_1 - V_4}{V_1 + V_4} \) and \( y = \frac{V_2 - V_3}{V_2 + V_3} \).

We have measured all coefficients from \( A_0 \) to \( A_9 \) for 16 MPM-electrodes which have been installed in the linac system. In these coefficients, \( A_0 \) is an offset of the electrode and \( A_1 \) is often used for first-order approximation. Typical values for \( A_0 \) and \( A_1 \) were several ten microns and 8.59 mm, respectively. All coefficients from \( A_0 \) to \( A_9 \) will be stored in the computer system for calibration purposes.

3. Design of Circuits

The BPM circuits have four channels which measure outputs from \( V_1 \) to \( V_4 \). The linearity required in order to measure the beam position with a 0.1 mm accuracy is 1%. This specification is very hard, and none of the circuits described later satisfy this linearity. Further improvements should thus be made. We
also consider compensating the linearity using computer software.

The circuits are to be installed under very strong electromagnetic noise, the frequency spectrum of which has been measured. There is very strong electromagnetic noise under 20 MHz. Two types of narrow-band amplifiers with a pass band over 20 MHz have been investigated.

**Circuit-type 1**

We first designed a circuit which cover 65 dB. Though a 10 nC/bunch is the maximum accelerated charge, the BPM design covers twice this (20 nC/bunch), taking into account future improvements. The minimum charge in the specification is 0.64 nC/bunch for the positron beam, though 0.2 nC/bunch is for positron beam commissioning. Therefore, the dynamic range for the beam intensity is 45 dB, and a dynamic range of ±10 dB is added to it for beam displacement within ±7 mm. A dynamic range of 65 dB is divided into three overlapping ranges, each of which has 34 dB. The circuit comprises a band-pass filter, limiting amplifiers, a double-balanced mixer and a sample/hold circuit (1, 2). The dynamic range of the circuit is satisfactorily, but the linearity does not meet our requirement. The linearity will be compensated using a computer.

**Circuit-type 2**

The circuit described above covers all of the beam modes; a common circuit can be used through the linac. Other possible means is to make two types of circuits which can cover from the beginning of the linac to the positron target (10 nC/bunch-1.28 nC/bunch) and from the positron target to the end of the linac (1.28 - 0.2nC/bunch), respectively. Two types of circuits having different gain levels and the same dynamic range of 35 dB satisfy our requirements. In this alternative, we aim for simplicity and low cost of the circuits; also, a beam displacement within ±5 mm is assumed. If the circuit is simple and low cost, we can then make the same number of the BPM circuits as the BPM electrodes, and can measure one beam trace with one beam pulse; otherwise, several BPM electrodes will be connected to one common circuit through switches, requiring several pulses of beams to measure one beam trace. A beam-position measurement with one identical beam is very attractive and leads to a second circuit.

This circuit comprises a band-pass filter comprising an RC differentiating circuit and RC integrating circuits. A schematic diagram of the type-2 circuit is shown in fig. 2. The differentiating circuit is followed by three stages of integrating circuits. The output from the band-pass part is amplified and stretched. Figure 3 shows the input vs. output of the circuit. Pulse width of input pulse was 1 ns and horizontal axis shows attenuation of pulse generator. Band pass characteristics of the circuit are also shown in fig. 4. Center frequencies for both differentiating circuit and integrating circuits are 50 MHz. Although the stability of the circuit is satisfactorily, linearity of this circuit is worse than our requirement.

4. Conclusion

We have developed two types of BPM circuits. Type-2 has been investigated very recently, and has some room for improvements. It was very difficult to obtain a linearity better than 1% for both circuits. The linearity will be compensated for using a computer. Both will be tested in a real field from September, 1995.

References


2) H. Kobayashi, T. Urano, T. Suwada and A. Lazos; Proc. 20th Linear Acc. Meeting in Japan Osaka, Japan 1995, p. 245
Fig. 1. BPM electrode.

Fig. 2. Diagram of Circuit-2.

Fig. 3. Input vs. output of Circuit-2.

Fig. 4. Band-pass characteristics of Circuit-2.
DEVELOPMENT OF AN ION IMPLANTED THIN ALUMINA BEAM PROFILE MONITOR

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Abstract

It is very important to get a real image of the beam from the injector linac. Therefore, it is desirable to monitor the beam position and beam profile as well as the beam current in the linac. Alumina screen (Desmarquest AF995R, chromium-activated alumina ceramics), is often used as a beam profile monitor for diagnosis of a linac beam. Typical thickness of alumina phosphor screen is about 1mm. Especially for the low energy beam part of the linac, scattered electrons in such a thick screen produce enlarged beam profiles. A thin film phosphor screen with chromium ion implanted alumina has been designed and manufactured to produce a high-precision beam profile monitor.

1. Introduction

The demand of a low-emittance electron linac has increased in these years, for applications such as the free-electron laser, coherent synchrotron radiation, and others. It is very important to transport and accelerate the beam emitted from the cathode with negligible emittance growth.

There is some attempt to build up an emittance measurement system for a low emittance beam. A plastic scintillator which is 10 μm thin and has a fast scintillation characteristic has been adopted to measure the beamlets' image with a high temporal and spatial resolution. Silver (30 Angstrom thin) was deposited on the scintillator surface by vacuum evaporation to avoid charge-up. This experimental set up is for off-line use. An inorganic scintillator with thin thickness is necessary for the injector linac.

We try to make an oxide layer on aluminum surface. With ion implantation technique, we could get a polycrystalline ruby in oxide layer on aluminum surface. As the first trial, we have made preliminary experiments to show the possibility to make nearly 10 μm thin oxide layer on aluminum and to make polycrystalline ruby layer on alumina with chromium ion implantation technique.

2. Experimental

The aluminum anodizing technique has been established and is widely applied to metal surface technology to coat or color the surface of aluminum. We applied this technique to produce thin film scintillator.

Aluminum plates of purity 5N were electrically polished in a 3N NaOH bath at room temperature with a dc density of 500 mA/cm². Reactions are as follows,

Anode

$$2\text{Al} + 3\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 6\text{H}^+ + 6\text{e}^-$$

Cathode

$$6\text{H}^+ + 6\text{e}^- \rightarrow 3\text{H}_2$$

The average direct anodic current was fixed at 20 mA/cm². Thickness of alumina layer as a function of oxidation time is shown in Figure 1.

![Figure 1. Thickness of alumina layer as a function of oxidation time.](image-url)
Compared with other methods (for example, vacuum evaporation technique or sputtering technique), one could easily get a nearly 10 μm thick oxide layer with reasonable time by the aluminum anodizing technique.

Alumina plate of thickness 0.125 mm purchased from ASAHIKASEI Co. was prepared as a starting material. Purity of alumina was 99.9 wt. % Al₂O₃. Specimen size was 20 mm x 20 mm. Specimens were implanted at room temperature with 200 keV or 800 keV chromium to fluences in the range 1 x 10¹² /cm² - 1 x 10¹⁶ /cm². Chromium ion implantation profiles have been generated for alumina using the simulation code TRIM. Figure 2 shows the implantation profiles for 10 keV to 1 MeV chromium ions in alumina.

3. Results

Optical measurements were done with specimens as implanted. Compared with Desmarquest AF995R, no light emission from implanted alumina was observed yet. Naramoto et al.4) pointed that in the temperature range of 1200 °C to 1300 °C, substitutional damage recovery has taken place in both the Al and O sublattices, and at these temperatures, one begins to see significant Cr incorporation into substitutional lattice sites. Recovery process is necessary to get emission from this specimen.

References
2) M. Miyagi et al., Applied Optics Vol.26, No.6, (1987) 970
3) D.G.W. Goad and M. Moskovits, J. Appl. Phys. 49 (5) (1978) 2929
4) Naramoto et al., J. Appl. Phys. 54 (1983) 583

Fig. 2. Implantation profile of Cr in Al₂O₃.
Development of Visual Beam Adjustment Method for Cyclotron

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Abstract

We have developed a computer-based visual assistance system for JAERI AVF cyclotron operation. This system provides a CRT display about the cyclotron beam trajectories, feasible setting regions (FSRs), and search traces designed to improve beam parameter adjustment. As a result of the test in actual operation, it was realized that simulated beam trajectories and FSRs nearly agree with actual beam conditions.

1. Introduction

A cyclotron design requires a large number of physical theories, calculation codes and analysis of the beam trajectory. These codes and analyzed results have not been used in actual operation. For a new cyclotron control technique, we have developed a computer-based visual assistance system\(^1\) for the JAERI AVF cyclotron\(^3\) by using the above codes. To examine the reliability of this system, the result of the simulation was compared with that of the actual operation.

2. Human Interfaces

The visual assistance system provides three functions of human interfaces for beam parameter adjustment; (a) Beam trajectory is rapidly calculated and graphically displayed whenever the operators change the cyclotron parameters, (b) Feasible setting regions (FSRs) of the parameters which satisfy beam acceptance criteria of the cyclotron's are indicated, (c) Search traces, which are historical visual maps of beam current values represented by various colored dots, are superimposed on the FSRs.

The system has been applied to three blocks of the cyclotron: the axial injection, the central region and the extraction. This system is constructed by the language of C and works on workstation of VAX-3100 connected through Ethernet with computers controlling\(^4\) the cyclotron.

3. Evaluation of Simulation

3.1 Axial Injection Block

The axial injection block is a region between the bottom of the cyclotron yoke and the inflector. There are four Glaser lenses (GLs) with adjustable focal lengths. The beam is led into the cyclotron by adjusting these lenses through a small gap of the inflector entrance. The FSRs are limited mainly by the geometry of the inflector entrance.

We have compared the human interfaces with the results of actual operation in the accelerating conditions of H\(^+\) 45 MeV (harmonic mode 1: h=1), H\(^+\) 10 MeV (h=2) and \(^{40}\)Ar\(^{8+}\) 175 MeV (h=3). It was found that there was a discrepancy between the simulated FSRs and the search traces obtained in actual operation. The simulated beam trajectories deviate from the search trace just after last GL. This deviation is caused by the leakage of magnetic field from the main magnet.

3.2 Central Region Block

The central region block is followed by the axial injection block. The first turn of the beam trajectory after the inflector is determined in this block. The adjustable parameters in this region are dees voltages, trim coil currents and the phase of beam buncher voltage. These parameters are adjusted so that the beam passes through two sets of phase slits. The beam trajectory and FSRs are calculated as functions of these parameters and magnetic and electric field data. The FSRs are limited mainly by the geometrical condition of the phase slits.
Fig. 2 Beam trajectory simulation at the extraction block.
The spiral beam trajectory is shown as a stretched line in this diagram.

At the first place, we have compared the position of actual beam trajectory with the simulated beam one to evaluate the simulation model of beam trajectory. The actual beam positions were measured by the following methods: (a) Searching a beam position of the maximum beam current monitored at the main cyclotron beam probe by moving the phase slit, (b) Searching a beam position by measuring turn patterns using the main probe. Figure 1 shows the top view of a cross section of this block and a simulated trajectory in a solid line and actual slit positions. The trajectory passes through the actual slit positions. The simulations are in good agreement with the actual condition.

We have tested the system for different values of the magnetic field of the central region and the phase of beam buncher voltage. The intensities of magnetic bump field produced by circular trimming coils little influence the position of actual beam trajectory. The beam phase dependency on the beam position could not be measured because the beam intensities were decreased drastically in changing phase of the beam buncher.

3.3 Extraction Block

The beam in the final turn is led into the deflector and the magnetic channel, deflected from the circular orbit, and finally extracted from the cyclotron. In this block, the system simulates the deflected beam trajectory. At the first step, the beam trajectory entering the deflector is calculated on the basis of the magnetic field data and two beam positions detected by the main and the deflector probes. At the second step, the beam trajectory in the deflector and the magnetic channel is simulated on the basis of the deflector position, the deflecting field and the magnetic channel field. The FSRs were calculated as functions of the above parameters, and the clearance of the deflector and the magnetic channel.

An example of simulated beam trajectories for nominally 20 MeV $^4$He$^{+2}$ ions is shown in Fig. 2. We have executed simulations to obtain the beam trajectories, passing through the exit of the cyclotron, for several beam energies. The most suitable energy for the trajectory in actual operation condition is in a range from 18.98 to 19.06 MeV. On the other hand, the beam energy is evaluated at 19.10 MeV (-4.5%) from the magnetic field of the analyzing magnet after the cyclotron. The simulated beam energy is in agreement with the beam energy measured by using analyzing magnet.
mm. A deflector probe provides the beam intensity before the deflector. A magnetic channel probe provides the beam intensity after the passing through the deflector. We have tried to estimate the beam energy by following techniques.

1) Orbit radius method; The beam position is measured by the main radial probe. The energy (E) is evaluated from the simulated trajectories passing through the exit of the cyclotron. As shown in Fig. 4, the beam energies depend on the beam positions of the final turn trajectory.

2) Three point method; The beam positions in the three points were measured by the main probe, the deflector probe and the magnetic channel probe, respectively. The beam energy (E') is estimated from simulated beam trajectory passing through the above three points.

Figure 5 shows the relation between the energy E and the estimated energy E'. The solid line shows the energy estimated experimentally and the dotted line shows the ideal one. The result of estimations for beam energy, data has an uncertainty within ±2% from linear approximation formula.

4. Upgrade of the System

Application of the system has been limited to several accelerating conditions of ion beams. In the early stage of development, it is not required to execute simulations for all the available particles and energies. At present, this system has been upgraded to simulate the beam trajectories and FSRs in all accelerating beam conditions for the JAERI AVF cyclotron. We can obtain the operating parameters for new ion acceleration by using the new system.

5. Future Activity

Precise comparison of the simulated beam trajectory and the actual beam trajectory is planned for the extraction block in new accelerating conditions. The extracted beam energy will be measured accurately by other methods, such as kinematics and TOF method. It is expected that the result will be fed back to improve the system. We will expand this technique to the beam transport system.

