Proceedings of the 1981 Linear Accelerator Conference
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October 19—23, 1981

Edited by
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(Conference Summary by P. Grand, page xv, concluded the  
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EDITORS' NOTE

The 1981 Linear Accelerator Conference was held at Bishop's Lodge, Santa Fe, New Mexico, using exactly the same format that was so successfully initiated at the previous conference in 1979. This was the eleventh conference, and again was the largest, with 230 registrants. Of these, 87 were from Los Alamos and the others were from 28 domestic and 19 foreign institutions. Forty-one papers were presented orally, and 54 as posters; the split between the United States papers and the international ones was almost half-and-half, indicating the strong activities in this field around the world.

The papers are presented in the Proceedings in the same order that they were given at the meeting. We thought this might recall some of the pleasant memories of the meeting itself. The poster sessions were set up to have a mixture of topics. The papers are printed as received; the assistance of the session secretaries and the authors in reviewing the original manuscripts during the conference is very much appreciated.

The discussion following the oral papers was recorded and transcribed, then rewritten, with heavy pruning, in the form of further remarks by the speaker. The editor takes full responsibility for any errors that may have occurred; the speakers did not edit these remarks.

The hard work of all those on the acknowledgment page is hard to applaud enough. It was a real pleasure to work with such a top-flight team. However, a special thanks must be made to Jim Stovall and Sue Nicol, who helped with everything, to Stacey Fradkin who directed the word-processing capabilities, and to Louise Taylor for handling these Proceedings.
CONFERENCE SUMMARY
Pierre Grand

The 1981, eleventh Linear Accelerator Conference was held from October 19 to 23, in Santa Fe, New Mexico, sponsored by the Los Alamos National Laboratory. This meeting can be termed a great success, thanks to the organizers in the Accelerator Technology Division of Los Alamos. I will single out here Bob Jameson and Jim Stovall, who as chief cooks, did most of the organization, and also Sue Nicol who carried the brunt of the work for them. The choice location for the conference helped a great deal. Bishop's Lodge, despite some trepidations about sufficient accommodations, proved to be the most congenial Shangri-la, providing just the right amount of spice to the meal. However, success would have been impossible without first class meat and potatoes; these were provided in 95 good technical papers presented during the conference. Thanks to all participants who made it possible.

Linear accelerator conferences have been held since 1960. First started at Brookhaven at a time when large proton linear accelerators were being planned, these meetings gained impetus with the design and construction of LAMPF, and the linac injectors for the BNL-AGS and FNAL synchrotrons. In the 1970s interest remained high. Transfer of information on experience gained in machine operation, and proposals for new linear accelerator facilities kept attendance up. In fact, attendance at linac conferences has grown. From about 50 attendees in the early 1960s, it reached about 150 in the 1970s. The 1981 conference gathered 230 participants. Foreign participation was especially strong, with good representation from Japan and Western Europe. This record attendance is a good indication of the continuing interest and excitement in the field of linear accelerators. Better understanding of the theory and new technologies are opening up new applications that may be promising for solving long-term energy needs, as well as providing radical improvements in accelerators being designed or under construction.

The meeting opened with a remarkable reminiscence on the MTA project by P. Livdahl. Although classified for many years, this project, which was terminated after a few years of intense accelerator development, has had long-lasting fruit in the training of a generation of accelerator builders, particularly linear-accelerator builders. This was a time when new ideas could be tested, even if it meant the construction of a 12-MHz, 60-ft-diam drift-tube
linac, with drift tubes weighing forty tons, having bore holes large enough for a man to crawl through. This was a time when things could get done; over a 5-year period the group under Lawrence's direction actually built four large accelerator prototypes, from the so-called MTA to the A-48, 7.5-MeV working deuteron linac. This was a time when machines could be built successfully without fancy computer programs, and especially without environmental impact statements. Well, so much for that. Now, to the highlights.

Although it is difficult in a few words to relay the tone of the conference, we can classify it as forward looking: very few papers dealt with existing operating machines; on the other hand, a number of ongoing projects and proposals were presented, pushing the state-of-the-art in all aspects of machine development.

A number of papers reported on the progress of FMIT (a 35-MeV, 100-mA, 100% duty factor deuteron linac being developed for Fusion Materials Irradiation Testing). It is the first attempt at continuous-wave (cw) linacs since the now famous MTA project, almost 30 years ago. The development of this accelerator is important to future applications of linacs. The last few years have seen a renewal of interest in the United States and Canada in the use of accelerators for production of nuclear fuel. These would require proton or deuteron beams in the gigaelectron volts energy range and several hundred milliampere continuous currents. The success of FMIT could therefore strongly influence the future of cw linac applications. It is viewed as a proof-of-principle demonstration of the ability to handle large beam currents and manage the problems associated with continuous radio-frequency (rf) power. The unique problems concerning continuous beams were discussed with respect to ion source design, nondestructive beam diagnostic, etc. Of course the major machine development sparked by the FMIT project has been the RFQ (radio-frequency quadrupole).

The RFQ, first proposed in this country in 1978, owes its success to the Los Alamos group who enthusiastically pushed its development for its application for FMIT and other projects. In principle, the RFQ offers enormous advantages over presently used linac-injector schemes; it replaces very high voltage Cockcroft-Waltons, choppers, and conventional bunchers while offering simplicity and close to 100% bunching efficiency. In only 3 to 4 years, laboratories around the world have joined the RFQ development effort. No less than 14 papers from 7 institutions were presented on the subject (out of 95 papers).
Specific plans are already being made to apply RFQs as integral parts of new or retrofitted injectors for several heavy ion and polarized proton-accelerator projects.

Another important technological advance that will greatly influence the design and operation of future linacs is the development of rare-earth permanent magnets. The importance of this development was evident by the number of speakers on the subject. After a modest beginning (the use of permanent-magnet-focusing quadrupoles was first proposed at Los Alamos for their PIGMI project) and a fear of losing the ability to adjust quad fields, New England Nuclear Corp. took a bold step of faith in adopting this technology for their 40-MeV proton linac constructed for the production of radiopharmaceuticals. This has given the impetus to develop an entirely new technology of permanent-magnet designs from dipoles to quadrupoles and sextupoles, as well as designs of adjustable field-magnet systems. Papers dealing both with the theory of design and with the engineering of these magnets indicate that the technology is maturing and will be used extensively on new linac designs. Even now, two commercial companies are in the business of producing and selling these components to the accelerator community.

The other high point of the conference was the very exciting development taking place in our understanding of beam dynamics. Ever since the classic work of L. Smith, R. Gluckstern, R. Chasman and others in the late 1960s, theorists have been at a loss to explain beam-emittance growth phenomena observed in operating linacs. Typically, factors of 2 to 3 emittance growth were measured, without obvious explanation for the growth. A number of workers have addressed the problem and, using somewhat different approaches, are shedding new light on the subject. In particular, L. Smith (LBL), R. Jameson (Los Alamos), I. Hoffman (Max Planck) and K. Mittag (KfK) presented papers on detailed treatment of beam-bunch behavior during acceleration, demonstrating the effect of space charge, mismatching, and tight coupling between transverse and longitudinal phase spaces resulting in the onset of instabilities within the bunch. These mismatches and instabilities lead to emittance growth that appears to be consistent with those observed experimentally. This work indicates that beam-emittance growth can be controlled by properly matching the transverse and longitudinal particle temperatures within the bunch, or, to use the newly coined
term, by equipartitioning. It is encouraging to see a picture emerging that will help clarify these effects and possibly provide the means of beam-emittance-growth control. However, there is still much to do before we will have good quantitative prediction of bunch growth. Other effects also influence the beam behavior, for example, longitudinal rf coupling, image effects, etc. This beam quality parameter will be very important in future applications of linacs where high beam currents, or very small output emittances, are required.

Also worthy of highlight are papers dealing with ongoing accelerator projects and those dealing with development of future projects.

F. Cole (FNAL) reviewed the field of collective acceleration. Although collective accelerators are types of linear accelerators, they have never been an integral part of these conferences. Collective accelerators in principle hold the promise of very high acceleration gradients (>100 MeV/m), hence the interest. However, although the physics principles appear sound, practical working devices have never been demonstrated. Of the many collective accelerator concepts developed, the electron ring accelerator (ERA) received substantial support during the 1970s. It was abandoned in this country and in Europe a few years ago. The work on this accelerator is apparently continuing in Russia with some measure of success. Among the many other concepts, several are being pursued in the United States at modest rates.

Another technology, which in the 1960s and 1970s appeared very promising and generated many interesting conference papers, was superconductivity as applied to linear accelerators. Superconducting linac cavities have met with some success, particularly as beam separators and heavy ion post accelerators (for example, raising the energy of ion beams exiting from Van de Graaffs). In both cases, beam currents are very small. In this context it was gratifying to listen to the only two papers on superconducting linacs, both from Argonne, describing the successful commissioning and routine operation of their heavy ion superconducting linac booster. This success demonstrates the viability of the technology for certain applications.

Another paper described the very recent coming on-line of the 40-MeV New England Nuclear proton linac which, after a 4-year construction period, has just accelerated a proton beam. This is noteworthy on two counts: it is the very first proton linac built by industry for industrial purpose (production of radio pharamaceuticals) and, as mentioned earlier, it is the first proton.
linac that uses permanent-quadrupole-magnet focusing throughout the entire machine. It is still too early to assess the success of that technology; the linac community will be following the commissioning and operation of this facility with great interest.

At this time, a number of proposed linac projects are generating good developmental work, some of which was reported at the conference. The long-standing program at Chalk River, to develop electronuclear fuel breeding using a nominal 300-mA cw, 1-GeV proton linac, has led them to concentrate on the development of high-current ion sources, injectors, and the low-energy front end of the linac, as well as development of disk-and-washer (DAW) structures for energies >150 MeV. The papers presented described some of their experiments and the difficulties one has to face with cw accelerators dealing with high current densities, multipactoring, thermal effects, etc. A developmental project called ZEBRA was described; it will consist of a 300-mA, 10-MeV front-end linac for what eventually might become a demonstration electronuclear breeder.

In a similar vein the most ambitious linac project presently on paper, the SNQ from KfK (Karlsruhe), was presented. The project generated a number of good, original papers describing various parts of the design study. This proton linac, to be a spallation neutron source primarily for neutron scattering research, will be a 1.1-GeV, 100-mA, 10% duty-cycle machine. A. Citron (KfK), who presented the project, is mildly optimistic and hopes that it may be the next large German accelerator project. Most interesting to the community was the development of a 325-MHz, 1-MW klystron rf power source for this project. Tests to date indicate tube efficiencies in excess of 70%. This is impressive.