6. References

CONTROL SYSTEM FOR THE JAERI TANDEM ACCELERATOR

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Abstract

A new control system for the JAERI tandem accelerator has been developed using concurrent programming and multiprocessor technology. There are eight transputers in the system including front end processors of CAMAC serial highways. This paper reports an experience of the development and the operation of the system.

1. Introduction

The JAERI tandem accelerator[1] had been controlled by a traditional minicomputer since 1979. However, we had some difficulties to stay on the old base. They are the difficulty in maintenance of the old-fashioned computer and shortage of the computing power for a further expansion of the system. So, we have developed a new control system to replace old one.

In the new system we use concurrent processing technology using multiple microprocessors. In a logical aspect, a control of a particle accelerator is a set of various processes controlling and/or monitoring many control objects, that is to say, accelerator devices. Those processes are not strongly coupling each other and have logical concurrency. This implies that the
control system is a good field of application of concurrent processing technology. Using multiple processors, a merit of concurrent processing is enhanced in the system performance.

2. Overview of the System

The control system is using transputer[2] and concurrent processing technology. We call the system ACCELL[3]. Figure 1 shows a block diagram of the new system. The new system consists of 1)a host system using a work station, 2)a central system, 3)serial highway drivers, 4)a CAMAC serial highway system[4,5] and 5)two personal computers. The main roles of the host system are to support execution of the central system and to work as a part of a man-machine interface. Data of the central system needed to control the accelerator are loaded from the host. A bit map display of the host is embedded in the operator console of the accelerator. Programs based on X-window system[6] are used on the display. Connection to the central system is an INMOS link[2] and a S-bus link adapter. The host system is also used as a file server. The central system is a multi processor of four T800 transputers[2] with local memory of one mega bytes to 16 mega bytes. It works as a main element of data processing. We can change number of transputers to optimize loads of transputers. The serial highway drivers are front end processors of the central system to CAMAC system. Transputers are also used in the drivers. They have charge of low level control of the CAMAC serial highways. CAMAC serial highway system is almost the same as the old system. Nineteen CAMAC crates are distributed on the four serial highways. Two of the crates are dedicated to the control console. The control console has assignable valuators, which are called shaft encoders, assignable and dedicated meters etc. to control and monitor data points. Programming languages for the transputers are parallel C(INMOS ANSI-C)[7] and OCCAM2[8,9]. Programs of the transputers are developed on the personal computers. They are also used for monitoring a system operation.

3. Early Experience of Operation and Improvement of the System

The first version of the new system had started daily operation for the accelerator control in October of 1992. The reliability of the system has been good enough. But, performance of message transfer between concurrent processes in the system was not so good as expected. In the system, messages between application processes are transferred through processes named monitors.

In October of 1993, the performance of the message transfer was greatly improved from about 2 milliseconds to about 0.3 milliseconds per one message transfer. In the work, We analyzed program execution times of several instructions of the transputer and used new programming technic for better performance. So we could make the improvement without any change of external specifications of the monitors.

A new function of linked control using a virtual data points[3] was tested in March of 1994. The virtual data point named final energy(Ef) and its control process, scaling process, were installed in the test. It was intended to work as that a change of Ef reflects to several data points by the scaling rule[10] process, in the manner that beam transport of the accelerated particle is maintained and the final energy is set equal to setting value of Ef. The mechanism follows not only to a step of the change but also to the continuous change of the virtual data point. Some mismatch between valuators of the control console and the new function was found by the test. On the other hand, it was shown that system performance of message passing and calculation was enough for smooth operation. Introduction of the function into daily machine operation should be suspended till improvement of the valuators.

4. Development of the Concurrent Program

We have used OCCAM and Parallel ANSI-C as programming language. Concurrent programming enables us programming through natural modeling of the target
system that has intrinsic concurrency. It is a most important advantage of the concurrent programming. On the other hand, programming of the concurrent system has only a limited length of history in a practical world. Methodology of the programming is not well known yet. Especially, there is a problem about a deadlock in the world of concurrent programming. It is a situation in which two (or more) processes mutually wait for the other process to become ready to receive messages and the processes cannot execute further operations. A small mistake in the programming introduces probability of the deadlock. Programmers sometimes cannot follow action of the system where several processes running concurrently. We needed training different from usual sequential programming. We met several additional difficulties about development tools etc. In spite of the difficulties, the concept of concurrent programming has been attractive one.

References

A TREATMENT BEAM CONTROL SYSTEM FOR IRRADIATION GATED BY RESPIRATION OF A PATIENT


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Abstract

A beam control system for irradiation treatment gated by respiration of a patient has been developed at HIMAC to minimize an unwanted irradiation to normal tissues around tumor. The system employs rf-knockout extraction with gate function. Preliminary experimental results, which were carried out with moving phantom and simulating signal of respiration, are encouraging.

1. INTRODUCTION

Clinical trial has been successfully progressing since June 1994, after commissioning of a heavy ion accelerator complex, HIMAC, dedicated to medical applications [1].

A high irradiation accuracy is required in heavy ion therapy because of the high dose localization. In treating a tumor moving along with respiration of a patient, in particular, damage to normal tissues around tumor is inevitable without beam control that gates irradiation according to respiration. A beam delivery scheme, which can respond to irregular respiration, should be applied in order to minimize the unwanted irradiation to normal tissues around tumor. At HIMAC, therefore, such a system has been developed [2,3].

The design considerations and the preliminary experimental results are reported in the paper.

2. BEAM CONTROL SYSTEM

A beam control system for the irradiation gated by respiration requires essential design considerations as follows. (1) Beam extraction method should respond quickly to a trigger signal according to irregular respiration. (2) Operation pattern of synchrotron should give maximum irradiation dose rate. (3) An aborting system of residual beam should be provided in order to avoid undesired activation by unused beam.

2.1 Extraction method

Concerning the irradiation gated by respiration, it is important to start and stop beam extraction promptly according to the beam "on/off" signal. One of the suitable extraction methods for this purpose is beam extraction using a transverse rf field resonated with a horizontal betatron tune, while a separatrix is kept constant, which is called "rf-knockout extraction". The transverse rf electric field is applied with frequency and amplitude modulation. The frequency modulation increases an extraction efficiency because it broadens a frequency bandwidth corresponding to a horizontal tune spread at a resonant extraction. The amplitude modulation is applied to control a spill envelope of an extracted beam. Advantages in the present method are 1) prompt response to start and stop of the beam extraction because of using an rf electric field with a faster response compared with magnetic elements, and 2) a small emittance in the horizontal direction due to a constant separatrix. The results from experiments showed that the response is within 1ms and the horizontal emittance of beam extracted by the present method was reduced by about 70% compared with that by the ordinary extraction method. The extraction efficiency in the present method was more than about 85% which was comparable with that in the ordinary method. The details were reported in Ref. [2].

2.2 Operation pattern of synchrotron

To optimize an operation pattern of synchrotron, it is assumed that a respiration pattern is independent of an operation pattern of synchrotron, and an irradiation for treatment is continued infinitely. Under the condition, an irradiation dose rate is maximized at an extraction duty factor of 50%, because a beam can be extracted as long as the extraction period is coincident with an irradiation period permitted by the respiration pattern. If the extracted beam intensity can be infinitely increased, on the other hand, the dose rate is increased as increasing the duty factor. At HIMAC, therefore, the dose rate is maximized at the duty factor of 50% in the 0.3Hz operation of synchrotron. The effective dose rate in this operation can be kept at the operational value if the extracted beam intensity is increased by 70%, which will be easily realized.

All of the accelerated beam should be extracted
as soon as the extraction signal is generated, to reduce effective irradiation period. On the other hand, an irradiation period more than 10 times longer than that of wobbling magnets is required to obtain a uniform dose in the lateral distribution. The amplitude of a transverse rf field is determined so that all of the accelerated beam is extracted during about 400ms in order to satisfy the above requirements.

2.3 Beam aborting system

In the irradiation gated by respiration, the residual beam has to be aborted around synchrotron, because the accelerated beam should not be extracted from synchrotron as long as a "beam off" signal is generated. Decelerating the residual beam to an injection energy as a beam aborting system is proposed to avoid unwanted activation around synchrotron. As a result of the preliminary test, the deceleration efficiency was about 80%. Details will be presented elsewhere[4].

Summarizing the above considerations, an operation pattern of the beam control system for the irradiation gated by respiration is schematically shown in Fig. 1.

3. EXPERIMENTAL RESULTS

An irradiation gated by respiration was preliminarily experimented by using a phantom moving along with a simulating signal of respiration [3]. In the experiment, synchrotron is operated by a cycle of 0.3Hz with a duty factor of 45%. Carbon beams with the energy of 290 and 400MeV/n are extracted from synchrotron by the rf-knockout method, and delivered through an irradiation system to an isocenter at a treatment room. Concerning the experimental setup in the treatment room, a phantom placed at the isocenter is moved with a stroke of 25mm and, is driven by a 0.33Hz sinusoidal wave that pretends respiration. The simulating signal is generated by a sensitive strain gauge set on the phantom. A collimator with an aperture of 40mm square is placed in front of the phantom in order to define an irradiation field, and is 450mm distant from the phantom.

Figure 2 shows a typical result of a beam extraction gated by the simulating signal. As can be seen in the figure, the beam was successfully extracted in only the permitting irradiation signal. A penumbra size was also obtained by measuring z density of an exposed X-ray film attached with the phantom moving along with the simulating signal. Three cases, i.e., a fixed phantom, a gated irradiation to moving phantom, and an ungated irradiation to moving phantom were investigated as shown in Fig. 3. The penumbra size $P_{80-20}$ in three case were obtained as 2.4, 6.1 and 19.4mm, respectively, where $P_{80-20}$ is defined at the distance of the lateral dose falloff from 80% to 20%.

The $P_{80-20}$ in the fixed phantom is naturally less than that in the gated irradiation, because the phantom in the latter case moves somewhat during the irradiation due to applying a sinusoidal wave as the simulating signal. However, the $P_{80-20}$ in the gated irradiation is considerably reduced to 6.1mm from 19.4mm in the ungated irradiation.

4. CONCLUSION

The beam control system for irradiation treatment gated by respiration is developed. The beam control system's ingredients are; rf-knockout extraction that can respond to a respiration signal quickly, a 0.3Hz, 50% duty operation of synchrotron that maximizes dose rate, and a beam deceleration as a beam aborting system.

As preliminary results of experiment, an extraction gated by a simulating signal of respiration was successfully achieved. The penumbra size was also measured by using a phantom moved along with the simulating signal, and was considerably reduced to 6.1m from 19.4mm in the ungated irradiation. The system will play an important role in clinical study such as treatment for a lung or liver cancer moved along with respiration of a patient.
Fig. 2 Beam extraction gated with the simulating signal of respiration in 400MeV/n carbon beam.
(a) Simulating signal of respiration, (b) Beam spill, (c) Operation pattern of synchrotron, (d) Permitting irradiation signal.

Fig. 3 The lateral dose distribution in 290MeV/n carbon beam. (a) fixed phantom, (b) gated irradiation to moving phantom, (c) ungated irradiation to moving phantom.

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6. REFERENCES

DEVELOPMENT OF 3-DIMENSIONAL IRRADIATION SYSTEM FOR HEAVY-ION RADIATION THERAPY

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Abstract

A three-dimensional irradiation system using a broad beam was installed at HIMAC facility for a heavy-ion radiation therapy. The thickness of the wedge absorber and the shape of the radiation field made by the multi-leaf collimator were changed during irradiation in order to sweep the Bragg peak only in the target area. In this report we discuss the three-dimensional irradiation system of HIMAC and also results of preliminary irradiation tests using $^{12}C$ beams.

1 Introduction

It is one of the most important goal of any radiotherapy to shape the treatment volume as exactly as possible to the tumor as the target volume. In most cases a sharp cutoff of the dose is needed in order to spare the surrounding healthy tissue or critical structures to a maximum extent. It is necessary to use a flat-top depth-dose distribution extending several centimeters, even tens of centimeters to encompass solid tumors. For this purpose heavy ion beams are delivered to the treatment volume by the beam scanning method [1] or the broad beam method. The clinical port at HIMAC facility is designed by the latter method and shown in fig.1. The system consists of a pair of wobbler magnets (a), a scatterer (b), a ridge filter (c), a range shifter (d), a pair of wedge absorber (e), a multi-leaf collimator (f), a compensator (g) and a monitor system. The wobbler magnets and the scatterer are used for spreading the beam uniformly over the radiation field [2]. For 2-dimensional irradiation, the ridge filter is used to spread the sharp pristine Bragg peak. A spread-out Bragg peak (SOBP) is made by superposing shifted Bragg peaks with suitable superposing ratio. Irregular shape of radiation fields are obtained by blocking the uniform beam with the multi-leaf collimator. Fine adjustment of heavy ion range in patient is performed by the range shifter. And the compensator is used for adjusting position of the distal part of the target.

For a tumor conform treatment, a 3-dimensional irradiation using a synchronized fast sweeping technique is also possible in HIMAC irradiation system and presently developed. This novel technique implies some important advantages. The 3-dimensional dose distribution can be shaped exactly to the tumor volume in order to prevent particles from depositing their biologically very effective dose outside the target volume. Using the sweeping technique, complex 3-dimensional scanning procedure is no longer needed saving irradiation time. And the system can be extended from the present 2-dimensional irradiation system reducing the costs. In the following the principles of the 3-dimensional irradiation are discussed and the first results obtained with the system at HIMAC are presented.

2 Method of 3D irradiation

Figure 1: Schematic diagram of HIMAC irradiation port. Devices labeled (a)~(g) are explained in text.