Two papers presented by commercial firms described some of the work done to improve rf power sources. This is a subject that is always of great interest to linac designers. When considering future applications of linear accelerators, for example, spallation sources, heavy ion fusion drivers, etc., one is struck by the fact that the driving cost for these facilities is the cost of rf power. For the case of a 1-GeV, 300-mA cw electronuclear breeder, for instance, the cost of rf power is estimated at 70% of total accelerator-facility cost. Thus, advances in the technology of klystrons and power tubes are of the utmost importance, especially as they apply to increased efficiencies and lower costs. Development of high-power, low-frequency, gridded tubes
at EIMAC was described, as well as work taking place at Thomson-CSF on high-power klystrons. From these presentations, the SNQ work, and other papers at this conference, one is left with the feeling that this country is lagging in pushing development of new, better rf power sources, while Europe and Japan appear to be investing rather heavily in the further development of the technology.

Finally, portions of the conference were devoted to electron linear accelerators. Interest centers on two relatively new developments. On the one hand, a number of technically interesting papers dealt with pushing the state-of-the-art in microtrons, and especially racetrack microtrons. A number of ongoing microtron projects generated some fresh ideas on the subject. At the other end of the spectrum, SLAC participants described the development work taking place for the Single Pass Collider. This experiment presents some unique accelerator control problems dealing with the handling of a single, intense electron bunch.

Now, it is impossible to do justice to all papers presented during a week-long meeting, and many interesting presentations are not discussed here, such as the ongoing development of induction linacs for heavy ion fusion, the rather interesting medical electron-linac design discussed by Benguang (Republic of China), the status of ion source technology, advances in computer codes such as SUPERFISH evolving to ULTRAFISH, various computer control and diagnostic instrumentation schemes that always have a touch of home cooking, etc. Nor does this review do justice to the real value of holding the 1981 Linac Conference in a congenial, secluded spot conducive to discussions and the exchange of information and ideas.

Overall, it remained (as have all linac conferences to date) a highly technical meeting continuing the tradition of excellence in this somewhat specialized and eclectic field. Ongoing work and development on existing machines, as well as plans for future projects, promise an even better fare for the next Linear Accelerator Conference to be held in 1984.
ABSTRACT

The 1981 Linear Accelerator Conference was held at Bishop's Lodge, Santa Fe, New Mexico, October 19-23, 1981. This publication contains the texts of the invited and contributed papers.
THE LIVERMORE MTA PROJECT AND
ITS INFLUENCE ON MODERN LINACS

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In the early 1950's, a series of linear accelerators were built at Livermore, California which constituted part of the Material Testing Accelerator (MTA) Program. These linear accelerators, and subsequent development activities which derived therefrom, will be discussed.

Introduction

In the late 1940's, a program was initiated by Professor Ernest O. Lawrence and the University of California Radiation Laboratory (now known as the Lawrence Berkeley Laboratory) and the United States Atomic Energy Commission to investigate the possibilities of electronuclear breeding of Pu239, U233 and Tritium by irradiation of depleted uranium with accelerator-produced neutrons. A summary of the objectives of the entire program was written by C. M. Van Atta in 1977. A major component of the program was research and development of high current accelerators.

Since the program objectives were classified at the time of inception (declassified in 1957), as well as a production process being a goal, a site apart from the University of California, and an industrial partner were sought. The site selected was a World War II Naval Reserve Training Station at Livermore, California (this site is now known as the Lawrence Livermore National Laboratory). The Standard Oil Company of California formed a subsidiary called the California Research and Development Corporation (CR&D) to be the industrial partner.

The role of CR&D was to produce the engineering designs for the accelerators as well as the supporting facilities, and to construct and operate the MTA accelerators.

The MTA program was terminated in the mid 1950's with the discovery of what was then regarded as ample uranium deposits to meet the needs of the nuclear program. Thus the role for CR&D came to an end and the Corporation was disbanded.

The combination of the demise of the corporation, with the consequent dispersal of much of the staff, as well as the long delay in declassification of the corporation reports, etc., have conspired to keep much of this program from coming to the attention of any large section of the linear accelerator designers.

These factors have made the documented characteristics and performance of the prototype accelerators built during this program sketchy at best. This paper must therefore be viewed as a compilation of data available from the few actual reports I have and my recollections relative to the project.

I worked as an accelerator physicist on the prototype accelerators of the MTA program. In the course of design and construction of subsequent linacs I have discussed some of the features of the MTA machines with other linear accelerator specialists. Such discussions, coupled with a curiosity about the MTA accelerators, have motivated the Program Committee for this conference to invite me to prepare this paper.

To achieve the ultimate electronuclear breeding capability it was realized that the deuteron energy would need to be in the range of 350 MeV with average beam currents of at least tenths of an ampere. Since these requirements were far beyond any previous experience, it was determined that the Mark I accelerator would be constructed to investigate high current ion production at lower energies. Thus Mark I was a prototype for a much larger facility which was concurrently being planned for construction at Weldon Springs, Missouri.

MTA Linear Accelerators

There were a series of linear accelerators built and tested during the MTA program. This section of this paper will record the characteristics and performance of the prototypes, and how the prototype experience influenced future linacs.

MTA Preaccelerator

The limitation imposed by available high-voltage, high-current, dc power supply technology determined many of the characteristics of the preaccelerator. The development of the ion source and pre-accelerator has been described in the technical literature by Lamb and Lofgren. Figure 1 is a drawing of the Mark I preaccelerator.

Parameters for operation of the ion injector at the largest dc beam currents of protons that were maintained over periods of hours, are shown in Table 1. Maximum deuteron beam obtained was about 10% smaller. Much larger beam intensities were achieved for short periods of time.
The Mark I pre injector was common to each of the MTA linear accelerators.

Its operation and continued development led to: a) the development of more reliable and better regulated high voltage dc power supplies; b) a more complete understanding of the behavior of electrical discharges in vacuum; c) a realization that very high currents of ion beams can be achieved reliably and with ion beam characteristics that would be useful for not only the MTA program but for future generations of accelerators and plasma devices as well.

**Mark I Accelerator**

The first linear accelerator built as a part of the MTA program was called the Mark I accelerator. The design criteria for this accelerator were determined from what was deemed at that time to be practical from the point of view of the state of the art of existing hardware and technology.

![Figure 1. The Mark I pre-Accelerator.](image)

The only linear accelerator which had previously been built was the 32 MeV linac built at UCRL in Berkeley by Luis Alvarez. The accelerating cavity of that machine resonated at 200 MHz and the rf excitation power was supplied by surplus World War II radar transmitters. The tubes for these transmitters were unreliable and were severely limited by average power and duty cycle ratings.

Another 200 MHz, 68 MeV linac was concurrently being built at the University of Minnesota. It's construction was started in 1949 but completion was substantially delayed by difficulties in the development of a suitable rf power source. Before the "resonatrons" for this machine were available, the first cavity (10 MeV) was operated with "Frank" oscillators.

The Radio Corporation of America (RCA), had by the late 1940's produced prototype triodes for CW operation in the range of kW of rf power output per tube with an upper frequency limit of 12 MHz. Figure 2 is a photograph of the RCA 5831, which was commonly - but not necessarily endearingly - called the "bucket-of-bolts," due to its method of construction. The anticipated availability of those tubes determined the operating frequency - 12 MHz. This, together with the desired output energy - 15 MeV protons - determined the design dimensions of the cavity.

The Mark I linac cavity was a single resonant structure, 60' in diameter and 60' long, containing 8 full drift tubes, with 1 half drift tube at the low energy end of the cavity. Magnetic focusing was provided which was produced by solenoidal magnets housed in each drift tube. The shell of the resonant cavity was constructed of a water-cooled copper liner which was housed in a vacuum enclosure made of welded and reinforced 1/2" thick steel plate. Figure 3 is a photograph of the vacuum tank for Mark I with the building being constructed around it.

Figure 4 is a photograph of the inside of the Mark I accelerating cavity and Figure 5 is a cross sectional drawing of the Mark I accelerator.

<table>
<thead>
<tr>
<th>Continuous Operation</th>
<th>Pulsed Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Grid</strong></td>
<td><strong>Ground Electrode Grid Used</strong></td>
</tr>
<tr>
<td>Beam current</td>
<td>-2.0 A at 100 kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>-2.0 A at 100 kV</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>3/4 A at 100 kV</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>3/4 A at 100 kV</td>
</tr>
<tr>
<td>Beam divergence, 1/2 angle</td>
<td>70 in. from the source &lt;5°</td>
</tr>
<tr>
<td>Arc chamber hydrogen pressure</td>
<td>1.1 A</td>
</tr>
<tr>
<td>Arc voltage</td>
<td>50 μ</td>
</tr>
<tr>
<td>Arc current</td>
<td>35 V</td>
</tr>
<tr>
<td>Source magnet</td>
<td>80 A</td>
</tr>
<tr>
<td>Source magnet</td>
<td>3200 gauss</td>
</tr>
<tr>
<td>Ground electrode magnet</td>
<td>200 gauss</td>
</tr>
<tr>
<td>Focusing magnet</td>
<td>3000 gauss</td>
</tr>
<tr>
<td>Vacuum tank pressure</td>
<td>2 x 10⁻⁷ mm Hg</td>
</tr>
<tr>
<td></td>
<td>2 x 10⁻⁷ mm Hg</td>
</tr>
</tbody>
</table>

Table 1

Proton performance of the MTA preaccelerator.
Fig. 1. Cross-sectional drawing of the Mark I accelerator.

Table 2
Mark I Accelerator Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Injection Energy</td>
<td>80 KeV</td>
</tr>
<tr>
<td>Proton Exit Energy</td>
<td>15 MeV</td>
</tr>
<tr>
<td>Frequency</td>
<td>12 MHz</td>
</tr>
<tr>
<td>Cavity Length</td>
<td>60 feet</td>
</tr>
<tr>
<td>Cavity Diameter</td>
<td>60 feet</td>
</tr>
<tr>
<td>No. of accelerator cells</td>
<td>8-1/2</td>
</tr>
<tr>
<td>G/J</td>
<td>0.25</td>
</tr>
<tr>
<td>Synch. Phase Angle</td>
<td>-74°</td>
</tr>
<tr>
<td>Proton End-to-End Voltage (Peak)</td>
<td>22.5 My</td>
</tr>
<tr>
<td>Average Gap Gradient (Peak Volts)</td>
<td>1.5 My/ft</td>
</tr>
</tbody>
</table>

RF System - 18 oscillators, 0.5 Mw ea  
tube type 5831

Vacuum System - Mercury Diffusion Pumps  
48 - 32" Diameter  
Liquid N$_2$ Baffles on each

Roughing System - 1500 CPM Kinney Pumps  
- 54 each  
- with Liquid N$_2$ Traps
Operation of Mark I was terminated in late 1952 after having accelerated protons to about 15 MeV for short periods of time. Peak currents as high as 225 mA of protons were achieved at a duty cycle of more than 20% and 100 mA were accelerated in a CW operating mode.

Mark I had revealed that the operating gradient required for the acceleration of deuterons, at least a frequency of 12 MHz, was much too high and that sparking in the first accelerating gaps, with such large stored energy in the cavity, so badly damaged the surfaces of the low energy end drift tubes that operation could only be sustained - even for proton acceleration - for short periods of time.

This experience initiated an expanded program of development effort to a) develop rf amplifier tubes with a higher frequency limit; b) develop a research program to understand sparking phenomena and to determine practical limits for operational accelerating gradients; c) develop new vacuum techniques, such as linear jet diffusion pumps, low-temperature refrigeration systems to replace the liquid nitrogen requirement for mercury pumps, and investigate electronic ion pumps; and d) develop accelerating geometries to circumvent the low-energy accelerating gap voltage holding problems.

RCA had by this time developed a triode which had a ceramic cylinder vacuum enclosure in which all vacuum seals are welded, or brazed. They had further developed the shielded grid concept for large power amplifier tubes. These factors lead to the successful completion of the 2332D which were capable of delivering 600 kW cw at 50 MHz. Figure 6 is a photograph of this tube. This development ultimately resulted in the 7835 which has commonly been used for U.S. linacs at 200 MHz.

At Berkeley a group started a research program to investigate rf sparking phenomena. Although no complete theory was evolved which explained the influence of all of the parameters such as, gap length, pressure, presence of contaminants, surface condition, surface material, stored energy, frequency, etc., a criterion, thereafter called the Kilpatrick criterion, was identified which quite accurately defined a threshold for sparking with rf or dc voltages. This criterion relates the energy, \( W \), which can be gained by an ion crossing a gap with the cathode gradient \( E \). This empirical relationship can be expressed as:

\[
W_0 = \frac{1.7 \times 10^5}{E} e^{\frac{1.8 \times 10^{14} V^3}{CM^2}}
\]

where \( I_0 \), the current in the gap is expressed by \( IE^2 e^{-b/E} \). This relationship was plotted relative to the experimental data recorded at that time as shown in Fig. 7.

Beyond this investigation there have been later efforts at MURA and subsequently at CERN to develop a more substantial physics basis for vacuum sparking. These efforts have offered a better understanding of the phenomena but the criterion postulated by Kilpatrick still serves as
was energized by six RCA 2332 amplifier tubes each
magnets the drift tube configuration was designed
The resonant frequency was 18.6 MHz. The cavity
cavity. Proton output energy was about 500 keV,
oscillator or by a feedback signal from the
amplifier could be driven either by a master
drift tubes with 3-in-diameter bore throughout.
constructed of copper-clad steel and contained 22
to operate in the 2 BA mode. The cavity was
operating at 100 kV and an Alvarez cavity about 12
operation in 1954, consisted of the ion injector
delivering 100 kW of continuous rf power. The
cavities and to calculate particle trajectories in
accelerators of the MTA program.

cavities although with modern day vacuum
techniques the criterion has proven to be very

cavities. Both cavities were tuned to the
two resonators were excited independently,
each by an RCA 2332 amplifier tube. Both
amplifiers were driven from a common rf source with
variable delay line to adjust the phase between
the cavities. Both cavities were tuned to the
driving frequency by servo-controlled, variable
capacity tuners mounted directly below the drift
tubes. The continuous beam from the injector was
bunched at the accelerator frequency and adjusted
in phase for maximum acceptance at the first
accelerator gap. In addition to the drift-tube
magnets, solenoidal magnets were located between
the buncher and the first accelerating gap, between
the two cavities and at the output end of the
second accelerating section. An average axial
magnetic field strength up to 10 kG could be
maintained along the beam path. This field
strength proved to be adequate to prevent
significant radial beam losses for both proton and
deuteron acceleration. The quarter-wave
accelerator was capable of accelerating 300 mA of
protons to 500 keV with the injector operating at
87 kV and 0.5 A. Deuteron acceleration again was
limited due to the voltage limitation of the
injector power supply.

Quarter Wave Accelerators

Concurrently with A-54 operation a
quarter-wave stem accelerator as shown in Fig. 8
was built and tested. Each of the two resonators
consisted of a drift tube mounted on a stem which
was the center conductor of an open-ended 3/4 λ
transmission line, adjusted to oscillate at 24.3
MHz. To provide room for solenoidal focusing
magnets the accelerating gaps were spaced at 3/2
βλ. The two resonators were excited independently,
each by an RCA 2332 amplifier tube. Both
amplifiers were driven from a common rf source with
a variable delay line to adjust the phase between
the cavities. Both cavities were tuned to the
driving frequency by servo-controlled, variable
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protons to 500 keV with the injector operating at
87 kV and 0.5 A. Deuteron acceleration again was
limited due to the voltage limitation of the
injector power supply.
A-48 Accelerator

The A-48 accelerator\(^{12}\) consisted of the quarter-wave accelerator described above followed by two Alvarez-type cavities each about 12 feet in diameter and 20 feet in length which were resonant at 48.6 MHz (see Fig. 9). The drift tube configuration was designed to operate in the 18 mode with solenoidal magnets in the drift tubes. The required injection energy was matched to the output of the quarter-wave accelerator. The output energy was 3.75 MeV for protons and 7.5 MeV for deuterons. Since the quarter-wave accelerator operated at half the frequency of the Alvarez cavities, the beam was bunched into every other accelerating gap. The design rf gradient was slightly less than 1 MV/m for deuterons, which was easily maintained. At half this gradient proton beam currents in excess of 100 mA cw were accelerated. Deuteron currents were limited to 30 mA by two factors: the voltage limit on the injector power supply and by activation and damage to the target by 7.5 MeV deuterons. At this time in the program (1955) the funding for MTA accelerator development was eliminated and the program was stopped, the cavities were disassembled and the building space was utilized for fusion research.

To achieve these goals required the courageous and visionary leadership of persons like Lawrence and Van Atta as well as a willingness on the part of the government to pursue projects which are considered to be a gamble. Does this same level of leadership and adventurous spirit continue today?

The project spurred high intensity investigations of ion sources, pre-accelerators, magnet focusing systems, rf power sources, accelerator cavity design, power supplies and vacuum components. All of these have played an important part in bringing technology to the state of development that accelerators enjoy today.

Acknowledgements

After thirty years it is impossible to credit all of those persons who worked on the project but I want to particularly thank Dr. C. M. Van Atta, who is now retired from the Lawrence Livermore National Laboratory, and Dr. John Frazier of Chalk River Laboratory in Canada who were of great help in finding reference material.

References

4. L. Alvarez et al, Berkeley 40 MeV Proton Linac, UCRL-236
Discussion

One spin-off I didn't mention; they anticipated extending the accelerators to 350 or even 500 MeV, so a program for manufacturing copper-clad steel was started. The warehoused copper-clad steel later built the Hilac, A-48, and the linac tanks for ANL and BNL. It was a resource that we enjoyed for many years.

A comment on the drift-tube stems: they were vertical in the original design, but in the modified design they had to be slanted to get the proper drift-tube spacing. We were very worried about the stem currents, but we never saw any effect in operation.
Summary

Experience with rf joints in a cw Alvarez linac is reviewed together with details of renewed tests on a flexible drift tube suspension. Mechanical and rf design of a replacement 268 MHz linac are discussed.

Introduction

Linear accelerators with a 100% duty factor (cw) are being operated at the Chalk River Nuclear Laboratories as part of a program to develop an economic fissile fuel breeder. The high average power density deposited by cw operation introduces problems on rf cavity joints and penetrations. A 25 cell Alvarez tank with a design field gradient of 2.0 MV/m has been operated at full power and has been used to accelerate 1-2 mA proton beams up to 3 MeV. This tank continues to be used as a test bed for the investigation of high-power cw rf problems. Based on experience gained from the operation of the existing tank a replacement linac is being designed to test several new design concepts.

Description of Linac

A cross section of the Alvarez accelerator is shown in Fig. 1. Input and output energies are 0.75 MeV and 3.0 MeV respectively. The 0.711 m diameter cavity is 1.605 m long and resonates in the TM010-like mode at 267.5 MHz. Power to the structure is delivered by a RCA 2054 triode. To attain the 2 MV/m design gradient requires 168 kW of cw power. The cavity has no adjustable tuner and has a frequency shift with power of 0.9 kHz/kW. Tank frequency is used to correct the frequency of the low power oscillator that feeds both the tank high-power rf system and the amplifier driving a single gap 267.5 MHz buncher.

The half-drift-tubes of the first and last accelerating cells are mounted on flexible end plates. These copper plates (Fig. 1) form the ends of the rf cavity and are connected to the tank vacuum end wall with bellows. The end plates are electrically connected to the cylindrical cavity walls through a spring loaded copper-copper knife edge contact and can be used to adjust field tilt along the length of the structure.

Drift-tubes are mounted to the outer wall by a complex mechanical system that permits drift-tube alignment from the outside. Each drift tube has a quadrupole electromagnet with a 9 mm bore radius and 6.5 kg/cm² field gradient. The drift-tubes were aligned conventionally with a high quality optical telescope centred on the magnetic quadrupole magnet centres.

Vacuum during operation is maintained by a 1000 g/s ion pump that is connected to the tank via a manifold in which a sublimation pump is mounted for additional pumping during rf conditioning. The tank vacuum connection is made with a series of water cooled slots. A copper plate is mounted inside the manifold to reduce the penetration of rf field from the tank into the ion pump.

Rf power is coupled to the tank by a central horizontal nominal 150 mm (6-1/8 inch) coaxial line not shown in the figure.

Cooling for the tank shell is provided by water circulating in long pipes soldered to the tank body. The rf end plates are cooled near the center by conduction from the water cooled half-drift-tube and by a cloverleaf pattern of water tubing brazed to the outside surface. End plate cooling, particularly in the area of the joint to the cylindrical tank wall, is barely adequate for cw operation.

The beam line from the injector to the linac is 7.5 m long and consists of seven quadrupole doublets, a quadrupole triplet and two 45° bending magnets. A single gap buncher, powered by a separate 400 W amplifier, is located 1.26 m from the first linac accelerating gap. The buncher aperture is 15 mm. The high average power of dc beams in the input beam line requires careful cooling all along the beam line, particularly at the first bending magnet and at the entrance to the tank and buncher. Cooled apertures are built into the line at several locations and all bellows are lined with cooled solid shields to protect them from scattered beam.

The output beam line consists of a quadrupole doublet, a beam diagnostics section and a high power beam dump. For the initial beam measurements a fast kicker magnet has been used in the
diagnostic section. An energy analyzing magnet capable of operation in the cw beam is presently being fabricated.