Figure 2: Illustration of Three-Dimensional Irradiation.
made by the wobbler magnets and the scatterer in the same way of the 2-dimensional irradiation. “Slightly” spread-out Bragg peak (we call it s-SOBP in this paper) is made by the ridge filter. The s-SOBP is shifted by inserting the wedge absorbers in the beam course. By combination of the two wedge absorbers, the total thickness of the absorber is uniform in the radiation field. A SOBP that should be conformed to a target shape (we call it total-SOBP in this paper) is made by superposing shifted s-SOBP by changing the absorber thickness during the irradiation with suitable superposing ratio. During the sweep of the s-SOBP in the target region, needless part of the irradiation field can be cut by adjusting the irradiation field with the multi-leaf collimator.

In order to realize this conformation therapy, we have to develop the fast movements of the wedge absorbers and the multi-leaf collimator and their synchronism. Specifications of the wedge absorber and multi-leaf collimator installed at HIMAC are shown in fig.3.

[Wedge Absorber]

![Wedge Absorber Diagram]

Sliding Wedge Absorber

- Height: 75 mm
- Width: 750 mm
- Sliding Speed (max): 270 mm/s
- Position accuracy: 1.25 mm

[Multi-leaf Collimator]

![Multi-leaf Collimator Diagram]

- Field Size: 150 x 220 mm
- No. of Leaves: 23 x 2
- Leaf Material: Iron
- Pitch of Leaves: 6.5 mm
- Leaf thickness: 140 mm
- Sliding speed: 80 mm/s

Figure 3: Specification of wedge absorber and multi-leaf collimator.

3 Measurement of dose distribution

The first test of the 3-dimensional irradiation confirming with eyes was carried out using 290 MeV/n carbon beam. The target volume was assumed to be a ball of 7 cm in diameter, which is embedded in Polymethyl methacrylate (PMMA) material. To monitor the beam profile in the target material, a ZnS screen was inserted between PMMA blocks and placed almost parallel but slightly tilted to the beam direction. The movements of the wedge absorbers, the multi-leaf collimator and also the beam profile along the beam axis were recorded by video camera. In each slice scintillation light from the ZnS screen lay almost within the target area and results were satisfactory.

For the quantitative test of the performance of the 3-dimensional irradiation, a depth dose distribution was measured for 10 cm width total-SOBP using 290 MeV/n carbon beam. The SOBP was designed to make a uniform biological dose distribution using a thick ridge filter (ridge filter A). The 5 mm width s-SOBP was made by a thinner ridge filter (ridge filter B) that was used to make a uniform biological dose distribution. Three types of radiation fields were made:

(a) 10 cm width SOBP directly made by 2D irradiation using the ridge filter A
(b) 5 mm width SOBP made by 2D irradiation using the ridge filter B
(c) 10 cm width total-SOBP made by 3D irradiation using ridge filter B.

In each irradiation the physical dose was measured with a standard ionization chamber. The preliminary results for the depth dose distribution are shown in fig.4. Open circles, diamonds and closed circles represent measured physical dose of (a), (b) and (c), respectively. Lines are calculated depth dose distribution. The measured dose by 3D irradiation were slightly larger than those by 2D irradiation. However, measured and calculated results by 3D irradiation were agreed among themselves. This shows that the total-SOBP realized by 3-dimensional irradiation method can be improved by optimizing the shape of the s-SOBP.

Figure 4: Measured and calculated physical dose distributions.
To reproduce the 2D SOBP ((a) in fig.4) using the 3D irradiation, a new ridge filter for the modulated s-SOBP of 5 mm in width was designed. Figure 5 shows the calculated results for the physical dose distribution. It is seen that the total-SOBP of the modulated ridge filter is closer to the 2D results (within ±4.6 %) than those of the ridge filter B. Needless to say that the further study is needed to optimize the shape of the s-SOBP and other test experiments using the 3-dimensional irradiation method with the modulated ridge filters are planned. In order to evaluate the quality of the radiation field made by the 3-dimensional irradiation (uniformity, penumbra), the monitoring systems for the dose distribution have to be developed. For this purpose we have planned to develop a proportional chamber (for 1-dimensional distribution), a silicon strip detector (for 2-dimensional distribution) and a pile of ionization chambers (for 3-dimensional distribution).

4 Concluding remarks

An irradiation system of 3-dimensional conformation therapy was designed and installed at HIMAC facility. The 3-dimensional irradiation for a ball shaped target of 7 cm diameter was performed using 290 MeV/n carbon beam. The wedge absorbers and the multi-leaf collimator were controlled satisfactorily during the irradiation for conformation therapy. Preliminary results of a dose distribution of the 10 cm SOBP made by superimposing 5mm width SOBP using the sliding wedge absorbers was obtained to check the function of the wedge absorbers.

In order to improve this system, we plan to develop the optimizing methods to design a ridge filter and the dose measurement methods.

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References

PHYSICAL STUDIES OF BEAM DELIVERY SYSTEM FOR PROTON AND HEAVY ION TREATMENT

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Abstract

We report design and optimization of beam delivery system for proton and heavy ion particles, which will be constructed in charged particle therapy facility in Hyogo Prefecture. Penumbra sizes were calculated for different systems to optimize device parameters under considering effects of multiple scattering and energy loss of beam. It was found that penumbra size of carbon ion beam was about three times smaller than that of proton, and that devices which affect physically in particle delivery system should be placed as upstream as possible to reduce penumbra size.

1. Introduction

It is reported here the results of physical investigation for beam delivery system using proton and heavy ion beam to construct facility of charged particle therapy in Hyogo Prefecture. In this facility, the three fixed beam ports which deliver proton and heavy ion (helium and carbon) beam and a rotatable gantry using proton are planned for treatment issue. The beam delivery system which include such beam ports and gantry have not yet been constructed in Japan.

In the design of the beam delivery system, important devices are wobbler magnets, scatterers, ridge filters and range shifters, because they scatter beam particles and affect penumbral size. Position of these devices are investigated, assuming sizes of the devices which are slightly different from those used in Heavy Ion Medical Accelerator in Chiba (HIMAC) in National Institute of Radiological Sciences (NIRS) but structures of them are almost same as those in HIMAC. Penumbras of the delivery systems which were designed under specification were calculated. Since it is necessary for accurate treatment that penumbras are to be as small as possible, the goal of their size is about 2 mm.

2. Design of the beam delivery system and calculation for penumbras designed

In calculating penumbra, the method developed in NIRS was employed. Physical meaning of the calculation is as follows. Particle distribution is obtained as an approximated solution of the Boltzmann equation. In this case, multiple scattering and energy loss are assumed when particles pass through material in the devices of the delivery system. Fermi and Eyges showed that radial deflection and its angle of the particles passing through materials under those assumptions could be calculated. At the formulation, the quantity D which corresponds to the emittance squared in the beam transport are to be written as

\[ D = \varepsilon_y^2 \frac{\varepsilon_{\phi}^2}{\varepsilon_{\phi,2}^2} + \varepsilon_{\phi,2}^2 \]

where \( \varepsilon_y^2 \) and \( \varepsilon_{\phi}^2 \) are the variances of \( y \) and \( \phi \), respectively and \( \varepsilon_{\phi,2}^2 \) is cross term. It is important that effects of multiple scattering and energy loss are already included in them. \( D \) is calculated by \( \varepsilon_y^2 \), \( \varepsilon_{\phi}^2 \) and \( \varepsilon_{\phi,2}^2 \) which are values on the material at each grid point segmented small enough along the beam direction. Penumbras \( P_{10\%} \) are to be written as follows;

\[ P_{10\%} = 1.68 c_y L_c \]

\[ c_y^2 = D/\varepsilon_y^2 + \varepsilon_{\phi,2}^2 \left( \varepsilon_y^2/\varepsilon_{\phi,2}^2 - 1/L_{\phi}^2 \right) \]

where \( L_c \) and \( L_{\phi} \) are the distances from isocenter to collimator and wobbler magnet, respectively. Here the quantitative definition of the penumbra is the distance between 80 % dose point compared to the dose of isocenter and 20 % point of that on lateral dose distribution. This calculation method have much advantage for its analytically solved results than the usually used Monte-Carlo method, because it is easy to understand about the effect of positions of the devices and materials and takes much less times to calculate. For example of position of the devices, it is important to place a collimator to a patient body as close as possible. The results of this method for beam delivery systems in HIMAC have been found to agree within 1 mm or less, which is about 16 % of the penumbra size measured by X-ray photograph.

Figure 1 shows an example of fixed beam port used for proton and heavy ion beam. Calculations for this system were made for 165 and 230 MeV energies of proton and 320 MeV/u energy of carbon ion beam. Figure 2 shows an example of rotatable gantry for proton only. Calculations for this gantry...
were made for 165 MeV energy of proton beam. Maximum range of each kind of beam through these delivery systems are about 17 cm for both 320 MeV/u carbon ion and 165 MeV proton beam and about 30 cm for 230 MeV proton, respectively. Distance, \( L_c \), between collimator and isocenter was set to be 40 cm.

3. Results and discussions

Firstly, for the fixed beam delivery system shown in the Figure 1, field radius, maximum range and spread out Bragg Peak (SOBP) width were set to be same in carbon ion and proton beam. The maximum range and SOBP width were taken as 17 cm mentioned above and 6 cm, respectively. Dependence of penumbra size on field radius which was adjusted by scatterer thickness and radius of wobbler were estimated. It was found that the dependence was small but the absolute value of penumbra in the case of proton beam were about three times larger than those of carbon ion beam in the same range. The results are shown in Figure 3. It was also demonstrated that the heavier ion, such as carbon, can perform more accurate treatment.

In next step, effects of scattering in compensator and inside of a patient body were estimated. For simple studies, water was placed after a collimator and its thickness was changed. Water is often used in estimation of scattering in compensator and human body, because density of water is almost the same as polyethylene which is the material of compensator and as a human body. Figure 4 shows the dependence of penumbra size on water thickness in this calculation. It was found that the size of penumbra caused by scattering in the body was smaller than that by the delivery system. It was also shown that the effect of scattering in the compensator was much smaller than that in the body because of difference of path length. As is in the Figure 3, absolute penumbra size of proton beam in the Figure 4 was also found to be about three times larger than that of carbon ion.

In the last study, penumbra size was calculated by changing the position of ridge filter in the gantry shown in the Figure 2 for proton. The results are shown in Figure 5. It can be seen that the distance between scatterer and ridge filter is longer, the penumbra size is larger. The dependence of penumbra size on the positions of devices which scatter beam particles is not only for ridge filter position but also for those of scatterer and range shifter. Scatterer, ridge filter and range shifter should be placed closely each other and as upstream as possible, and the distance from range shifter to the isocenter is to be taken as long as possible. However, it is much difficult in working upon the ridge filter, because the thickness and gaps of the ridges should be much smaller. Selection for material which is easily worked upon or oscillating bar ridge filter and rotating spiral ridge filter are to be taken into account.

Three-dimensionally conformed (3-D) irradiation system is under planning in this facility, because it has much advantage for dose localization. Searching parameters of devices in beam delivery system for adjusting irradiation field can also be simplified using the 3-D system. Dynamic 3-D system without devices which scatter particles and absorb energy of the beam will be installed in this facility to use maximum range of initial beam energy and minimum penumbra size by initial emittance.

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Figure 2. Rotatable gantry for proton beam. Total length shown here is 350 cm.

Figure 3. Dependence of penumbra size on field radius at 6 cm of SOBP width.

Figure 4. Dependence of penumbra size on water thickness. Water is placed downstream of collimator.

Figure 5. Dependence of penumbra size on ridge filter position in gantry for proton.
DOSIMETRY SYSTEM FOR HEAVY-ION RADIOTHERAPY

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Abstract
This paper describes a dosimetry system for the heavy-ion radiation therapy installed at HIMAC facility. Daily check of the dose monitor, a species of the accelerated particles, their energy are carried out every morning. And the dose calibration of the monitor for each patient condition are also carried out every morning. The variations of the monitor responses were less than 2% during 3 months of treatment term. In order to shorten the time for the check, a simplified dosimetric system for the dose calibration of the monitor was installed from this autumn.

1. Introduction
A radiation therapy using a carbon beam has been started at HIMAC facility from last year[1]. The heavy-ion radiotherapy is expected to be superior to the conventional radiation because of its excellent dose localization and its high biological effectiveness. Then, it is important to irradiate patients as previously planned by a treatment planning system. Around 18 times of exposures are given to the same patient in the heavy-ion radiotherapy. And it takes over one month to finish the treatment. It is necessary to guarantee daily exposure dose to be the planned exposure. In order to guarantee these things, the check of the dose monitor, a species of the accelerated particles, and their energy are carried out every morning. The dose calibration of the monitor for each patient condition are also carried out every morning. These check is very important for the assessment of the irradiation port.

In this paper, the dosimetry system for the heavy-ion radiation therapy installed at HIMAC facility is presented and discussed in detail.

Fig. 1. Illustration of the therapeutic beam port

2. Monitor system
In the HIMAC irradiation course for the radiation therapy, 5 monitors are installed. Fig. 1. shows the illustration of the therapeutic beam port of HIMAC and indicates the location of the monitors in the beam course[2]. Monitors which are shown as up-stream 1,2 and down-stream 1,2 are the parallel plate ionization chamber. The up-stream chamber has two signal electrodes and three high voltage electrodes of the parallel plate ionization chamber. The one signal is fed into a high-
speed amplifier and used for monitoring the time structure of the beam. The other output signal is fed into I/F converter which output a pulse for every 1000 pC. The pulse train is input to a preset counter which is connected to a beam shutter for controlling the exposure dose to the patients. We have another dose controlling monitor, SEM (Secondary Emission Monitor). We have anxiety that beams may have a big spike in the beam spill. In that case, accurate dose can not be measured by the ionization chamber monitor because of recombination effects in the big spike. Then, we used the secondary emission chamber for the back-up of the ionization chamber.

At just up-stream of the beam collimator, a down-stream monitor was placed. The monitor is also a parallel plate ionization chamber, and has one signal plane which is sandwiched by two high voltage electrodes. On one side of the signal plane, there are 29 signal electrodes of 20 mm in diameter which are distributed in the guard earth. This ionization chambers are used for roughly monitoring the uniformity of the irradiation field. The other side of the signal plane of the down-stream chamber is a signal electrode which cover the whole uniform irradiation field. This output is used as another back-up monitor of the exposure dose.

Using these monitor system, the irradiation dose to the patients are controlled and monitored.

3. Dose calibration system

Standard procedure of the dose calibration using the above system is as follows;
1) Depth dose distribution of a spread Bragg peak which has 6 cm width is measured by a standard dosimeter. The standard dosimeter is a parallel plate ionization chamber, which is fabricated by Far West Technology, Co.,. We use a binary filter to change a depth in water in the measurements of the depth dose distributions. The binary filter consists of 9 PMMA (Polymethyl methacrylate; Lucite) sheets of 0.5, 1, 2, 4, 8, 16, 32,64 and 128 mm thickness and 10 x 10 cm area. Inserting these sheets in the beam course, the target thickness is changed. The thickness of the PMMA is transferred to water equivalent thickness.
2) The measured dose distribution is compared with a calculated depth dose distribution. From the comparison, variations of the residual range of the carbon beam at the irradiation site and absolute value of the output of the standard chamber are recorded for the check of the beam energy, and the species of the particles. Fig.2 shows the variation of the range of the 350 MeV/u carbon beam checked by the

![Fig. 2. Daily change of the monitor calibration factor and the peak shift](image-url)
comparison with the calculation. The variation of the dose at 0 absorber position in the measurement of the depth dose distribution is also shown in the figure.

3) The information of the treatments, the excitation current of the wobbler magnets, thickness of the scatterer, sort of the ridge filter, thickness of the range shifter and so on, are send to the irradiation control computer. And the devices are adjusted according to the transferred information. The thickness of the binary filter is set so as for the residual range of the carbon beam to be half of the width of the spread-out Bragg peak. The standard chamber is set to the center of the spread-out Bragg peak, center of the target volume in the simulated phantom. Dose calibration of the monitor chamber is again performed under this treatment condition several times. These calibration factors are used for the real exposure to the patient.

4. Simplified Calibration

In the actual clinical trials, it takes about 30 minutes for taking the depth dose distribution, and about 5 minutes for taking each dose calibration factor of each patient. It takes an hour and half for the total calibration procedure of 12 patients. This calibration procedure is necessary whenever the initial energy of the carbon beam is changed. We use 290 and 350 or 400 MeV/u carbon beams in one day at HIMAC clinical trials. At that case, it takes 3 hours for the calibration. In order to shorten the calibration time, we are going to adapt a simplified calibration procedure from this autumn. The procedure is as follows;

1) The depth dose distribution is measured by a multi-layer ionization chambers in one exposure.
2) The dose calibration measurement for the each patient condition is performed only at the first treatment. The ratio of the dose calibration factor to the entrance dose of the depth dose distribution is recorded and used for the next treatments. The dose calibration factor for the later treatment is obtained by the ratio times the entrance dose of the depth dose distribution of that day.

From these simplified procedure of the dose calibration, it is possible to shorten the calibration time without making the accuracy of the dose calibration worse.

References

BEAM-QUALITY MEASUREMENTS ON HEAVY ION THERAPEUTIC BEAM OF HIMAC

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Abstract

Fluence spectra of fragment particles caused by spallation reactions between heavy ion beams and PMMA (polymethyl methacrylate; Lucite) target were measured with ΔE-E counter telescope method for each fragmented element. Measurements were carried out for carbon beams of 290 MeV/nucleon and 400 MeV/nucleon at Heavy Ion Medical Accelerator in Chiba (HIMAC), and 135 MeV/nucleon carbon beam at RIKEN Ring Cyclotron with changing the thickness of target material. Incident beam was broadened with a pair of wobbler magnets and a scatterer, in the same way of clinical trials which have been carrying out at HIMAC. Results were compared with the calculational expectations.

1. Introduction

In tumor therapy using heavy ion beams, it has been well known that incident heavy ion particles cause spallation reactions with the elements which compose the body. Hence, various kinds of particles were produced and hit the target. It is of importance to measure their fluence spectra for each fragmented element to estimate their influence on tumor therapy, and to brash up our treatment planning as well.

2. Experimental Setup

Figure 1 shows schematic diagrams of detector systems for measurements at RIKEN and HIMAC. According to Bethe formula, fragment particle can be identified with the parameter $AZ^2$ by measuring its total energy E and energy loss ΔE. The systems were based on the counter-telescope method [1]. Incident beam was sufficiently uniformed to 10.0 cm in diameter with the flatness of 95% at the iso-center by a pair of wobbler magnets and a scatterer[2]. A beam monitor, made of NE102A plastic scintillator of 1.5 cm in thickness, had front surface of 20.0 cm by 20.0 cm to count the total number of incident particles. The beam diameter was less than 5 cm at this beam monitor position. A stack of the plates of PMMA was selected as target material as it has similar composition with muscles. At the irradiation site, the detectors for the particle identification were placed. The detectors had comparatively smaller front surface to avoid entering plural fragment particles. In the setup at RIKEN, a coincidence detector, made of annular NE102A plastic scintillator, of 5.0 mm in diameter was positioned to distinguish an event by one fragment particle from those by noises. A proportional counter with tissue-equivalent gas was used to estimate the amount of energy transferred to biological system. A totally depleted silicon surface barrier detector of 11.3 mm in diameter and 1.0 mm in thickness was used as a ΔE counter to measure the energy loss ΔE in the detector and to make energy calibration. At the end of the beam line, a BGO scintillator was utilized as an E counter to measure the residual energy E of incident particle. The scintillator had a cylindrical form, 15.0 mm in diameter and 15.0 mm in length. The measurements were carried out for carbon 135 MeV/nucleon beam at E5 port.

![Fig. 1 The schematic diagram of the detector system.](image-url)

In the setup at HIMAC, a NE102A plastic scintillator of 40.0 mm by 40.0 mm and 5.0 mm in thickness was used as a ΔE detector instead of Si semiconductor detector. Energy...
resolution of plastic scintillator is generally inferior to semiconductor detector, however, scintillator has very superior characteristic on particle identification regarding that the response function of scintillator tends to enhance the difference of $A^2$ on lighter elements such as hydrogen or helium which are important to be well identified on this work, whereas the output of Si semiconductor detector is strictly proportional to $A^2$. In this setup, Si semiconductor detector was used for energy calibration. A larger BGO scintillator of rectangular form of 40.0 mm by 40.0 mm by 300.0 mm was used as an E detector. Measurements were carried out for carbon 290 and 400 MeV/nucleon beams at the bio port, therapy port BHC and CHC of the HIMAC.

3. Analysis

Figure 2 illustrates an example of particle identification by E-ΔE scatter plot obtained from incidence of carbon 290 MeV/nucleon beam to the target material of 120.7 mm in thickness. The abscissa represents the residual energy $E$ measured by the BGO scintillator and the ordinate denotes the energy loss $\Delta E$ from the plastic scintillator. Fragment particles were clearly separated to some groups. To identify each group in the $\Delta E$-E scatter plot, the amount of energy deposited in the Si semiconductor detector was compared with the calculational expectation for each fragmented element which was regarded on $\Delta E$-E scatter plot as filled in Fig.2. Experimental energy deposition of each fragmented element was derived by picking up upper and lower channels of the distribution spectra on Si semiconductor detector. Here, the channel of Si semiconductor detector was calibrated by corresponding a peak channel of the group regarded as primary carbon with its amount of energy deposition calculated for each thickness of target material. As for calculational expectation of the energy deposition, maximum and minimum values were given by the fragment produced just before the detector and the fragment produced at an entrance of target material, respectively.

The result was summarized in Fig.3 for the incidence of 290 MeV/nucleon carbon beam in PMMA of 112.1 mm in thickness. The experimental and calculational range of deposited energy was well overlapped for each other on each fragmented element. Therefore, it can be said that fragment particles were clearly identified from carbon to hydrogen with the difference of $Z$ and $A$ by regarding the highest group as primary carbon in E-ΔE scatter plot.

Fig. 2 The scatter plot of the residual energy $E$ and the energy loss $\Delta E$ for 290 MeV/nucleon carbon beam in PMMA 120.7 mm in thickness.

Residual Energy $E$ (BGO)

Fig. 3 Experimental and calculational energy deposition on Si semiconductor detector for 290 MeV/nucleon carbon beam in PMMA of 112.1 mm in thickness.

Fluence spectra of each element were derived from the number of particles in each group by normalizing with the total number of incident particles because of the flatness and the broadness of the incident beam. Figure 4 to 6 displays the fluence spectra at the incidence of 135, 290 and 400 MeV/nucleon carbon beam respectively. In these figures, dots represents the results of this work and lines are
Fig. 4 Fluence Spectra of fragments for 135 MeV/nucleon carbon beam.

Fig. 5 Fluence Spectra of fragments for 290 MeV/nucleon carbon beam.

Fig. 6 Fluence Spectra of fragments for 400 MeV/nucleon carbon beam.

4. Conclusion

Fragment particles included in the therapeutic beam were well identified with the ΔE-E scatter plot by a thin plastic scintillator and a BGO scintillator. The fluence spectra were obtained for each fragmented element and agreed well with the calculational expectations.

References

calculation results by Sihver et al. [3] for the sake of comparison. The experimental data show good agreement with calculational ones.
OUTLINE OF JHP SYNCHROTRON DESIGN

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Abstract

An outline of the JHP synchrotron design is described.

1. Introduction

The Japanese Hadron Project (JHP) was revised very recently. [1] The revised JHP consists of the following three accelerators;

1. injector: 200 MeV proton linear accelerator
2. booster: 3 GeV proton synchrotron
3. main ring: 50 GeV proton synchrotron

The accelerators will be constructed at the north site of the KEK and the whole plan view of the accelerator complex is shown in Fig.1.

The first stage of beam acceleration of the JHP is provided by the linac. The linac accelerates H⁺ ions up to 200 MeV. The expected peak beam current in the Injector linac is at least 20 mA and the pulse duration and the repetition rate of the beam is more than 400 μsec and 25Hz (50 Hz in future), respectively.

The H⁺ beam is injected into the booster by charge-exchange multi-turn injection and accelerated up to 3 GeV. The 3 GeV booster will be constructed in the exiting tunnel for the present KEK-PS main ring. All of the components of the KEK-PS main ring such as dipole magnets, quadrupole magnets, vacuum chambers and others will be removed. The booster is a rapid cycling proton synchrotron and its repetition rate is 25 Hz. The expected beam intensity in the booster is $5 \times 10^{13}$ ppp (protons per pulse), therefore, the average beam current becomes 200 μA. The total power of the extracted beam from the booster reaches 0.6 MW. The accelerated 3 GeV protons are supplied into three experimental facilities; a pulsed spallation neutron source facility (N-arena), a meson facility (M-arena) and an unstable nuclei facility (E-arena), and into the 50 GeV main ring.

Protons from the booster are injected into the main ring and accelerated up to 50 GeV. The expected beam intensity in the main ring is $4 \times 10^{14}$ ppp and the repetition rate is about 1/6 Hz, respectively. Thus, the average accelerated beam current reaches 10 μA in the 50 GeV main ring. The 50 GeV protons are extracted by a slow and fast extraction scheme for two experimental areas, respectively; one is for the experiments using secondary beams ($K, p, \bar{p}$) and primary beams by slow extraction, and the other for the neutrino oscillation experiment by fast extraction.

In addition to acceleration of high intensity protons, heavy ion and polarized proton beams are also requested. Using the 500 MeV booster of the KEK-PS as an injector of the 3 GeV booster, it becomes feasible to accelerate these particles.

2. Outline of the ring design

The 3 GeV booster is a rapid cycling proton synchrotron where the repetition rate of the acceleration is 25 Hz. (This repetition rate will be amended up to 50 Hz in future by adding more rf acceleration system.) In order to accomplish this high repetition rate, the maximum magnetic field strength of the dipole magnets has to be less than 1T. The power supply for each group of the magnets is operated with an independent resonance circuit system.

The lattice design of the booster is pre-
presented in detail in this proceedings.[2] The booster ring comprises 48 bending magnets and 48 quadrupole magnets. Parameters of the booster ring are presented in Table 1. Since the ring should be placed in the present KEK-PS tunnel, the superperiodicity of the ring is chosen to be four. There is no transition energy during beam acceleration.

In the 50Hz operation, about 800kVrf voltage is needed for beam acceleration. Thus, a large number of straight sections is necessary for the rf cavity stations. The rf parameters of this ring will be presented in the proceedings.[3] In the present design, there are 24 straight sections and the length of each one is 6.57m.

The requested apertures for each component of the 3GeV booster are summarized in Table 2. In this estimation, the beam emittance of 320 π.mm.mrad at the beam injection for both horizontal and vertical directions, and the momentum spread of ±0.5% and the COD of 5mm are assumed.