Rf Operation

The main overheating problem encountered during rf commissioning was associated with the bellows connecting the drift-tube stems to the cylindrical cavity walls. Severe heating of the bellows occurred initially at about 10% the design power. Several techniques were tried to short the rf currents that feed through the bellows but were unsuccessful. As a temporary solution copper shunts were soldered between the stems and the tank wall. This solution, however, does not permit mechanical realignment and makes replacement a very difficult task.

The drift-tube stem was extended and a waveguide beyond cutoff approach, where the rf field should be highly attenuated before reaching the bellows, was then attempted on the last drift-tube stem because it was the most accessible. Severe heating (~40°/kW) again was found to occur. Shifting the cell boundary by flexing the high-energy end plate 5 mm outward from its design position reduced this heating to <0.1°C/kW, with an associated small charge in on-axis field pattern along the tank. This experiment showed that net stem currents arising from unequal charging currents on adjacent cells were the main cause of heating. A careful choice of stem location on the drift-tube boundary might minimize the net currents. Shifts in tuner or postcoupler positions, once operation of the tank begins, would be expected to easily perturb this balance, and a renewed search for a current-shorting mechanism was started.

Figure 2 shows a stem-to-tank wall geometry that has been high power tested. Two 3.68 mm diameter (uncompressed) copper-beryllium springs were located between grooves on the 25 mm diameter stem about two stem diameters from the inside wall of the cavity. This geometry which is similar to one tested in a TEM mode cavity at Los Alamos kept the bellows temperature rise at full power to about 1°C even at the correct end plate position mentioned above. Tests are continuing to accumulate many hours of operation before disassembly and inspection of spring contacts. The measurements do demonstrate the suitability of such a joint for high-power cw DTL tanks.

High power cw operation has resulted in a number of coupling loop problems and in overheating of the end plate-to-cylinder joint. The coupling loop problems are described in a companion paper at this conference. New construction techniques described below should eliminate the end plate problem.

Future Development

A 2.0 MeV output energy radiofrequency quadrupole (RFQ) will serve as the injector for the Alvarez linac of the ZEBRA accelerator. A 2.0 MeV drift-tube cell is essentially identical to a 2B cell at 0.5 MeV. It is therefore possible to model the early cells of a higher energy 2B linac with a conventional injector. A 14 cell 2B replacement tank (2BLAT) that models the first cells of the ZEBRA linac is being designed. Output energy will be 2.6 MeV and cw proton beam current will be 20 mA. The existing 750 kV injector at CRNL will be used but will be run at 600 kV to improve reliability. The operating frequency will be 268 MHz to make use of the existing high power rf source.

The tank shell will be made of solid copper because of difficulties in obtaining copper-clad steel. A girder drift-tube suspension scheme will be used to gain experience for future accelerator breeder structures where remote handling may be necessary. The use of the girder system permits the end plates to be an integral part of the tank shell and removes one source of overheating encountered on high duty factor tanks. A spring joint similar to the one described above will be used to short rf currents at the stem-girder interface.

Two tuners will be used to stabilize tank frequency against shifts with temperature. Cavity joint problems similar to those experienced with the drift tube stems are expected with the tuners and will be initially investigated on a 270 MHz resonant rf load that is under construction. Post couplers on every second cell will be used to stabilize the accelerating fields against tilts introduced by the tuners.

Permanent quadrupole magnets purchased from New England Nuclear Corp. will be used in the first five drift-tubes to obtain experience with these magnets in a cw accelerator. The drift-tube diameter, however, is maintained at 135 mm to allow these drift-tubes to be replaced with ones containing electromagnets should the need arise.
The increased cell lengths afforded by higher injection energy of the RFQ permit shaping of the drift-tube faces of the first cells to improve the shunt impedance (up to 35%) while maintaining sufficient quadrupole magnet space. The maximum gradient on the drift tubes is 1.25 times the Kilpatrick limit. This value is twice the field in the present linac.

Conclusions

Experience with cw operation of a drift-tube linac demonstrates a continuing need for improved rf contacts. A workable solution has been found for drift-tube stem joints. It is expected that this solution should suffice also for post-couplers. A new linac to be completed in 1983 is being assembled. It will allow testing of tuners and several new construction techniques.

References

8. J.C. Brown and R.M. Hutcheon, "Design Considerations for a Developmental High Power Coupling Loop to Drive a Resonant Load", proceedings of this conference.

Discussion

In our sparking experiments, we will have 400 kW available, enough to exceed twice the Kilpatrick limit. We do not include a transit-time correction in our Kilpatrick limit numbers.
A review is given on five years of operation of the Unilac heavy ion linear accelerator. Important developments of subsystems and their present status are described. The current upgrading, initiated mainly to increase the output energy to 20 MeV/u for the heaviest elements, includes also an extensive improvement program of existing equipment. The injector beam line is completely reconstructed in order to increase the radial acceptance by a factor of three, and, in addition, part of the control system is prepared for multi-beam operation.

Introduction

Experiments with the Unilac started in 1976. The first Uranium beam was accelerated by beginning of April 1976. The development of operation and the performance of components were described in a previous status report. References for the different parts of the machine and for special features are given there, too. More recent research and development activities as measurements of the Widemann space charge limit, beam diagnostic and rf high power amplifiers have been reported elsewhere. A five months shut down from August '81 to January 1982 will be used to increase the energy of the Unilac by adding two Alvarez tanks. Details have been outlined in a previous paper.

Unilac Operation

The development of Unilac operation statistics can be seen from figure 1, which displays the time fractions of the total operation time since 1976. Target time means beam on target for production runs of the main experiment. Retuning of source or beam transport is not included, nor the number of parasitic target hours which are possible due to the beam splitting system. The tune-up time contains both the tuning of the accelerator and the transport and matching to the experiment. Unscheduled down time is not only accounted for hardware failures but also for time lost by unduly strong plasma oscillations of the ion source or retuning difficulties of the operation crew.

The fraction of target time was continuously increasing since the commissioning in 1976. The efficiency in the first year was affected by initial five days instead of seven days operation and major problems with rf-components and magnet power supplies. Target time was increased further in 1977 despite a decreasing reliability of some components. The two shut downs of four to six weeks each per year were dedicated to necessary improvements or completions of equipment but there was hardly time for extensive check-out of new equipment nor for accelerator experiments. In 1978 more shifts for accelerator experiments, development and additional short-term maintenance were introduced resulting in a significant reduction of unscheduled down time. Also the tuning time went down despite the introduction of the beam splitting and increasing demand for good micro structure of the beam with respect to time and energy width of beam bunches needing especially careful tuning of the machine. As the major hardware improvement programs had been finished it was decided to change the schedule by beginning of 1979. Every fourth week was then scheduled for maintenance and development. Maintenance and improvement work is partially done in shifts. This operation rhythm proved favourable for the Unilac and led finally to about 60 percent target time in 1981. This figure corresponds to about 75 % of scheduled time. The fraction of parasitic target hours is in the range of 25 to 30 % of total operation time. Beams for parasitic experiments cannot be provided if the intensity requirements of the main user leave no reserve, if frequent energy changes would take too much tuning time or if multi charge operation is required in the straight through Y-branch for very high intensities.

The increasing support by the computer control system both by off-line and on-line programs had helped to reduce tuning time despite of a significant increase of isotope and energy changes per year since 1979. The connection of rf systems to the computer control and the reconstruction of the injector, which will be described later, will lead to a further improvement in this respect. The latter should also help to reduce the stress of ion sources and the number of replacements. The time lost for source replacement and corresponding retuning is about 1 hour on the average for most of the elements. If sophisticated isotope separation is requested as e.g. for a clean 208Pb beam from natural material the average is about 2 hours.
In 1981 mainly rf systems, injectors and magnet power supplies contributed to the down time of the Unilac. For the various rf systems the problems are of different nature. The Wideröe amplifiers showed reliable rf performance despite of the fact that they are run up to 40 % above their design values, but the amplifier electronics caused increasingly down times because of corrosion on electronic prints.

During several years tube problems did not allow to run the Alvarez structure at power levels which would be necessary for the acceleration of gas stripped very heavy elements. Within the last two years this situation has changed. Alternate programs for the Alvarez rf amplifiers to achieve 1.6 MW peak power offer now three solutions. Some failures of the presently used tube type have been fixed by the manufacturer, and an alternate tube for the same plate circuit is on the market. In addition, a new final amplifier was developed from an industrial manufacturer with another tube, having successfully demonstrated 1.6 MW at 25 \% duty cycle.

The rf amplifiers for the single gap cavity structure could not be operated at the full power ratings in the past because the frequency tuning of the tanks did not have an adequate range. Now, with a new tuning device there are problems with the final amplifier stage at full power.

Down times of the injector are mainly caused by control electronics and ion source failures as short circuits between the sputter electrode and the anode, breaks and deformation of filaments or simply by too poor yield of an ion source.

Two years ago it was anticipated to exchange all magnet power supplies. The original system had 350 power supplies and 65 different types. The development of a thyristor-supply, of which a prototype is powering one inflector magnet, will help to reduce the variety. Accelerator experiments and operation practice have shown that the number of individual supplies for magnets and lenses can be reduced, too. Therefore, the substitution of power supplies will be first limited to the mostly stressed sections as Wideröe tank 1 and the stripper section. In addition, the different types of steerer power supplies have been substituted by one type. For the very unreliable degaussing units an inhouse development was used instead. However, the fraction of down time due to magnet failures is still about 20 \%. Half of it is caused by peripheral magnet equipment as thermoswitches and flow meters, and half by power and control electronics, too. A prototype for a new control-interface unit is being tested. It is equipped with a microprocessor and is designed for future multi-beam operation of the Unilac.

The computer system will be stepwise supplemented by microprocessor interfaces. The use of microprocessors should make it possible to move tasks from the local PDP 11 computers to microprocessors, and from the central computer to the PDP-level. One necessary condition for this is the present implementation of the RSX11-M system software for the PDP computers and the corresponding software structure changes. On this basis it should be possible to come to a new computer control configuration by 1985 without affecting the Unilac operation.

**Status of the Upgrading Program**

The occasion of the five months shut down necessary for the energy increase of the Unilac was equally used for other important improvements of the Unilac as the modification of the injector beam transport and diagnostics, the installation of a microprocessor system for the computer control of the rf generators and new rf power lines for the whole poststripper accelerator. In addition, major changes are being made in the control electronics of rf generators to improve their reliability.