Table 1. Parameters of the 3 GeV Booster

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy</td>
<td>0.2 GeV</td>
</tr>
<tr>
<td>Maximum energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>5 x 10^13 ppp</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Circumference</td>
<td>339.36 m</td>
</tr>
<tr>
<td>Magnetic rigidity</td>
<td>2.15 - 12.76 Tm</td>
</tr>
<tr>
<td>Lattice configuration</td>
<td>FODO</td>
</tr>
<tr>
<td>Tune</td>
<td>(7.3,4.3)</td>
</tr>
<tr>
<td>Transition energy:γt</td>
<td>7</td>
</tr>
<tr>
<td>Total number of cells</td>
<td>24</td>
</tr>
<tr>
<td>Number of B-magnets</td>
<td>48</td>
</tr>
<tr>
<td>Number of Q-magnets</td>
<td>48</td>
</tr>
<tr>
<td>B-magnet length</td>
<td>1.75 m</td>
</tr>
<tr>
<td>Q-magnet length</td>
<td>0.5m</td>
</tr>
<tr>
<td>Maximum magnetic field strength of B-magnet</td>
<td>0.95T</td>
</tr>
<tr>
<td>Maximum magnetic field gradient of Q-magnet</td>
<td>5.4 T/m</td>
</tr>
<tr>
<td>Natural chromaticity</td>
<td>-6.77, -5.84</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>4</td>
</tr>
<tr>
<td>RF frequency</td>
<td>1.99 - 3.43 MHz</td>
</tr>
<tr>
<td>RF voltage</td>
<td>389 kV</td>
</tr>
<tr>
<td>Beam emittance (injection)</td>
<td>320 π.mm.mrad</td>
</tr>
<tr>
<td>Beam emittance (extraction)</td>
<td>53.9 π.mm.mrad</td>
</tr>
</tbody>
</table>

Table 2. Apertures of the 3 GeV booster.

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending magnet</td>
<td>92.9 mm</td>
<td>95.3 mm</td>
</tr>
<tr>
<td>Quadrupole magnet</td>
<td>106.0 mm</td>
<td>106.6 mm</td>
</tr>
</tbody>
</table>

Magnets are divided into three groups such as bending, focusing and the defocusing. Each group is excited using an independent resonant circuit. The design of the magnets and their power supplies are summarized in this proceedings.[4]

There are several design constraints for the 50 GeV main ring as shown below.

1. Max. field of bending magnets :<1.8 T (for normal conducting magnet)
2. Max. field gradient of quadrupole magnets:< 25 T/m
3. No transition energy: Less than 1% beam loss during beam acceleration
4. Small beam size: Ebeam at beam injection ~ 5 x 10^13 ppp
5. No dispersion at straight section: Internal gas target experiment and Siberian snakes for polarized beam
6. Numbers and length of a long straight section: 4, >40m

The circumference of the ring is almost four times larger than that of the KEK-PS ring because of the site limitation. Superconducting magnets are very attractive from the point of view of the site limitation described above, however, there are several problems, such as beam induced quenching, to be overcome. In the present lattice design, we assume to use normal conducting magnets. Thus, the maximum magnetic field strength of bending magnets and the maximum magnetic field gradient of quadrupole magnets are set to less than 25 T/m, respectively.

In an ordinary FODO lattice, the γt roughly equals the horizontal tune. Thus, using an ordinary FODO lattice, it is inevitable to have transition energy during beam acceleration up to 50 GeV. One of the features in the main ring design is that an imaginary γt lattice is employed.[2] Therefore, no transition energy crossing exists during beam acceleration. When the total integral of the dispersion function in the bending magnets is negative, the momentum compaction factor is negative and γt becomes imaginary. In order to realize imaginary γt, the arc section of the ring comprises a series of cell units. Each cell unit consists of three DOFO normal cells where the central cell has no bending magnets. To accommodate the dispersion free straight sections, total horizontal phase advance, varc, in the arc is set to integer times 2π. In this design, we set that varc=5x2π. With this optics, γt becomes 2π. In order to avoid a seri-
ous radioactivation problem in high intensity mode acceleration, the beam loss should be kept small, therefore, small beam size is desired; $b_{\text{max}}$ should be made small and flat as much as possible. The high intensity mode lattice was also designed from this point of view. Details of the lattice design are presented in this proceedings.[2]

The requested apertures of the 50 GeV ring are summarized in Table 3. In this estimation, the beam emittance of 54 $\tau \text{mm.mrad}$ at the beam injection for both horizontal and vertical directions, and the momentum spread of $\pm 0.5\%$ and the COD of 5 mm are assumed, respectively.

Table 3. Apertures of the 50 GeV main ring.

| Bending magnet | horizontal | 46.1 mm | 43.8 mm |
| Quadrupole magnet | 52.6 mm | 44.5 mm |

Space charge effects for the beams in the 3 GeV booster and the 50 GeV main ring are anticipated to be very large.[5] Using Laslett tune shift formula, the space charge effects are estimated. The incoherent and coherent space charge limits for both rings are summarized in Table 4. In this estimation, the Laslett tune shift is -0.25.

Table 4. Space charge limit

| 3 GeV Booster | Incoherent | Coherent |
| 50 GeV Main Ring | $5.6 \times 10^{13}$ | $1.2 \times 10^{14}$ |

The general parameters of the 50 GeV main ring are summarized in Table 5.

3. Summary

The outline of the JHP circular accelerators are described. In parallel with optimization of the beam optics and dynamics in the both rings, some R&D's for hardwares have already started.

(1) R&D of the rf acceleration system which can stand for heavy beam loading in both rings.

(2) R&D of the magnet power supply with a resonant network for the 3 GeV booster.

(3) R&D of the ceramic beam duct and rf shield for the 3 GeV booster.

References


Table 5 Parameters of 50 GeV Main Ring.

| Injection energy | 3 GeV |
| Maximum energy | 50 GeV |
| Beam intensity | $4 \times 10^{14}$ ppm |
| Repetition rate | $-1/6$ Hz |
| Circumference | 1442 m |
| Average radius | 229.5 m |
| Magnetic rigidity | 12.76 - 170 Tm |
| Lattice configuration | 3 - cell DOFO x 6 module |

| Tune | (24.25, 20.7) |
| Transition energy: $\gamma t$ | 27 i (imaginary) |
| Total number of cells | 88 |
| Number of B-magnets | 96 |
| Number of Q-magnets | 176 |
| B-magnet length | 6.2 m |
| Q-magnet length | 1.5 m and 2 m |
| Maximum magnetic field strength of B-magnet | 1.8 T |
| Maximum magnetic field gradient of Q-magnet | 25 T/m |
| Harmonic number | 34 |
| RF frequency | 6.83 - 7.03 MHz |
| RF voltage | 200 kV |
| Beam emittance (injection) | 53.9 $\tau \text{mm.mrad}$ |
| Beam emittance (extraction) | 4.1 $\tau \text{mm.mrad}$ |
1. Introduction

The RARF proposes "RIKEN RI Beam Factory" as a next facility-expanding project. The factory takes the aim at providing RI (Radioactive Isotope) beams of the whole mass range with the world-highest intensities in a wide energy range up to several hundreds MeV/nucleon. This paper describes a conceptual design of an accelerator complex most suitable for realizing the factory, and briefly presents Multi-USc Experimental Storage rings (MUSES) proposed as a new type of experimental facility.

2. Accelerator Complex Proposed for RIKEN RI Beam Factory

The best means to generate such RI beams is the utilization of the so-called "projectile fragmentation." In general, the reaction cross section for this projectile fragmentation steeply enhances with increasing an energy of a primary beam up to 100 MeV/nucleon, and it saturates above around this energy. Thus, in order to efficiently generate RI beams of the whole mass range using this method, firstly, primary-beam energies are required to exceed at least 100 McV/nucleon even for very heavy ions such as uranium. Due to this condition, the availability of RI beams at the present RARF is restricted to their mass less than around 60. Secondly, needless to say, intensities of primary beams must be as high as possible. Thirdly, from the cost-effectiveness point of view, the existing machines should be exploited and utilized as much as possible. Based upon these considerations, we propose an accelerator complex as illustrated in Fig. 1 which possesses such acceleration performance that a 100-MeV/nucleon uranium beam with the intensity over 1 pA is obtainable.

A new injector composed of a frequency-tunable folded-coaxial RFQ linac (FCRFQ) equipped with an 18-GHz ECR ion source (ECRIS-18) is under construction in order to greatly upgrade the RILAC performance especially in the beam intensity. We use this machine as the initial-stage of the accelerator complex.

A high-intensity heavy-ion d.c. beam produced by the ECRIS-18 is bunched and accelerated by the FCRFQ with the transmission efficiency of as high as 85% even at 1 mA. The value of the efficiency was calculated by the computer code BEAMPATH. This pre-accelerated beam is fully accepted and accelerated by the existing RILAC.

The output beam from the RILAC is passed through a charge-state multiplier (CSM, under design) to reduce its magnetic rigidity with the velocity unchanged, and injected into the existing RRC. The CSM consists of an accelerator, a charge stripper and a decelerator. The accelerator and decelerator are of frequency-tunable IH linacs, whose operational radio-frequencies are twice that of the RILAC to double an acceleration gradient. In the present design a maximum gap voltage is set to be 350 kV, and total lengths of these linacs are 12.4 meters.

Fig. 1. Schematic diagram of the Heavy-ion Accelerator Complex proposed for the RIKEN RI Beam Factory.
(the partition into three or four units are necessary) and 5.5 meters, respectively. Transmission efficiency through the CSM depends only on charge state distributions behind the charge stripper foil because the 6-dimensional emittance of the RILAC beam is already adiabatically damped so as to be fully captured by the acceptance of the CSM linacs. We estimate the yield of a given charge state in terms of Shima's formula\(^{4}\) which is reliable in the relevant energy region. The CSM is a decisive device to obtain a higher-intensity or higher-energy very-heavy-ion beam in the proposed accelerator scheme; with this device the magnetic rigidity of a most-probable charge-state beam can be decreased down to the acceptable value of the RRC even when the injection velocity into the RRC is increased.

Velocity of the RRC output beam is amplified by a factor of 2.26 with a six-sector superconducting ring cyclotron (SRC, under design)\(^{6,7}\), when the mean extraction radius (5.70 m) of the SRC is taken to be 2.26 times the mean injection radius (2.37 m). This mean injection radius is 2/3 times the mean extraction radius of the RRC. To meet a good matching condition, the harmonic number in the SRC is set to be 6 as that in the RRC is 9. The preliminary calculation of betatron-frequency excursions implies that when we set the sector angle to be 23.5 degrees the maximum attainable energy is limited to be around 400 MeV/nucleon to avoid the crossing over \(\nu_2 = 1.0\) resonance.\(^{6}\)

Here, we illustrate the acceleration of a uranium-ion beam up to 100 MeV/nucleon. The rf frequency of the RILAC is 23.0 MHz. A \(^{238}\text{U}^{16+}\) beam with an intensity (\(\text{IECR}\)) of 145 \(\mu\text{A}\) from the ECRIS-18 (this intensity is extrapolated from the 10 GHz CAPRICE data) is accelerated by the RILAC-CSM to 1.07 MeV/nucleon (\(\text{ERILAC}\)). In the CSM the charge state is increased from \(16^+ (\text{q}_{\text{ECR}})\) to \(49^+ (\text{q}_{\text{CSM}})\) by the stripping at 2.48 MeV/nucleon. The yield of \(49^+\) and the transmission efficiency of the FCRFQ are estimated to be 0.17 and 0.85, respectively, and thus a beam intensity of 1.3 \(\mu\text{A}\) is to be obtained. This beam intensity (\(\text{q}_{\text{SRC}}\)) is preserved up to the final energy, provided that the transmission efficiency of both of the RRC and the SRC is 100\% (this can be achieved by the off-centering acceleration technique which is routinely used for the RRC). The RRC output energy (\(\text{E}_{\text{RRC}}\)) is 17.5 MeV/nucleon, and the SRC final energy (\(\text{E}_{\text{SRC}}\)) is 100 MeV/nucleon. The SRC sector field at the extraction (\(\text{B}_{\text{SRC}}\)) is needed to reach to 3.9 T. Similarly, the maximum beam intensities for typical gaseous elements are obtained as listed in Table 1, provided that the sector field (\(\text{B}_{\text{SRC}}\)) of 4 T at the maximum can be achieved.

Quite high beam intensities can be provided especially for light ions, but use of such primary beams is not realistic from a viewpoint of the radiation-shielding problem. We consider that a primary-beam intensity of \(1 \mu\text{A}\) is sufficient to generate RI beams with desirable intensities in the whole mass region: These primary beams will give us possibility to create and identify as many as one thousand kinds of new isotopes.

### Table 1. Prospects of primary-beam intensities of typical heavy ions.

<table>
<thead>
<tr>
<th>Element</th>
<th>RF freq</th>
<th>(\text{q}_{\text{ECR}})</th>
<th>(\text{E}_{\text{ECR}})</th>
<th>(\text{E}_{\text{RILAC}})</th>
<th>(\text{q}_{\text{CSM}})</th>
<th>(\text{E}_{\text{RRC}})</th>
<th>(\text{q}_{\text{SRC}})</th>
<th>(\text{B}_{\text{SRC}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>16(\text{O}^8)</td>
<td>38.1</td>
<td>6</td>
<td>800</td>
<td>2.94</td>
<td>8</td>
<td>50.5</td>
<td>113</td>
<td>3.4</td>
</tr>
<tr>
<td>40(\text{Ar}^{17})</td>
<td>37.0</td>
<td>8</td>
<td>750</td>
<td>2.77</td>
<td>17</td>
<td>47.4</td>
<td>364</td>
<td>3.8</td>
</tr>
<tr>
<td>34(\text{Kr}^{30})</td>
<td>34.9</td>
<td>14</td>
<td>200</td>
<td>2.46</td>
<td>30</td>
<td>41.8</td>
<td>300</td>
<td>3.4</td>
</tr>
<tr>
<td>129(\text{Xe}^{38})</td>
<td>30.3</td>
<td>15</td>
<td>140</td>
<td>1.85</td>
<td>38</td>
<td>31.0</td>
<td>200</td>
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<tr>
<td>238(\text{U}^{85})</td>
<td>30.3</td>
<td>28</td>
<td>27</td>
<td>1.85</td>
<td>59</td>
<td>31.0</td>
<td>200</td>
<td>0.04*</td>
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<tr>
<td>238(\text{U}^{58})</td>
<td>27.2</td>
<td>22</td>
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<td>58</td>
<td>24.7</td>
<td>150</td>
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<tr>
<td>238(\text{U}^{49})</td>
<td>23.0</td>
<td>16</td>
<td>145</td>
<td>1.07</td>
<td>49</td>
<td>17.5</td>
<td>100</td>
<td>1.3</td>
</tr>
</tbody>
</table>

* The charge-stripping is done in between the RRC and the SRC. The yield is assumed to be 30\%.

### 3. Multi-Use Experimental Storage Rings (MUSES)

Figure 2 displays a quite preliminary lay out of the RI beam factory. The MUSES, installed downstream of an RI-beam generator (Big RIPS) for the SRC, consists of Double Storage Rings (DSR) and a small-sized Accumulator-Cooler Ring (ACR). The DSR permits various types of unique colliding experiments: ion-ion merging or head-on collisions; collisions of electron and ion (stable or RI) beams; internal target experiments; and atomic and molecular physics with cooling electron beams. On the other hand, the ACR functions exclusively for the accumulation and cooling of RI beams by the multi-turn injection plus RF-stacking associated with the electron cooling as well as for the acceleration of electron beams from 0.5 GeV up to 2.5 GeV and their radiation damping; i.e., RI or electron beams are improved in quality by the ACR, and are injected into the DSR by one turn. With the ACR, the acceptance required for the DSR is significantly
reduced. In the figure, the schematic drawing of the DSR is shown, but that of the ACR are not given.

In the DSR two rings of the same specifications as shown in Table 2 are vertically stacked. Each lattice structure takes the form of a racetrack to accommodate two long straight sections. These straight sections of one ring vertically intersect those of the other ring at two colliding points. The ring circumference is 202.08 m, which is 6 times the extraction circumference of the SRC. The maximum $B_p$-value becomes 12.76 Tm when a dipole field strength is 1.5 T at the maximum. If high-energy ion beams are demanded, the DSR serves as an ion synchrotron as well. The maximum energy is given, for example, to be 3.0 GeV for protons; 1.2 GeV/nucleon for light ions of $q/A=0.5$; and 0.82 GeV/nucleon for $U^{92+}$ ions. For electrons the ACR boosts them up to the maximum energy of 2.5 GeV, and these electrons are stored in the DSR. In the present lattice structure, the betatron tune values are 6.335 (horizontal) and 5.763 (vertical). The operating ion-beam energy is kept to be under the transition energy, since the transition gamma is as high as 4.86. At the colliding points the beta-function amplitudes are 0.6 m for both directions. The field-free section near the colliding points where experimental detector systems are installed is 16.7 m in length. These two long straight sections are dispersion-free in horizontal and vertical directions.

One of the key researches planned in the DSR is the colliding experiment of an electron beam with an RI beam: 2.5 GeV electrons accumulated in one ring of the DSR are collided with an RI beam stored in the other ring. At 2.5 GeV, the de-Broglie wave-length of the electrons in the rest frame of the RI beam becomes 0.2 fm, which is sufficiently short to study the nuclear structure. To keep a sufficiently long Touschek lifetime, the RF voltage of 2.0 MV is applied to the electron beam. The number of stored electrons amounts up to 1.9x10^{12} particles which is limited due to the longitudinal coupled bunch instability. The typical colliding luminosity for the electrons and RI ions is estimated to be 5.6x10^{26}/cm^2/s, provided that 1x10^7 particles of RI ions are stored and synchronously collided with electron bunches.

Other experiments such as ion-ion merging collisions at small angles are also envisaged. The luminosity is expected to be around 1x10^{26}/cm^2/s when the number of stored ions are assumed at the space charge limit of 4x10^{12} particles and the colliding angle is 10 degrees.

For internal target experiments in the DSR, the stochastic cooling method is used. The band width is conservatively assumed at 500 MHz, and the feedback gain is 130 dB which is limited by an available wide-band RF power of 100kW.

Various aspects of beam-dynamic problems related to the detailed design of the DSR is being studied (one of them is given in Ref. 8), and the optimization of parameters of the ACR is under way.

### Table 2. Parameters of the DSR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference $C$ (m)</td>
<td>202.078</td>
</tr>
<tr>
<td>Max. $B_p$ (Tm)</td>
<td>12.76</td>
</tr>
<tr>
<td>Average Radius $R$ (m)</td>
<td>32.178</td>
</tr>
<tr>
<td>Radius of Curvature $p$ (m)</td>
<td>8.506</td>
</tr>
<tr>
<td>Max. Beam Energy</td>
<td></td>
</tr>
<tr>
<td>proton (GeV)</td>
<td>3.00</td>
</tr>
<tr>
<td>ion ($q/A = 0.5$) (GeV/nucleon)</td>
<td>1.20</td>
</tr>
<tr>
<td>ion ($q/A = 0.387$) (GeV/nucleon)</td>
<td>0.82</td>
</tr>
<tr>
<td>electron (GeV)</td>
<td></td>
</tr>
<tr>
<td>Betatron Tune Values ($Q_x/Q_y$)</td>
<td>6.350/5.763</td>
</tr>
<tr>
<td>Momentum Compaction</td>
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<tr>
<td>Transition $\gamma$</td>
<td>4.859</td>
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<tr>
<td>Max. Betatron Amplitude ($\beta_x/\beta_y$, m)</td>
<td>22.0/13.5</td>
</tr>
<tr>
<td>Max. Dispersion Function ($D_x/D_y$, m)</td>
<td>3.023/0.666</td>
</tr>
<tr>
<td>Betatron Amplitude</td>
<td></td>
</tr>
<tr>
<td>at Interaction Point ($\beta_x^<em>/\beta_y^</em>$, m)</td>
<td>0.600/0.600</td>
</tr>
<tr>
<td>Length of Field-free Section</td>
<td></td>
</tr>
<tr>
<td>at Colliding Section (m)</td>
<td>16.708</td>
</tr>
</tbody>
</table>

Fig. 2. Preliminary lay out of the RI beam factory.

References

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2) O. Kamigaito et al., in this proceedings.
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FEMTOSECOND ULTRAFAST QUANTUM PHENOMENA RESEARCH

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Mikiko AIDA, Toshiaki KOBAYASHI, Toru UEDA and Kenzo MIYA

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Abstract

Femtosecond quantum phenomena research project is proposed at Nuclear Engineering Research Laboratory, University of Tokyo. The research facility consists of an X-band (11.424GHz) femtosecond electron linac, a femtosecond wavelength tunable laser, two S-band (2.856GHz) picosecond electron linacs and measuring equipments. Especially, we aim to generate a 100fs (FWHM) electron single bunch with more than 1nC at the X-band linac. Ultrafast processes in radiation physics, chemistry, material science and microscopic electromagnetic phenomena are going to be analyzed there. The specification of the facility is presented.

1. Introduction

A subpicosecond (700 fs in FWHM) electron single bunch was produced and measured at the S-band linac of Nuclear Engineering Research Laboratory, University of Tokyo, in 1994. Since then electric charge has been enhanced up to 1 nC per bunch. Now the subpicosecond pulse-radiolysis measurement for radiation physics and chemistry is under way. Here we propose the femtosecond pulse-radiolysis measurement for radiation physics and enhanced up to 1 nC per bunch. Now the subpicosecond wavelength tunable laser, two S-band electron linacs and several diagnostic and analyzing equipments. This facility enables us to measure, analyze and visualize excitation, ionization and relaxation of atoms and molecules and ultrafast process of radiation damage and surface phenomena of materials.

2. Specification of the facility

The specification of the facility is described below. The layout of the machines are shown in Fig.1. The main design parameters are summarized in Table 1.

(i) X-band femtosecond electron linac

We have chosen X-band (11.424GHz) as the main accelerating RF according to the following reason. We think we have already optimized the operation parameters of magnetic pulse compression to produce a subpicosecond single bunch from a 10 ps (FWHM) original bunch at the S-band (2.856GHz) linac[1]. Actually we have developed and validated the so-called nonlinear energy modulation. Further, measured pulse widths agreed well with numerical results based on the three dimensional particle tracking analysis. This indicates that the beam parameters such as emittance and energy spread which we used are rather reliable. Then we figure out that we have to have a shorter bunch and smaller emittance before the compression in order to produce a 100 fs single bunch. To fulfill the former requirement, we should introduce higher frequency RF, namely X-band (11.424GHz). X-band klystron, accelerating tubes and other components are under development for a future linear collider at KEK and SLAC[2,3,4]. We are to use 40 MW or less RF power and 300 ns or longer pulse duration of the X-band klystron. Two travelling wave accelerating tubes of 2/3λ mode and constant impedance are used. The length of the regular accelerating tube is 0.6 m and the field gradient is 40 MV/m at the entrance and 25 MV/m at the exit. The former tube have a buncher section, where the RF phase velocity varies from 0.7c to 0.9c, at the entrance. The final energy is 35 MeV. In order to fulfill the latter requirement, we have chosen the 200 kV thermionic electron gun and to produce the peak current of 100 A with the pulse width of 200 ps (FWHM) by using the fast grid pulser. We found by using PARMELA that we have to use two subharmonic bunchers of 476 MHz and 2.856 GHz to get a single bunch without satellites. Pulse width and electric charge per bunch were calculated to be 1 ps and 1 nC, respectively. Finally, the achronic arc-type magentic pulse compressor achieves a 100 fs single bunch.

(ii) Femtosecond wavelength tunable laser

The laser is used as a probe light source in the light absorption pulse-radiolysis. Main oscillator and amplifier are Ti-sapphire which produces 100 fs light pulses of the wavelength of 720-850 nm. The wavelength can be expanded from 700 nm to 1.1 μm by using the wavelength converter. The repetition rate of laser pulses is tuned to be 79.3 MHz by the lock-to-clock. The single pulse operation is also available by the pulse selector of pockel cells synchronized by the main trigger system.

(iii) High charge S-band electron linac

It is important to study fast quantum phenomena not only in the femtosecond time domain but also in the picosecond and nanosecond time domains to understand their whole process. From point of view of measurement with high signal-to-noise ratio, it is beneficial to use an S-band linac for the study in the picosecond and nanosecond time domains since it can obtain more electric charge per bunch than an X-band linac. For the purpose we plan to use a 200 kV thermionic electron gun to get as much charge per bunch as 5 nC at the first S-band linac. It consists of the 200 kV gun, the 476 MHz subharmonic buncher, two travelling wave accelerating tubes and the
achromatic arc-type magnetic pulse compressor so that the wide-ranged pulse structures such as 500 fs - 10 ps single bunch and 5 μs macro pulse are available.

(iv) Cherenkov radiator S-band electron linac
The second S-band linac is used as a Cherenkov radiation source in the light absorption pulse-radiolysis. Its specification is the same as the first S-band linac except the 90 kV gun which is the same one as the current machines have. Further, an advanced RF electron gun with a laser photocathode is to be tested at the second linac.

(v) RF control and trigger system
476 MHz has been chosen as the main RF generated by the master oscillator. S-band RF (2.856MHz) and X-band RF (11.424GHz) are generated from 476 MHz RF by the frequency multipliers. On the other hand, 79.3 MHz RF which is 1/6 of 476 MHz is generated by the frequency divider to synchronize the femtosecond laser with the linacs. A trigger pulse is generated so as to be synchronized with a specified 476 MHz RF phase and fed to drive the electron guns, the femtosecond laser and the streak camera.

(vi) Pulse width measurement equipments
A new femtosecond streak camera with the time resolution of 50 fs is now under development. After the development is completed, we plan to introduce it for both on-line pulse diagnosis and femtosecond pulse radiolysis. We are also going to construct the Michelson interferometer for off-line pulse diagnosis via optical transition radiation[5].

(v) Analyzing equipments
The following analyzing equipments plan to be installed for wide-ranged utilization; sample temperature control system, electron spin resonance analyzer (ESR), electrospectroscopic chemical analyzer (ESCA), Fourier Transform Infrared Spectrometer (FTIR), time-resolved plasma monochrometer and mass-spectrometer, high power wide-ranged wavelength tunable laser with narrow bands etc.