The new beam transport has been completed now for one of the two injectors. The terminal beam transport has been changed and an additional emittance measurement device was installed at the high voltage platform. The first part of the beam transport line to the Wideröe, which is used for the isotope separation, is now equipped with quadrupoles of 80 mm aperture giving a normalized acceptance of 0.05 cm m for the whole system. This is three times higher than before. In first test runs with the new beam line peak intensities of up to 1200 µA could be achieved for Ar and up to 50 µA for Pb and U at the Wideröe entrance. The beam diagnostics has been changed accordingly.

All rf generators are being connected to the computer control system via a microprocessor link, which allows for multi-beam operation, too. At the Wideröe section this new control has been already successfully tested with rf.

The helix rebuncher in the stripper section was replaced by a spiral resonator from Frankfurt University. An additional one is being prepared for installation behind the charge analyzing system for an improved matching to the Alvarez structure.

The modification of the poststripper section, the leading activity in the present shut down is already completed: The single gap cavities are moved to the far end of the slightly extended linac tunnel and are now combined into one group of 17 units (see fig. 2). This was necessary to make room for two new Alvarez tanks which are now in place, under vacuum and connected to the utilities, magnet supplies and rf feed lines.

The fabrication of the new tank, described earlier, presented no problems: The requested diameter tolerance of \( \pm 0.5 \) mm was achieved and the final copper plating of the circumferential welding seams proceeded as determined on a prototype.

Difficulties arose during drift-tube fabrications. The manufacturer omitted the prescribed shoulder fit of the roll-pressed end caps to the cylindrical sheet metal body tubes and applied a too heavy welding seam. This resulted in a length shrinkage of \( 1 \pm 0.5 \) mm. Because this error was nearly the length increment from cell to cell, each drifttube was installed one cell further upstreams and a new end drift tube was fabricated for both tanks from available spare parts. Some units have been length corrected by copper plating. It was equally necessary to remachine the fit for the alignment target according to the magnetic axis, due to bore tube distortions, resulting from an overly heavy weld.
Flattening of the field distribution was easy by means of the envisaged fixed tuning bodies. A so far unexplained frequency error of ~100 kHz was corrected for by a previously not foreseen tuning bar. It consists of two plated tubes, 1.7 m in length and 5 cm in diameter, spaced 2 cm apart from the cavity wall by elbow-shaped endpieces joining blanks at the position of available flange holes. At half length of the tube an additional support had to be supplemented in order to suppress mechanical vibrations. The remaining tube sections, four per cavity and of different length, performed as strip line resonators at or close to the nominal tank frequency and depressed the Q-value. By trimming the individual section lengths, it was then possible to displace their resonant frequency to a presumably adequate value.

The new rf window design, described earlier\(^9\), was easy to fabricate and was tested in a line type resonator. The observed arcing on the atmospheric side was suppressed by supplementary corona rings on both ends of the ceramic insulator tube. Equivalent forward power levels of 4 MW were obtained and 9 MW were obtained with an additional nitrogen flushing of the window area, clearing the ionized atmosphere.

The installation of a new generation of rf power lines is already finished for the Alvarez tanks, while for the single gap cavity structure this activity is still proceeding, as well as the improvements of the control electronics of this subsystem.

The new Alvarez tank IV was run up through severe multipactoring thresholds to the design peak power, rated for gas stripper operation and half of the maximum thermal power. The temporary limitations are due to amplifier and tube malfunctions. No bellow heating was observed on the drifttube stem heads. The aluminum rf and vacuum seals, which are tentatively installed at the end cover joints and which replace the earlier gold wire standard, are performing equally well.

The beam splitting system at the exit of the poststripper had to be shortened by a factor of two, requiring a twice as strong deflection of the first septum magnets. New coils and new 3,800 A power supplies were procured and are tested. The beam line between the end of the single-gap cavities and the beam splitting area is nearly rebuilt.

References


Discussion

In the rf system, we used the Thompson 518 in the past; there were serious problems but we think they have been solved. The alternate tube for the same plate circuit is the Siemens tube that has been on the market about one year. The new plate circuit developed by industry was based on an Eimac tube.
THE LINEAR ACCELERATOR FOR THE PROPOSED GERMAN SPALLATION SOURCE.
A. Citron, Nuclear Research Center, Institute for Nuclear Physics, P.O. Box 3640, 7500 Karlsruhe 1, Federal Rep.of Germany.

Summary
A Study has been submitted to the German Ministry for Research and Technology on the feasibility of a spallation neutron source (SNQ). It comprises a proton linear accelerator. The basic parameters of this accelerator will be discussed, in particular those typical for the application envisaged. Particular emphasis is put on the problem of beam loss.

The neutron source should have the following properties:

1. An average thermal neutron flux comparable to that available today from high flux reactors. The neutron yield is, in a very rough approximation, proportional to the power deposited by the beam in the target. Neutronics calculations, checked by recent measurements, show that a beam power of about 5.5 MW on a Pb target is needed.

2. A time structure of the thermal neutron flux is desirable. This is reflected in a modulation of the beam with a duty cycle of about 5%, giving a corresponding enhancement of the peak thermal neutron flux.

3. For experiments with epithermal neutrons and with neutrinos an even higher compression of the beam, by another factor of the order of 1000, is wanted.

At the present state of accelerator technology it was found that requirements 1 (and 2) can only be met by a linear accelerator. Requirement 3 necessitates the addition of an accumulator ring (a.r.). This option is part of our study, but falls outside the scope of this talk. It influences, however, the design of the linear accelerator in several respects:

1. Because of the space charge problem for the a.r., the final energy is chosen relatively high (1.1 GeV).

2. In order to facilitate the filling of the a.r., the option of accelerating H⁻ is kept open. This means provision for a vacuum of $2 \times 10^{-8}$ mbar to avoid gas stripping and low magnetic fields to avoid Lorentz-stripping. Both sources of loss should be kept below the desired beam loss limit (see below).

The novel feature of the linac is the high average current (and power) it has to carry. It makes the problem of minimizing beam losses more urgent than for linacs operated today. It is our aim to make hands-on maintenance possible shortly after switching off the accelerator, as is the case at the LANL accelerator. From estimations of activation, it follows that beam losses per meter below 1% at 10 MeV and below $2 \times 10^{-7}$ at 1 GeV are necessary. For the case that this aim cannot be reached immediately in some locations, we make provisions for remote-handling. But we definitely want to avoid having remote-handling as a permanent feature.

Thus in describing our proposed linac I shall stress those features that are dictated by the need to cut beam losses. Table I gives the fundamental parameters of the accelerator.

| Table I |
| Basic parameters |
| In brackets: options |
| Final energy | 1,100 | MeV |
| Particles | Protons (H⁻) |
| Peak current | 100 | mA |
| Average current | 5 (10) | mA |
| Burst length | 0.5 (1.0) | ms |
| Rep. rate | 100 | Hz |

Ref. 1) Realisierungsstudie zur Spallations-Neutronenquelle, 13 volumes, Arbeitsgemeinschaft SNQ Kernforschungszentrum Karlsruhe 1981
Kernforschungsanlage Jülich
The peak current was chosen as 100 mA, although higher peak currents have been achieved in many existing linacs. One reason is that, above 100 mA, space-charge forces start dominating and make accurate predictions about the tails of the beam populations in phase space less reliable. Also, the perturbation that the pulse beam represents for the cavity becomes more difficult to compensate. Measurements at the CERN linac have shown that these transient beam-loading effects cause beam losses. Another reason for limiting ourselves to 100 mA is economic. The additional investment in rf needed to double the peak current would increase the price of the accelerator by about 25%. One might reduce the duty cycle to reach the same average current, but this saving would be small in comparison.

The final energy is mainly given, as mentioned above, by considerations about the feasibility of the a.r. The users also favour a higher energy, which permits higher peak fluxes in spite of the restricted peak current. Finally, the heat-removal problem in the target is eased.

An overall layout is given in Fig. 1. We shall discuss:
1. The injection energy
2. The choice of the frequency for the low-energy (Alvarez) accelerator
3. The choice of frequency for the high-energy (disk-and-washer) accelerator.

The injection energy (450 keV) was chosen lower than the usual 750 keV because the experience of other laboratories seems to indicate that for high duty cycle machines the problems of breakdown in the accelerating column is increasing with voltage and current.

The injector is followed by a buncher adapted from the one used for the new CERN linac. A capture efficiency of 90% is expected. The corresponding beam losses occur mainly below 10 MeV and do not give rise to an activation problem.

Starting the Alvarez accelerator at an energy as low as 450 kV causes a problem. It was solved by choosing the frequency 108 MHz rather than usual 200 MHz. But this is not the only reason for choosing this low frequency. Emittance reserves both in transverse and longitudinal phase space are larger for the lower frequency. The danger of losing particles longitudinally due to space charge forces is also less at the lower frequency. We are particularly concerned about longitudinal emittance growth because there is a change of frequency in between the Alvarez and the DAW accelerator, which, of course, would give rise to losses if the longitudinal emittance is too large.
For the transverse motion under the influence of space charge, emittance growth is more probable at the lower frequency. Multiparticle computer simulations showed that for the parameter choice of the reference concept the transverse emittance growth is small and no instabilities are excited.

In summary we gave the preference to the lower frequency of $108 \, \text{MHz}$. It has the additional advantage that the same frequency is used in the Alvarez of GSI at Darmstadt. So we have the transmitters and other RF components readily available.

The transition energy from the low energy to the high energy structure was chosen at $105 \, \text{MeV}$. According to our calculations and also according to the computer simulations at this energy a jump of frequency by a factor 3 can be handled without loss of particles. The disk-and-washer structure is thus operated at the frequency of $324 \, \text{MHz}$. A higher frequency would be favoured here from the point of view of shunt impedance, but a higher jump in frequency, e.g. by a factor 4 would leave less reserve in longitudinal acceptance.

One point needs a comment. The problems of the high voltage column and of the acceptance into the beginning of the Alvarez could be avoided by adopting the RFQ-structure that replaces preaccelerator, buncher and the first part of the Alvarez. We are often being asked, why we do not adopt the RFQ-structure. The answer is that we do not exclude the RFQ-structure for the next phase of the study. For this first phase, however, which mainly concerns the feasibility of the accelerator, we feel that we should stick to the "classical" solution for two reasons:

1. The RFQ-structure is still under development, so it would be wise to wait for some operating experience.

2. It is essential that we can punch holes of one or several micropulses into a macropulse for purposes of switching from one experimental area to another without beam loss and also later for leaving an ejection gap in the filling of the accumulator ring. In both cases no beam should be present while switching elements are in an intermediate state. These holes can be conveniently punched in behind the dc-accelerator at a $450 \, \text{keV}$ level. An RFQ-structure would start at about $50 \, \text{keV}$ and would accelerate particles up to $2 \, \text{MeV}$. At the $50 \, \text{keV}$ level handling the beam is complicated because here it has to be neutralized to avoid blow-up due to space charge. At $2 \, \text{MeV}$ level the beam is already rather stiff, so that the deflector elements would have to be much more powerful. Breaking the RFQ-structure at an intermediate point, at $500 \, \text{keV}$ say, would mean to lose most of its advantages. It is possible that a way can be found around these difficulties. But since we could convince ourselves that the solution proposed is perfectly viable, this seems to us sufficient in this state of the project.

Coming back to the problem of beam losses, I have mentioned the following measures:

1. Choice of parameters leading to ample acceptance reserve both in longitudinal and transversal phase space.

2. Choice of a moderate peak current to keep the space charge problem under control.

3. Extensive computer simulations to check for instabilities, emittance growth and halo-formation.

Apart from these I would like to mention:

4. Use of the multipole ion source that has a low noise.

5. Very high stabilization in amplitude and phase of the accelerating rf.

6. The adoption of an adaptive forward-control-system that minimizes the transient in the rf amplitude and phase caused by the appearance of the beam in the cavity.

7. Diagnostic elements, correction elements and beam scrapers at critical positions for the detection and removal of beam halo.

As a result of our study we found that a linear
accelerator of the desired performance is perfectly feasible. Its cost including buildings and including the target (that was not discussed here), is estimated to 680 MDM. Table II gives a rough breakdown of this sum.

I like to conclude giving you the names of the scientists who have contributed to the Study (Table III). Some of them will also contribute to this conference.

Table II
Breakdown of cost estimate
for the whole SNQ facility (without options)

<table>
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<tr>
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<td>Target-block</td>
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<td>General engineering, licensing</td>
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Table III
KfK Linac Study Group

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<tr>
<td>Leader</td>
<td>J. E. Vetter</td>
</tr>
<tr>
<td>Beam Dynamics</td>
<td>K. Mittag</td>
</tr>
<tr>
<td></td>
<td>D. Sanitz</td>
</tr>
<tr>
<td></td>
<td>K. Bongardt</td>
</tr>
<tr>
<td></td>
<td>M. Pabst</td>
</tr>
<tr>
<td>Injection</td>
<td>B. Pioscyk</td>
</tr>
<tr>
<td>Acc. Structures</td>
<td>G. Dammertz</td>
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<tr>
<td></td>
<td>R. Lehmann</td>
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<tr>
<td>Beam handling</td>
<td>W. Kühn</td>
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<td>G. Schaffer</td>
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<td>Diagnostics</td>
<td>H. Schweickert</td>
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<td>RF System + Controls</td>
<td>G. Hochschild</td>
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<td>R. Hietschold</td>
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<td></td>
<td>A. Hornung</td>
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<td>D. Schulze</td>
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<tr>
<td>Gen. Engineering</td>
<td>H. Sebening</td>
</tr>
<tr>
<td></td>
<td>G. Böhme</td>
</tr>
<tr>
<td></td>
<td>B. Haferkamp</td>
</tr>
</tbody>
</table>

We had the kind aid of

E. Boltezar } S.O. Schriber } CRNL
K. Goebel } M.R. Shubaly } CERN
D. Warner } K. Crandall } LANL
M. Weiß } H. Hereward

*These persons made contributions to the present conference.

Discussion

The government will probably make a decision on the SNQ by the end of this year: to stop, continue as a study, or decide on a site for the full project. The potential users would be fundamental researchers in neutron scattering, materials scientists, persons from the nuclear physics community interested in intermediate energies and mesons, and finally, there is considerable interest from the neutrino community because the time structure and high average flux give unique opportunities for neutrino experiments.
OPERATING EXPERIENCE WITH MAMI I
Institut für Kernphysik, Universität Mainz, W-Germany

Summary
MAMI I, a 14 MeV room temperature racetrack microtron for c.w. operation, has been run for about 1200 hours during the past two years, showing quite satisfactory performance. We were especially pleased by the good reproducibility of beam optimization and excellent long term stability of the beam during a run. Nevertheless, the operating experience gave us several good hints on the construction of MAMI II (175 MeV).

Introduction
MAMI I is the first of a cascade of 3 room-temperature race track microtrons for c.w. operation [1]. The parameter of which are compiled in Tab. 1. MAMI has been set into operation in spring of '79 and has been run for about 1200 hours, mostly for machine studies, but also for nuclear physics experiments [2], [3], [5], [6], [7]. It is, to the best of our knowledge, the first room temperature microtron for c.w. operation.

<table>
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Injector and Interface
Fig. 1 Scheme of MAMI I with some analog control loops

A schematic view of MAMI I is shown in Fig. 1. The beam is chopped in the terminal of the van de Graaff by a coaxial cavity driven by a triode oscillator at half the operating frequency. This oscillator is phase locked from a bunch phase monitor at ground potential. This system works very satisfactorily.

The matching interface between van de Graaff and the microtron (described in more detail in ref. [4]) consists mainly of two achromatic straight sections for transverse matching and an r.f. section followed by two 180° bends (providing longitudinal dispersion) for longitudinal matching. Between the bends a pair of solenoid lenses rotates the beam by 180°, so that the transverse dispersions of the bends cancel on the following straight section. Inflection is done by an upright standing 180° bend.

The beam downstream the van de Graaff shows an energy ripple of several keV amplitude due to voltage ripple of the van de Graaff. The acceptance of the microtron, however, allows a shift of about 2 keV only. Thus an error signal from the van de Graaff terminal voltage is used to shift the phase of the r.f. in the matching section by means of a
quick phase shifter in such a way as to cancel the energy ripple of the van de Graaff to first order downstream the matching section. This system has proven to reduce the energy ripple reliably to a few hundred volts which is more than sufficient to allow stable operation of the microtron.

Much care proved to be necessary to adjust the interfacing system both with respect to longitudinal matching and dispersion free injection into the microtron. This once being done, however, the system works quite satisfactorily and stably. Transverse matching is done by two quadrupole doublets on the second straight section of the interface. With these quadrupoles being set to the values as calculated for optimum matching the beam is accepted by the microtron. It is, however, also accepted at somewhat different settings and it is hard to say which of the settings would really provide optimum matching (and thus the largest margins of safety against misalignments). Since we have no diagnostics for the beam envelope in the microtron a special matching procedure is presently being tried using the position monitors in the microtron.

The microtron

The microtron itself is shown with its diagnostic and correcting elements in fig. 2. The monitoring system involves beam position, beam intensity and bunch phase. It consists of r.f. resonant cavities which are excited by the bunched beam. Distinction between revolutions is done by marking the beam by 10 nsec bursts or blackouts respectively. Both horizontal and vertical deviations are detected in one cavity simultaneously. This system which has been described in detail elsewhere [1], [3], [9], [8] is working quite reliably and satisfactorily in burst mode. Beam offset of a few tenths of a mm from the linac axis is easily detected for each revolution. In the blackout mode the system works well at relatively low beam intensity. At intensities higher than about 20 μA however, its r.f. detectors suffer from overload. On the other hand, the beam is usually so stable that the use of the blackout mode for monitoring during operation at high beam intensity is less important than expected previously. Nevertheless, modified monitors have been developed which are essentially free from overload [10] yet are more sensitive and easier to manufacture. They will be used in the following stages.

The magnets are homogenized by means of correcting coils as described in detail in [4] to ± 1·10^-4 over the inner pole face area. They are turned on and off by a ramping procedure and may, if necessary, be cycled in a special manner. With a field error of ± 1·10^-4 the correcting steerers should not need to be excited to more than a few tenths of a mrad deflection to center the beam in the linac if the magnets are correctly positioned. We need, however, at a few steerers more than one mrad. We conclude that the field distribution in the fringe field region (which could not be measured with high accuracy) might not be adequate. Unfortunately, it is not possible to do accurate measurements there now without dismantling the whole microtron. For the following stages we will design the steerers for some more steering capability than planned initially.

The positioning of the main magnets is very critical indeed, as expected, and it turned out that, in practice, the only adequate criterion for minimizing steerer excitation is given by the beam behaviour in the operating machine. Therefore, in the following stages we will provide the possibility of magnet adjustment during operation by means of remotely controllable supports.

The r.f. system of MAMI I proved to be very reliable indeed. We are especially pleased by the fact

![Fig. 2 Scheme of diagnostic and correcting elements of MAMI I](image-url)
that we never experienced any difficulty with multi-pactoring in the accelerator section which is a slightly modified on axis coupled biperiodic structure of the Chalk River design \[1\], \[3\].

The beam transmission of the machine depends, of course, on the bunch length for which we usually use the chopping ratio (i.e. the beam intensity with the chopper turned off divided by beam intensity with chopper turned on) as a measure, the latter being adjusted by the power of the chopper oscillator. Beam transmission is 25 ... 30 % with an unchopped beam. It grows to 50 ... 90 % at a chopping ratio of about 10 and to 95 ... 100 % (within errors of a few percent) at a chopping ratio of 16. These numbers do not depend strongly on the beam intensity, but, generally, the lower number applies for high intensities (> 50 \( \mu \)A). The maximum intensity reached so far is 75 \( \mu \)A, at a bunching ratio of about 10, limited by beam emission.

Computer control allows us to set MAMI into operation to a large extent automatically by restoring all settings of one of the previous runs. Usually, if adjustments, etc., have not been changed in the meantime, the beampath will be available immediately at the output of the microtron. Small misalignments that might show up after the automatic setup procedure are quickly smoothed by the automatic beam-steering procedure described in the paper of H. J. Kreidel. Generally, the microtron itself proved to be considerably less critical than the injection system.

Emittance measurements have been done both in the interfacing system and downstream the microtron, using wire scanners and a pair of collimators and steerers respectively. All these measurements were perturbed more or less by some transverse beam jitter caused by spurious a.c. magnetic fields in the van de Graaff and along the injection path. Shielding is not everywhere possible and cumbersome in many places. Provisionally installed systems to suppress this jitter by countersteering were partly successful but difficult to handle. From the geometry of the gun we expect a normalized emittance of 0.7 \( \pi \) mm mrad vertically and 1.4 \( \pi \) horizontally. Downstream the microtron we measure values around 5 \( \pi \) which are clearly mainly given by beam noise. Incidentally, this value corresponds fairly well to the original design value \[1\], which had been assumed to be more than adequate. Clearly there will be ways to suppress beam jitter finally. Anyway, this effect is not strong enough to influence beam transmission significantly. The \( \Delta P/P \) width has been found to be around 1-10\(^{-3}\).