-----

Fig. 1 Layout of the facility for the femtosecond ultrafast quantum phenomena research
Table 1 Main design parameters of the facility

<table>
<thead>
<tr>
<th>X-band femtosecond electron linac</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulse width</strong></td>
<td>100 fs with compression</td>
</tr>
<tr>
<td><em>(FWHM)</em></td>
<td>1 ps without compression</td>
</tr>
<tr>
<td><strong>Electric charge</strong></td>
<td>1 nC per bunch</td>
</tr>
<tr>
<td><strong>Maximum energy</strong></td>
<td>35 MeV</td>
</tr>
<tr>
<td><strong>Electric gun</strong></td>
<td>200 kV thermionic</td>
</tr>
<tr>
<td><strong>Current at peak</strong></td>
<td>10 A</td>
</tr>
<tr>
<td><em>(FWHM)</em></td>
<td>200 ps</td>
</tr>
<tr>
<td><strong>Bunch mode</strong></td>
<td>single bunch</td>
</tr>
<tr>
<td><strong>Repetition rate</strong></td>
<td>50 pps</td>
</tr>
<tr>
<td><strong>Jitter</strong></td>
<td>&lt; 1 ps</td>
</tr>
<tr>
<td><strong>Subharmonic</strong></td>
<td>476 MHz (coaxial)</td>
</tr>
<tr>
<td><strong>Buncher</strong></td>
<td>2.836 GHz (nosecone)</td>
</tr>
<tr>
<td><strong>Accelerating tubes</strong></td>
<td>two tubes</td>
</tr>
<tr>
<td><strong>travelling wave</strong></td>
<td>2/3π mode</td>
</tr>
<tr>
<td><strong>0.6 m for regular</strong></td>
<td>40 - 25 MV/m</td>
</tr>
<tr>
<td><strong>Buncher</strong></td>
<td>0.7c -&gt; 0.9c</td>
</tr>
<tr>
<td><strong>Klystron</strong></td>
<td>&lt; 40 MW</td>
</tr>
<tr>
<td><strong>Achromatic arc-type magnetic pulse compressor</strong></td>
<td>&gt; 300 ns</td>
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</table>

<table>
<thead>
<tr>
<th>Femtosecond wavelength tunable laser</th>
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</thead>
<tbody>
<tr>
<td><strong>Pulse width</strong></td>
<td>100 fs</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>700 - 1100 nm</td>
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<tr>
<td><strong>Repetition rate</strong></td>
<td>79.3 MHz</td>
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</table>

<table>
<thead>
<tr>
<th>High charge S-band electron linac</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulse width</strong></td>
<td>500 fs with compression</td>
</tr>
<tr>
<td><em>(FWHM)</em></td>
<td>10 ps without compression</td>
</tr>
<tr>
<td><strong>Electric charge</strong></td>
<td>5 nC per bunch</td>
</tr>
<tr>
<td><strong>Maximum energy</strong></td>
<td>35 MeV</td>
</tr>
<tr>
<td><strong>Electron gun</strong></td>
<td>200 kV thermionic</td>
</tr>
<tr>
<td><strong>Klystron</strong></td>
<td>10 MW</td>
</tr>
<tr>
<td></td>
<td>5 μs</td>
</tr>
<tr>
<td></td>
<td>50 pps</td>
</tr>
<tr>
<td><strong>Achromatic arc-type magnetic pulse compressor</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Bunch mode</strong></td>
<td>single and multi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cherenkov radiator S-band electron linac</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron gun</strong></td>
<td>90 kV thermionic</td>
</tr>
<tr>
<td><strong>Laser photocathode RF gun</strong></td>
<td></td>
</tr>
</tbody>
</table>

3. Summary

Current design of the facility for the femtosecond ultrafast quantum phenomena research is described. We are going to evaluate three dimensional wake field in the buncher and regular cells at the X-band linac. Detailed design has also started. We have submitted the proposal to the government via University of Tokyo. The construction of the facility is expected to be done in 1996-1997.

Acknowledgement

The authors would like to thank the following researchers for their technical advises; Drs. H.Mizuno, T.Higo, H.Kobayashi, S.Ohsawa, S.Fukuda, A.Ogata, H.Nakajima and Y.-J.Choi of KEK and Dr. G.A.Loew of SLAC.

References

The Tohoku University Stretcher-Booster Ring

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Abstract

The Tohoku University Stretcher-Booster Ring Project was approved this year. This ring plays three roles: the pulse beam stretcher, the booster and the storage ring for the internal target nuclear experiment. It has four 3.1 m long straight sections and its circumference is 50 m. The maximum energy is 300 MeV as the stretcher and 1.2 GeV as the booster.

I. INTRODUCTION

In the 1970's, the intermediate energy electromagnetic nuclear physics had made the compelling needs for new high intensity continuous electron beam accelerators. Several laboratories in the world had actively studied design alternatives with the objective of constructing accelerators which can meet the needs of future research program. Some of which have been realized as the MAMI, Mainz microtron, the pulse stretcher rings with existing linacs at Saskatchewan, Bates and NIKHEF, and the entirely new superconducting linac at CEBAF. We have proposed the pulse stretcher ring projects since 1978.[1]-[7] A prototype 150 MeV stretcher ring (SSTR) [8] was constructed in 1981 and has been used for coincidence experiments for 14 years. The Tohoku University Stretcher-Booster Ring was approved this year and will be completed in 1997.

II. GENERAL DESCRIPTION

The Tohoku University Stretcher-Booster Ring (STB) plays three roles: the pulse stretcher ring mode which accepts pulsed beam from the 300 MeV Linac and delivers external continuous beam for the nuclear coincidence experiments, the booster ring mode which accelerates electrons up to 1.2 GeV and injects them into another storage ring by fast extraction, and the storage ring mode which holds the beam at 1.2 GeV for internal target nuclear experiments.

Pulsed electron beam from electron linacs is not suitable for the coincidence experiments, and then we need a pulse stretcher which stretches pulsed beam to continuous one. The energy of electrons extracted from a stretcher is the same as the injected energy, 300 MeV in this ring.

Figure 1 shows the layout of the STB. The circumference of the STB is 49.75 m and it has four 3.1 m long straight sections which are used for the injection, the extraction, the internal target experiment and the RF acceleration. Parameters of the STB are listed in Table 1.

The beam is extracted fast by using kicker magnets for the booster mode and is done slowly using the third integer...
resonance (v_x = 3.33) for the stretcher mode. The later case that the electron energy should be kept constant by RF acceleration is so-called "achromatic extraction." The STB has two RF acceleration systems, a 2856 MHz system is for the stretcher mode and a 500 MHz system for the booster and the internal target modes. No RF system is needed for stretcher mode operation under 250 MeV and electrons are extracted by means of "monochromatic extraction".

Table 1. Parameters of the STB

<table>
<thead>
<tr>
<th>Machine Parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>49.7512 m</td>
</tr>
<tr>
<td>Lattice</td>
<td>DBA</td>
</tr>
<tr>
<td>Super Period</td>
<td>4</td>
</tr>
<tr>
<td>Betatron Tune</td>
<td>v_x = 3.300, v_y = 1.200</td>
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<tr>
<td>Momentum Compaction</td>
<td>α = 0.037767</td>
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<tr>
<td>Chromaticity</td>
<td>δ_x = -5.7861, δ_y = -4.9791</td>
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<tr>
<td>RF Frequency</td>
<td>500.1/2856.24 MHz</td>
</tr>
</tbody>
</table>

Table 2. A quarter lattice of the STB

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>O_1 - QF - O_2 - QD - O_2 - BM - O_2 - QC - O_2 - BM - O_2 - QC - O_2 - QC - O_1</td>
<td></td>
</tr>
<tr>
<td>Drift Space</td>
<td>O_1 1.5625 m, O_2 0.50 m</td>
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<tr>
<td>Bending Magnet</td>
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<tr>
<td>Bending Angle</td>
<td>45°</td>
</tr>
<tr>
<td>Bending Radius</td>
<td>3 m</td>
</tr>
<tr>
<td>Length</td>
<td>2.355 m</td>
</tr>
<tr>
<td>Edge Angle</td>
<td>0°</td>
</tr>
<tr>
<td>Quadruple Magnet QM</td>
<td></td>
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<tr>
<td>Length</td>
<td>QF = QD = 0.3 m</td>
</tr>
<tr>
<td>Bore Radius</td>
<td>QC = 0.4 m</td>
</tr>
<tr>
<td>Focus (horizontal)</td>
<td>QF k = 2.0617 m²</td>
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<tr>
<td>QC k = 2.737 m²</td>
<td></td>
</tr>
<tr>
<td>Defocus (horizontal)</td>
<td>QD k = -2.2287 m²</td>
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<tr>
<td>Modulated Quadrupole Magnet PQM</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Bore Radius</td>
<td>0.05 m</td>
</tr>
<tr>
<td>k = 0.2 m²</td>
<td></td>
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<tr>
<td>Modulated Sextupole Magnet PSX</td>
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<tr>
<td>Length</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Bore Radius</td>
<td>0.06 m</td>
</tr>
<tr>
<td>k = 10 m⁻³</td>
<td></td>
</tr>
</tbody>
</table>

III. STRUCTURE OF THE STB

The STB lattice has a DBA (Double Bend Achromat) structure and consists of eight bending magnets, twenty quadrupole magnets, a modulated quadrupole and a modulated sextupole. Laminated iron plates are used for all STB magnets. The bending radius of the magnets is 3 m in order to install the STB in the existing experimental room which is 16 m wide, and to realize a long straight section for the internal target system. The magnetic field of bending magnets is 1.33 T at 1.2 GeV. Electrons are injected inside of the ring and the injection beam line from the linac crosses STB orbit. The outside extraction line meets the pulse beam line from the linac. Table 2 shows parameters of a quarter lattice of the STB. Also Figure 2 shows betatron and dispersion functions of a half part of the STB.
IV. RF SYSTEM

Two types of RF system are installed in the STB. One is 500 MHz system for the booster ring and internal target modes and the other is 2856 MHz system for the stretcher ring mode. Parameters of RF system are listed in Table 3.

For the booster ring and internal target modes, the 500 MHz system is chosen since a high power RF source is required for acceleration up to 1.2 GeV. Devices around 500 MHz are commonly used at many accelerator facilities and are available at reasonable price. The cavity is a single cell with two rose cones which has been optimized at KEK and its shunt impedance is 5 MΩ. A 100 kW klystron is adopted to accelerate and to compensate the synchrotron radiation energy loss in the bending magnets as well as the energy loss for higher order mode excitation.

The 2856 MHz system is installed for the stretcher mode to accept all the electrons from the linac without spill. In this mode, the stored current jumps up from zero to 300 mA within 0.5 μsec. and falls down linearly to zero until the next injection. This scheme is repeated at 300 cycles per second. Because it is difficult to control RF voltage and phase according with such rapid change, we adopt a cavity with very low shunt impedance and with input coupler of very large coupling constant (β=15). Then the voltage and phase of accelerating field are kept within small fluctuation.

V. CONCLUSION

All components of the STB, except RF system and magnet power supplies for booster operation, will be installed next spring, and we will start commissioning for stretcher mode operation.

The Tohoku 1.5 GeV low emittance storage ring proposal is under investigation, and it shall hopefully follow completion of the STB. The STB will provide electrons to the storage ring.

<table>
<thead>
<tr>
<th>Table 3. Parameters of the RF system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Energy</td>
</tr>
<tr>
<td>1.2 GeV</td>
</tr>
<tr>
<td>Maximum Current</td>
</tr>
<tr>
<td>RF Frequency</td>
</tr>
<tr>
<td>Harmonic Number</td>
</tr>
<tr>
<td>Shunt Impedance</td>
</tr>
<tr>
<td>Over-voltage Factor</td>
</tr>
<tr>
<td>Acceleration Voltage</td>
</tr>
<tr>
<td>Quantum Lifetime</td>
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<tr>
<td>Synchronous Phase</td>
</tr>
<tr>
<td>Synchrotron Freq.</td>
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<tr>
<td>Klystron Output</td>
</tr>
<tr>
<td>Wall Loss</td>
</tr>
<tr>
<td>Number of Cavities</td>
</tr>
</tbody>
</table>

VI. REFERENCES

NEXT-STEP ECRIS AND 2m LENGTH 4.52 GeV ADVANCED ACCELERATOR:
Novel Extraction of Trapped Ions and their Acceleration-Final Focusing
by Nonneutral and Neutral Plasmas

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Abstract For more efficient extraction of high-charge state (HCS) ion beams and for much shorter pulse beam production than presently achievable, we propose a pulsed, electric (E-) field to be induced inside an ECR ion source. Advantages over conventional upgrading technologies, right range of the E-field intensity, and low-emittance extraction hardware are described. It is shown that the E-field method can extract only HCS ions with a drastically high upgrading factor surpassing the e-beam method, without disturbing the rI-heated hot electrons inside ECR ellipse. Further, in order to accelerate heavy ion beams to a GeV/u energy (case: U238, Z=60) and to focus it to a submillimeter beam size we present preliminary studies on a high-acceleration gradient (9GeV/m peak) nonneutral plasma accelerator and a neutral plasma final beam focuser, respectively. A novel 4.52GeV accelerator coupled with a neutralizing and focusing z-pinch plasma seems feasible in an elliptical chamber of 2m length.

1. Introduction
The ECR ion source (ECRIS) has readily established its position as the most efficient HCS ions injector for heavy ion linacs and cyclotrons. This paper searches a way of further improvement of the performance not only in CW but also pulsed operations, so that it can evolve useful source for also synchrotrons. The work is based on our recent discovery of the physical scenario for upgrading the extraction efficiency of HCS ions beams in ECRIS11, the concept of which prompt us to design not only the next-step ECRIS but also an advanced accelerator.

As a positive use of the space-charge potential has let ECRIS grow as the best HCS ions injector, this paper suggests deepening and tailoring of the space-charge potential for accelerator applications. Concept of the heavy ion plasma accelerator (HIPAC) can be found in the literature2 and the experiments have been performed since 1970's. A radial potential difference of 300 kV was practically measured3 inside a toroidal chamber, whose minor radius a=8cm, by filling it with electrons at the density n0=1010 cm-3. Electrons are no need to be hot for the potential formation as long as they are confined in a 3D-topologically closed potential-well which can be formed with magnetically confined electrons. This paper describes a novel extraction and focusing of accelerated beams, which is impossible with a toroidal chamber but possible with an elliptical one.

2. Review of Upgrading Physics
The HCS ion beam current from an ECRIS is known to enhance significantly by employing so-called upgrade technologies such as (i) electron (e-) beam injection, (ii) wall-coating, and (iii) gas-mixing. The upgrading factor, η defined by the ratio of extracted ion beam-current 'with' to 'without' an upgrade technology increases sharply together with charge-state, Z. The physical scenario of upgrading mechanism was discovered based on the experimentally and numerically observable facts: (1) Remarkable similarity among the effects of (i)-(iii), (2) Experimental η that scales by exp Z, but only for the Z's above a critical one, Z0; existence of a potential-well which can trap the otherwise-lost HCS ions for a time enough for charge multiplication. (3) Parametric study of simultaneous rate-equations has indicated that the charge state distribution (CSD) may become anomalous, meaning that the HCS ion density increases with Z, only if the diffusion loss becomes negligible along with the charge exchange loss from a given system; existence of a negative potential.