MAMI has been running for users' experiments for about 200 hours total. Usually the machine behaved perfectly stable throughout a run (up to 10 hours), so it was possible to operate the machine by the user himself during the night, and the only knowledge needed was how to turn off the machine properly after the run.

\[1\] H.Herminghaus et al., Nucl.Instr. & Meth.138 (1976) 1
\[2\] Lecture notes on Physics, No. 108, Springer 1979
\[3\] Jahresbericht 1978/1979 Institut fur Kernphysik, Universitat Mainz

Discussion

Our initial pin-diode problems were only because the company shipped reverse-polarity diodes and it wasn't noticed. The total maximum power that the VCX pin-diode system would have to absorb is about 100 W of reactive power. The frequency band of the VCX is now 150 Hz; still small but increased from about 80 Hz initially, when we had problems with the amplitude control from things like the exact operating frequencies of the turbo-pumps, and so on. At 150 Hz, we don't have those problems. Also, if we run the linac at full fields, we are in lock 90% of the time and have to recondition resonators on the average of one every 2 to 3 days. If we can run at 80 to 85% of full field, we can run for months without reconditioning and with essentially 100% lock-in.

For Ni\(^{58}\), our proposed end energy is about 17 MeV/amu. For carbon and oxygen, it is about 25 MeV/amu; by the time you get to magnesium it is down to 21 to 22 MeV/amu and drops on down.

Our energy gain per meter is about 2.4. We don't completely understand what breaks down when we reach the maximum charge sometimes there is electron loading; sometimes not, but rather seemingly periodic breakdowns that do not seem to reflect the Q falloff. We suspect different types of cooling problems in the individual resonators. Qs are mostly at 10^8 or 10^9, but in some cavities there is a Q falloff—dramatically at higher field levels. We will be studying this further.

We have tested the Cockcroft-Walton system for the higher frequency system and it agreed with design calculations; we have not tested the prototype yet.

We have let the cavities up to both lead, filtered nitrogen and helium. We honestly don't understand what happens when we recondition resonators. The degradation we recondition for varies only dramatic from resonator to resonator, but let me point out that unless there is an accident, there is no serious degradation. We go through the reconditioning cycle, and when we succeed in finding a field level that gives stable operation for a few days, there will be no deterioration for a couple of months--our longest running time so far. From some accidents, we have concluded that large condensable gas loads on the surfaces are not an intrinsic problem—something else happens to the surfaces.
STATUS OF THE ARGONNE SUPERCONDUCTING-LINAC HEAVY-ION BOOSTER


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Summary

The Argonne Superconducting-Linac Heavy-Ion Booster is nearly complete. The linac now contains 22 of the complement of 24 resonators which will eventually be installed. During the construction period, the completed portion of the linac has provided useful beams for nuclear and atomic physics experimental programs. The linac-control system has been developed so that much of the more complex control functions are performed automatically.

Introduction

The Superconducting-Linac Heavy-Ion Booster has been developed as a prototype of ATLAS, the Argonne Tandem-Linac Accelerator System. When complete, ATLAS will accelerate heavy-ion beams to energies over 25 MeV/A.

The superconducting linac booster consists of four cryostats, which will contain a total of 24 independently phased split-ring superconducting resonators. The first 11 of these resonators will

have a matched velocity of 0.062c and the last 13 will have a matched velocity of 0.105c. At present the linac contains the full complement of high-beta (0.105c) resonators but only eight low-beta (.065c) resonators are installed. In this configuration, the linac now provides a total accelerating potential of 18 MV.

Heavy-ion beams are injected into the linac from an upgraded FN-tandem Van de Graaff accelerator. Typically, the tandem operates at an effective terminal voltage of 8.5 MV. The negative ions needed for injection into the linac are provided by an inverted sputter source.

In order to maintain the good beam quality from the tandem, it is necessary to bunch the beam into pulses approximately 100 ps wide at the entrance to the linac. This is accomplished with a two-stage bunching system. First, a room-temperature gridded buncher using a sawtooth-like waveform bunches 70% of the D.C. beam into pulses approximately 1 ns wide (FWHM). These pulses are further bunched to a width of 100 ps at the linac entrance, using a superconducting low-beta resonator.

Fig. 1. Overall layout of the accelerator system
This paper discusses the status of the project and the operating experience during the last two-and-a-half years. An associated paper in these proceedings discusses beam optimization on the linac and measurements of the linac beam quality.

Project Status

Construction

The fourth (and last) cryostat of the booster project was placed on-line in June 1981. At that time, four resonators out of an eventual complement of eight were installed. This brought the linac resonator total to 20, 13 high-beta and seven low-beta resonators. Due to improper assembly of the VCX fast-tuning system, two resonators in the new cryostat could not be operated. After providing beam for the experimental program through July and August, cryostat B was removed for repair and for installation of two additional low-beta resonators.

The B cryostat was placed on-line again on September 30. At this time, the cryostat contained six resonators. Subsequently, it was determined that the field pick-up line to one resonator was inoperative. The linac began providing experimental groups with heavy-ion beams again on October 14 with a total of 21 resonators operating: eight low-beta and 13 high-beta. The present physical layout of the facility is shown in Fig. 1.

The physical growth of the linac over the past two years caused the capacity of the original 100-watt helium refrigerator to be inadequate. This problem was solved in late 1980 with the installation of a 300-watt CTI-2800 helium refrigerator. This refrigerator has operated reliably since installation. Only two or three minor system problems have developed over this period.

One of the most important design decision for the heavy-ion linac was the use of independently phased resonators. This feature is essential for the efficient acceleration of a large range of heavy-ion species. Another important benefit of independent phasing is that the linac operation is largely configuration independent and it has been conceived from the beginning that repairs to components in one cryostat of the linac could be made while the remainder of the linac continued to provide useful beams for the experimental program.

This modular feature was fully exploited in the repair, expansion, and servicing of B cryostat in September. The cryostat was replaced in the linac by a beam pipe containing only a vacuum pump, beam scanner, and small steering magnet, and the experimental program was resumed. This meant that the beam pulses had to drift a distance of 4 meters before longitudinal refocusing could occur in the next resonator. We found this presented no practical problem in terms of beam quality. Ray-tracing calculations suggest that some distortion in the longitudinal phase ellipse occurred, but this is not a significant problem for experiments currently operating. In fact, timing resolution of 117 ps was obtained in an experiment using 229 MeV 28Si during this period.

Control System

The linac-control system is based on a PDP 11/34 minicomputer with 128K words of memory and a floating-point processor. Two fast disk drives provide a total of ten megabytes of storage space. The basic control system resides on one 2.5 megabyte disk, which allows the second disk drive to serve as a system backup. Permanent file storage is by floppy disks. An LSI 11/2 µ-processor is used for thermometry I/O operations.

The control-system software operates under the multi-tasking, multi-user RSX-11M. The multi-tasking allows many different functions to go on simultaneously, including those not directly related to system operation. The computer provides the major functions of linac control, linac monitoring, complex calculations, and system development.

During the past two years, the linac-control system has evolved from a rudimentary system providing essentially manual control of the linac into a system that is largely automatic in many aspects. For example, the linac tuning is completely automated, normally requiring operator assistance only to correct beam steering as the tune-up proceeds. Also, a change of the linac energy is now accomplished by a simple request from the user at the control console. Features of this type are essential because of the wide variety of beams accelerated and because the linac functions largely as a user-operated facility.

The linac-control hardware is interfaced to the computer system through a bit-parallel, byte-serial CAMAC highway. Control of the linac is executed by the setting of reference voltages. The system is monitored using multichannel ADC's for low-resolution data, such as thermocouples, and input registers for information requiring higher resolution. The basic system functions with only four types of commercially available interface modules, making it possible to stock replacement modules to be used in the event of a failure. In practice, CAMAC reliability has been excellent. In the past 2½ years, only two module failures have occurred, and the overall highway has performed flawlessly.

The operator interfaces to the system through a control console (shown in Fig. 2) consisting of the following items:

1) a 16-key touch panel,
2) two computer-assignable knobs for control,
3) a color TV,
4) hard-copy system console,
5) storage scope terminal,
6) line printer/plotter, and
7) B-W monitors for thermometry information.

The 1/0 for the console is through RS232 ports and a parallel CAMAC crate. Almost all functions normally needed for control of the linac are accessed through the touch panel. Manual control of an element can be requested and assigned to the knob assembly below the touch panel. In addition to the analog-like control of an element, a specific value can be requested for a parameter through a numerical key pad to the right of the touch panel.
The organization of the computer-control software system is shown in Fig. 3. The linac software is driven from a data-base table which contains all parameters of the linac and bunching system. The data base includes "temporary" parameters relevant to the current beam being accelerated (such as resonator phase angles, accelerating-field levels, and the beam-energy profiles along the linac) and also "permanent" parameters such as resonator type, distances between linac elements, and field calibrations.

The table-driven feature of the computer-control system results in a highly flexible system. Linac components can be effectively removed from the system, or the system I/O can be reconfigured to bypass a malfunctioning module by simple modification of the data base in the table.

Operating Experience

As the construction of the linac has proceeded, the existing portion of the linac has provided useful beams to experimental groups. From March, 1979 through September, 1981 the linac has provided over 7200 hours of scheduled beam time accelerating some 18 species ranging from $^4$He to $^{65}$Cu. In the last three years, the linac has evolved from a mostly developmental project into an operating accelerator. The percentage of total possible time devoted to providing beams for the research program has increased from 25% in 1979 to over 63% in 1981.

The research program undertaken at the linac has taken advantage of the high degree of flexibility of the tandem-linac system. The percentage of the total running time for various isotopic beams accelerated during the past is shown in Fig. 4. The trend towards higher-mass ions is reflective of the installation of low-beta resonators in late 1980, which opened the mass region above sulphur to serious exploration.
reconditioning, and that was accomplished in approximately four hours.

At present, the average on-line operating field level is 3.5 MV/m for the low-beta resonators and 2.7 MV/m for the high-beta resonators. In off-line tests, the average field obtained is 4.2 MV/m for the low-beta resonators and 3.7 MV/m for the high-beta resonators. The different performance of the resonators appears to stem from three nearly independent causes of comparable magnitude. These causes are: 1) a deterioration of the average high-beta resonator performance due to catastrophic vacuum accidents and other abuse over the past three years; 2) a difference between the average on-line and average off-line performance of high-beta and low-beta resonators, and 3) an intrinsic difference in the average performance of high-beta versus low-beta resonators. One factor which contributes to points two and three is that resonators can be conditioned more effectively off-line than on-line, and low-beta resonators can be more effectively conditioned than high-beta resonators.7

A systematic program is underway to understand, in detail, the causes for the field-level performance differences between on-line and off-line operation. The resonators which have experienced field degradation due to accidents will be removed and reprocessed as time permits. It has been our experience that reprocessing resonators restores their original field performance.

It has been our experience that when the resonators are operated with fields up to 90% of their maximum levels, the linac operates in an almost trouble-free manner. Specifically, the need to condition resonators is essentially eliminated for periods of weeks. In addition, the fraction of time in which one finds all resonators properly phased locked and the amplitude stabilized (known as "in-lock fraction") approaches 100%. When the experimental requirements demand operation at the maximum achievable energy, experience indicates 2% of all resonators require reconditioning each day. The in-lock fraction in this case will average approximately 90%.