Thus we were forced to draw a conclusion that the major role of all those upgrading technologies (i) ~ (iii) is to help-tapping the HCS ions otherwise-trapped quasi-indefinitely inside the potential-well. We have identified the mechanism to be the local lowering of potential barrier (LLPB) or bitten dog-food bowl (BDFB), by which the CW endloss current can locally increase its magnitude in the range of HCS. Here, the terminology of 'endloss' refers the leakage flown out of potential-end. In 3D-picture, 'potential-end' corresponds the surface of an ECR ellipse. On the other hand, 'local' refers a part of the potential-end. This paper will show that the LLPB tends to occur preferentially along the axisymmetric axis of ECR device even for the cases of (ii) and (iii).

2.1 Physical Proof of Experimental Results
The present day ECRIS's in the CW mode of operation are all tapping the endloss current, relying on an imperfection of the electrostatic confinement. The trapped ions at the charge state Z and energy kTe/Z can leak out of a potential-well of depth Δφ with probability exp (-ZeΔφ/kT) Zero probability (Δφ → ∞, kT/e → 0) is ideal for production of highly HCS ions and low emittance beams, but such a perfect confinement is not good as an ion source which should extract the maximum possible ion beam current, \( I_b = \frac{ZeS_p Gs}{kT} \).

\[ I_b = I_0 \exp(-\frac{ZeA}{kT}) \quad I_0 = 0.61 ZeS_p V_B n_0(0) \] (1)

Here, the expression of \( I_b \) is obtainable from the flux conservation, \( S_{end} G_{end} = S_p G_s \). The CW endloss current of \( I_b \) ions is \( I_{blin} = \frac{ZeS_{end} G_{end}}{kT} \), where \( S_{end} \) is the ion escaping surface at the potential-end. All the loss current, \( I_{loss} = S_{end} G_{end} \) was assumed to be extracted eventually via the sheath surface, \( S_p \) near the plasma electrode located at ECRIS exit. \( G_s \) is the ion flux at the sheath edge and known to be \( G_s = \frac{v_B}{(kT/e)n_0} \) is the Bohm velocity and the sheath edge density is \( n_0 = 0.61 n_0 \). Here, n0 is the density of HCS ions of interest in the peripheral plasma, which is assumed uniform with the
endd density just leaking out at the potential-end. \( n_{e}(t_{p}/2)=n_{e}(0)e^{\frac{2\pi Z_{e}E_{z}}{E_{z}}} \).

Suppose the light of \( \Delta \phi \) was lowered locally by an e-beam injection to \( \Delta \gamma - \Delta \gamma_{e} \). Eq. (1) gives

\[
I_{eh} = I_{0} \exp \left[ \frac{Z\Delta \phi_{eh}}{kT_{iz}} \right] \left( 1 - \frac{\Delta \phi_{eh}}{\Delta \phi} \right)
\]

This expression indicates that \( I_{eh} \) should increase as \( \Delta \phi_{eh} \) increases. This is consistent with experimental observation: the ion (i-) beam current enhanced as the e-beam current was increased. Thus, the e-beam must be lowering the \( \Delta \phi \) or increasing the magnitude of \( \Delta \phi_{eh} \).

If we take the ratio of Eq.(2)/Eq.(1) we have

\[
\eta = I_{eh}/I_{ch} = \exp \left[ \frac{Z\Delta \phi_{eh}}{kT_{iz}} \right] = \exp \left[ Z \right]
\]

This result agrees well with a number of experimental results where \( \eta = \exp \left[ Z \right] \) is evident. Provided that \( Z \geq 1 \) in the region \( \gamma > \gamma_{c} \), Eq. (3) would be better expressed by

\[
\eta(\gamma) = \exp \left[ C\frac{\Delta \phi_{eh}}{kT_{iz}} (\gamma - \gamma_{c}) \right], \quad (Z > 0)
\]

Here, \( \gamma_{c} \) is the threshold with which the confinement time is long enough for producing HCS ions of interest; \( kT_{iz} < Z_{o}t_{\gamma} \). \( \gamma_{c} \) increases proportionately with the ionization time needed for the \( Z \) of the atom of interest.

2.1 Wall-Coating and Gas-Mixing to Form an E-Beaam Like Electron Channel on Axis

The wall-coating works similar way as an e-beam gun. Secondary electrons \( n_{es} \) can be generated when HCS ions approach the wall which is coated with low work-function material like MgO. They are accelerated by the positive plasma potential towards the circumference of ECR-zone and there they tend to stagnate. Those \( n_{es} \) pointing the plasma potential towards the circumference of ECR-zone will be 'beamed' along the axis due to joining with incoming \( n_{es} \) together with MMF focusing effect; the \( n_{es} \) is thus at least two-times denser on axis than the \( n_{es} \) is constant. This Eq.(5) states that electrons experience a \( -z \) directed Lorentz force \( F_{z}=eB_{z}/E_{z} \) in the region where \( r \), \( \gamma \), and \( \gamma_{c} \) are approximately constant with \( r \) over the distance of Larmor radius, \( r_{L}=\gamma_{c}/\gamma \). Since \( \gamma_{c}=eB/m \), the axial motion of electrons can be expressed by

\[
\frac{d\gamma}{dt} = -eB_{z}/E_{z} B_{z} = -\frac{eB_{z}}{E_{z}} \mu_{c} Z \frac{d\gamma}{dt} = \frac{B_{z}}{B_{z}} \mu_{c} Z \frac{d\gamma}{dt}
\]

Since the total kinetic energy \( W = mv^{2}/2 \) is constant \( (dW/dt)=0 \). Eq. (6) gives the invariance of \( \mu_{c} \) or \( \mu_{c} \) from \( \gamma \) to \( \gamma_{c} \). However, \( B_{z} \) should equal \( B_{z} \) at the ECR surface since there produces the largest perpendicular energy \( W_{\perp} \). Should a particle move along the \( B \)-field line to a location \( B_{z}=B_{z} \), \( \gamma \) should be higher than \( \gamma \), \( \gamma_{c} \) from the invariance of \( \mu_{c} \) which is unlikely.

On the other hand, ions are not difficult to extract from a magnetic bottle since they are usually not well confined anyway due to the fact that \( r_{L} = r_{L} \) under \( T_{z} = T_{z} \), \( Z \) is very large. However, ECRIS ions are high-Z and \( kT_{iz} \) may be very low inside the space charge potential of electrons in the steady state. This can create the situation \( r_{L} = r_{L} \). Then, \( Z = \mu_{c}(B_{z}/\Delta \gamma) \), but \( \mu_{c} = \mu_{c} \gamma_{c}^{2}/B_{z} = kT_{iz}/B_{z} \). Thus \( \mu_{c} = \mu_{c} \gamma_{c}^{2}/B_{z} \), and the condition \( Z = \mu_{c} \gamma_{c}^{2}/B_{z} \) determines the minimum \( E_{z} \):

\[
E_{z} = \frac{1}{kT_{iz}} \frac{\mu_{c} \gamma_{c}^{2}}{B_{z}} \frac{d\gamma}{dt} = 90 \text{ V/cm}
\]

is the safe electric field to keep the ECR zone in position. On the other hand, ions are not difficult to extract from a magnetic bottle since they are usually not well confined anyway due to the fact that \( r_{L} = r_{L} \) under \( T_{z} = T_{z} \), \( Z \) is very large. However, ECRIS ions are high-Z and \( kT_{iz} \) may be very low inside the space charge potential of electrons in the steady state. This can create the situation \( r_{L} = r_{L} \). Then, \( Z = \mu_{c}(B_{z}/\Delta \gamma) \), but \( \mu_{c} = \mu_{c} \gamma_{c}^{2}/B_{z} = kT_{iz}/B_{z} \). Thus \( \mu_{c} = \mu_{c} \gamma_{c}^{2}/B_{z} \), and the condition \( Z = \mu_{c} \gamma_{c}^{2}/B_{z} \) determines the minimum \( E_{z} \):

\[
E_{z} = \frac{1}{kT_{iz}} \frac{\mu_{c} \gamma_{c}^{2}}{B_{z}} \frac{d\gamma}{dt} = 90 \text{ V/cm}
\]

Here, \( \mu_{c} \gamma_{c}^{2}/B_{z} = 50 \text{ eV/cm} \) was assumed. Right E-field should thus be within the range, \( 0.9 \leq E_{z} \leq 0.9 \).

3. Novel Extraction of Trapped HCS Ions

Conventional technologies (i)-(iii) are a destructive extraction in terms of the original light of ECR heated potential-well. We search a non-destructive but efficient way of extraction. The problem can be solved if only the trapped ions are accelerated by an axial electric field \( E_{z} \) inductively induced inside the ECR zone, without loosing the ECR heated hot electrons from the zone.

3.1 Theory of E-Field Extraction

Here we estimate a right range of the E-field intensity for the novel extraction technology proposed.
3.1.2 Motion of Charged Particles Inside an Electron Space Charge Potential of ECR Ellipse

Here, we study if heavy ions can indeed be extracted out of an ECR ellipse by applying an electric field. The original electron space charge potential inside of ECR ellipse is filled by ions but only partially, since the peripheral ions are heading outward walls from the time of the formation of potential well. Therefore, the potential barrier needed to cross for trapped ions is the potential barrier generated by the excess charge density, \( \Delta \phi \). In the energy-wise, \( \Delta \phi \gg kT_{iz} \) for high-performance ECRIS's and \( kT_{iz} \ll 50 \text{eV} \) for typical devices. The e-beam injection at LBL lowered the height of positive plasma potential \( V_p \) which is same to lower \( \Delta \phi \) by \( \Delta \phi_{eB} = 10\text{eV} \) to obtain \( \Delta \phi \). Their experiment can be explained well by the set of parameters: \( Z = 10 \), \( \Delta \phi_{eB} = 20\text{eV} \), and \( kT_{iz} = 50 \text{eV} \) for this. For this we need an extra \( E_z \) to satisfy \( \Delta \phi = 20 \text{eV} \). We choose \( E_z = 4 \text{ V/cm} \) which satisfies also the above condition \( 0.90 \lesssim E_z V/cm \lesssim 0.10 \). A drastic improvement in \( \eta \) is evident with the E-field method. Table 1 compares the \( \eta \) with the e-beam case.

**Table 1: Improved \( \eta \) by E-field method**

<table>
<thead>
<tr>
<th>( E_z = 4 \text{ V/cm} )</th>
<th>( Z = 10 )</th>
<th>( \eta (\text{e-Beam}) )</th>
<th>( \eta (\text{E-Field}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z = 15 )</td>
<td></td>
<td>24.5</td>
<td>169</td>
</tr>
<tr>
<td>( Z = 10 )</td>
<td>7.39</td>
<td>19.9</td>
<td>169</td>
</tr>
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</table>

Fig. 1 shows schematic drawings of the next-step ECRIS proposed. The emittance is expected good because of the use of drift tube with a gridded front and due to the fact that E-field method can extract highly HCS ions whose \( T_{iz} \) is likely zero due to their location of confinement close to the bottom of parabolic potential.

The axis of a cylinder of radius \( a = 1 \text{ m} \) filled with 100% electrons at density \( n_e = 10^{12} \text{ cm}^{-3} \) is holding a negative electric potential against grounded wall given by

\[
\Delta \phi = \frac{n_e e^2}{4\varepsilon_0} a^2 = 4.52 \times 10^{-9} n_e (\text{m}^3) \times a (\text{m})^2 = 4.52 \text{ GeV} \quad (8)
\]

Such a charge cylinder contains a huge acceleration gradient, \( E_z = 9.04 \text{ GeV/m} \) at the wall, although zero at \( r = 0 \).

This paper proposes a utilization of such space charge field for an economical alternative of heavy ion accelerators. We will use a fat elliptical chamber of length \( 2m \) filled with only electrons. In the both midplanes of its depth as well as of its length the electric potential distribution should be similar to the one for circular cross section of charge cylinders. If for an example, \( ^{238} \text{U} \) ions at \( Z = 60 \) were injected at one end of the ellipse, they would attain the energy \( 1.14 \text{ GeV/nucleon} \) at the midplane of ellipse. What is difficult is to extract particles right at the bottom of the potential-well. Our innovative idea of achieving this is to flatten the potential in the deceleration section by using a z-pinch plasma. A high energy, focused beam may be extracted from the other end of ellipse.

Fig. 2 shows a z-pinch device to be set along the axis starting from the midplane. The plasma will be fired at the moment when a bunch of ions impinged in to the first electrode. The metallic gas needed for producing solid-density plasma will be generated itself from electrode surfaces when flashes over. Inside the plasma the self-defocusing effect of ion beam can be neutralized and thus the IxB self-focusing effect may become effective before reaching the relativistic speed. However, our calculation shows that force density of the self-focusing is much smaller than the kinetic pressure of pinch plasma. With moderate to solid-state z-pinch densities, \( n_e = 10^{24} \text{ cm}^{-3} \), we obtain \( p = \frac{1}{2} kT = 1.6 \times 10^5 \text{ atm} \). Sumbillimeter focus size can thus be expected.

**Fig. 1.** E-field extracting, efficient ECRIS schematics.

**Fig. 2.** A 2m, 4.25GeV advanced accelerator schematics.

4) A. Irani and N. Rostoker, Particle Acc. 8, 107 (1978).
国際単位系 (SI) と換算表

<table>
<thead>
<tr>
<th>表 1</th>
<th>SI 基本単位および補助単位</th>
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<td>アンペア</td>
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<td>ケルビン</td>
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<table>
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(注)
1. 表 1 中には「国際単位系」第 6 交、国際度量局 1990 年改正による。ただし、1 eV および 1 J の換算は CODATA の 1986 年推薦値による。
2. 表 2 および表 3 中には有理数、無理性および数が含まれているが、1 個の単位で 2 で整理した。
3. 2.58 x 10^-15 C/kg は、JES では電荷の大きさを表す場合に使われ、2 のテラフリに分解されている。
4. RCDR/86 指令によっては、1 で示されて表中の単位を推奨するもので、表 2 のテラフリに入れ替える。

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(86 年 12 月 26 日現在)