Operational Problems

A persistent problem in the resonator operation has been in the slow-tuner control. The slow tuner is a pneumatic device consisting of a bellows assembly mounted to one end plate of each resonator. By pressuring the bellows with helium gas, the end plate is elastically deformed and the eigenfrequency of the resonator is modified. In the original design, the pressure in the bellows was controlled by automatically introducing or exhausting helium by means of fast-acting solenoid valves. These valves have proven to have a limited lifetime in this application.

In the last six months, a new slow-tuner control system has been implemented on 70% of the resonators. The system operates on a fixed quantity of gas in the slow-tuner system. By electrically heating a reservoir common with the bellows and thermally grounded to the liquid-helium system, the bellows pressure is varied as required. This system is still being refined, but the initial results indicate that this technique should be a significant improvement over the old control method.

Future Plans

The accelerator development is proceeding in anticipation of expansion of the present booster into the ATLAS accelerator. The ATLAS project will provide three additional cryostats containing a total of 18 resonators, resulting in a linac with a total of 42 resonators in seven cryostats. A new split-ring resonator with a matched velocity of 0.16c is being developed for this phase of the project. The new design uses the same housing as the present high-beta resonators, but a redesigned drift tube and ring assembly will be employed. The operating frequency will be at 148.5 MHz, which is 3/2 times the frequency of the present resonators. The fabrication of the prototype resonator is nearing completion.

The present mass limitation on ions which can be accelerated with the linac is set by the 90° analyzing magnet of the tandem. This magnet is over 20 years old and was originally installed for an EN tandem Van de Graaff. An isochronous superconducting-magnet system consisting of two 45° bending superconducting dipole magnets is planned to replace the current analyzing magnet. A third superconducting dipole will be used between the two linac sections in the ATLAS system. The prototype of these magnets has been designed and is in the construction phase.

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References

OCTUPOLE FOCUSING IN TRANSPORT AND ACCELERATION SYSTEMS

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Summary

The radio-frequency quadrupole (RFQ) linac is capable of accelerating high-current, low-velocity ion beams. In accelerator systems comprising an RFQ and higher velocity accelerating structures, the current bottleneck still typically occurs within the RFQ. This limiting current is quite high in most cases, but linacs with even higher currents may be required in the future. We have begun a study of higher multipole systems to determine their capability for focusing and accelerating very high currents. We have chosen first to examine a radio-frequency octupole (RFO) transport system, and have developed a smooth-approximation analytical description that includes the conditions for input radial matching of a zero space-charge beam. Further, we have constructed a multiparticle beam-dynamics simulation program that accepts the low-current matched beam and gradually increases the beam current as it is transported. This results in a matched high-current beam, and the procedure can be used to determine the saturation-current limit of a periodic octupole system. As expected, at high currents the beam develops a hollow radial distribution that reduces the space-charge defocusing; initial results show that high currents can be transported. For acceleration, we have formulated the design parameters for a section of RFO linac, including the potential function, acceleration, and focusing efficiencies, and the geometry of the radially modulated pole tips.

Introduction

We begin our study with an examination of the equations of motion for an RFO transport system. In the static limit, otherwise described as a quasi-static approximation, an octupole scalar potential can be written in cylindrical coordinates \((r, \psi, s)\) as

\[
U = \frac{V}{2\pi} \left( \frac{L}{a} \right) \cos 4\psi \sin \omega t,
\]

where \(V\) is the peak potential difference between adjacent poles, \(\omega\) is the angular frequency of the time-varying voltage on each pole, and \(a\) is the radial aperture (see Fig. 1). Instead of time we use \(z = s/L\) as the independent variable, where \(L = 2\pi v/\omega\) and \(v = ds/dt\). We obtain for the nonrelativistic equations of motion

\[
x'' + B (x^3 - 3xy^2) \sin 2nz = 0, \tag{2}
\]

and

\[
y'' + B (y^3 - 3yx^2) \sin 2nz = 0, \tag{3}
\]

where for a particle of charge \(q\), and mass \(m\), we define

\[
B = \frac{2qV \left( \frac{L}{a} \right)^4}{mv^2}.
\]

The displacements \(x\) and \(y\) are dimensionless quantities, defined as the ratio of the actual displacement to the focusing period \(L\). We use the convenient notation that \(x'' = d^2x/dz^2\) and \(y'' = d^2y/dz^2\).

The RFO Smooth-Approximation Solution

By analogy, with the smooth-approximation method for quadrupole focusing, we assume solutions of the form

\[
x = X(1 + u), \tag{5}
\]

\[
y = Y(1 + w), \tag{6}
\]

where the functions \(X\) and \(Y\), and their first and second derivative, are assumed to vary slowly enough to be considered constant over a period \(L\). As with \(x\) and \(y\), we define \(X\) and \(Y\) to be the dimensionless ratios of actual displacement to the period \(L\). The functions \(u\) and \(w\) are assumed to be periodic with period \(L\), and both \(u<<1\) and \(w<<1\). Furthermore, the mean values over a cell of \(u\) and \(w\), and their first and second derivatives, are assumed to vanish. Thus, the solution is assumed to consist of a product of a slowly varying function times a rapidly varying periodic function.

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†Los Alamos visitor from Kernforschungszentrum Karlsruhe and Universität Karlsruhe, Germany.
The slowly varying functions X and Y constitute what may be referred to as the smooth solution. After substituting the assumed solutions Eqs. (5) and (6) into the equations of motion Eqs. (2) and (3), and using the above approximations, we have obtained

\[ u = \frac{B}{(2\pi)^2} (X^2 - 3Y^2) \sin 2\pi z, \]  
\[ w = \frac{B}{(2\pi)^2} (Y^2 - 3X^2) \sin 2\pi z. \]  

Then, substitution of Eqs. (7) and (8) into the equations of motion averaged over a period, yields smoothed differential equations in X and Y:

\[ X'' + G_X(X^2 + Y^2)^2 = 0, \]  
\[ Y'' + G_Y(X^2 + Y^2)^2 = 0, \]  

where \( G \) is given by

\[ G = \frac{3\pi^2}{8\pi^2}. \]  

The equations of motion are coupled in general. For motion in the x,z plane, the smoothed uncoupled equation of motion is

\[ X'' + G X^5 = 0. \]  

This equation can be integrated twice to give an equation for smoothed phase advance per focusing period, \( \sigma_0 \), of uncoupled motion, which is

\[ \frac{B X_m^2}{\sqrt{32} \Gamma} = \frac{\sigma_0}{2}, \]  

where \( X_m \) is the smoothed amplitude. The symbol \( \Gamma \) represents a ratio of gamma functions; the numerical value is given approximately as

\[ \Gamma = \Gamma(7/6) \Gamma(1/2) \Gamma(2/3) = 1.2143. \]  

From Eq. (13) we see that the phase advance depends not only on the focusing strength \( B \), but also on the particle amplitude \( X_m \).

We have compared the predictions of Eq. (13) with the phase advance obtained by using zero crossings of the numerical integration of Eq. (2) for uncoupled motion (\( y = 0 \)), and find that the smooth approximation predicts the uncoupled phase advance to within a few per cent for phase-advance values up to 30°. The numerical-integration results also show that the uncoupled motion becomes unstable for phase-advance values equal or near to 30°, a result that has been independently discovered by Laslett.*

* L. J. Laslett, Lawrence Berkeley National Laboratory, personal communication, July 1981.

The RFO Current Limit

We have searched for a simple model for a smoothed charge distribution within the beam, which we can use to represent the beam in an extreme space-charge regime. In the following discussion we present the motivation behind this model, as well as the resulting formulas.

The smoothed equation of motion can be expressed in cylindrical coordinates. If a smoothed radial coordinate \( R \) is defined by \( R^2 = X^2 + Y^2 \), then the smoothed radial equation of motion for a particle, subjected only to the applied octupole force, can be written as

\[ R'' - \frac{J^2}{R^3} + GR^5 = 0, \]  

where \( J \) is a constant of motion, proportional to the angular momentum. The second term constitutes a centripetal force, and the third term represents the applied octupole force. To represent the effect of the internal space-charge defocusing, we assume that an additional smoothed space-charge term, which depends upon \( R \), can be added to Eq. (15). In an extreme space-charge limit, where the space-charge defocusing is barely balanced by the applied octupole focusing force, we assume that the first two terms can be ignored. Then we might expect that the beam charge would distribute itself, so as to minimize the free energy, by generating a space-charge term, which is balanced by the third term in Eq. (15) (the applied octupole force).

We are then led to assume a cylindrically symmetric charge model, where the smoothed space charge term has the same \( R^5 \) dependence as does the applied force. Gauss's law can be applied to the charge distribution, to yield an expression for the radial space-charge electric field given as

\[ E = \frac{1R^5}{2\pi R_0 \nu R_m^6 L}, \]  

where \( I \) is the beam current and \( R_m \) is the maximum smoothed amplitude (the smoothed beam radius). The charge density is given as

\[ \sigma = \frac{3IR^4}{\pi\nu R_m^6 L^2}. \]  

This charge density is zero at \( R = 0 \) and increases strongly with radius \( R \).

Within the context of this model, the smoothed equations of motion, (9) and (10), are modified to give

\[ X'' + G(1 - \nu) X (X^2 + Y^2)^2 = 0, \]  
\[ Y'' + G(1 - \nu) Y (X^2 + Y^2)^2 = 0, \]  

where \( \nu \) is the normalized phaseAdvance.
where

\[ u \mathcal{G} = \frac{qIZf^3}{2\pi mc^2B^2} \left( \frac{L}{a} \right)^6, \]  

(20)

and \( u \) is interpreted as a ratio of space charge to focusing force. We have introduced \( B = v/c \), and \( Z_0 = (e_0c)^{-1} \) is the impedance of free space. To evaluate a current limit, the smoothed beam radius \( R_m \) is re-expressed in terms of the radial aperture as

\[ R_m^2 = \frac{a^2}{f}, \]  

(21)

where \( f \) is a flutter factor that depends on the particle coordinates, but that we have approximated as

\[ f = \frac{1 + B \left( \frac{a}{2\pi L} \right)^2}{1 - B \left( \frac{a}{2\pi L} \right)^2}. \]

(22)

Equation (20) can be solved for the current \( I \), and Eqs. (4) and (11) can be used to obtain

\[ I = \frac{3qu}{\pi Z_0 mc^2 Bf} \left( \frac{LV}{a} \right)^2, \]  

(23)

which expresses the current in terms of the ratio of the voltage to the radial aperture and in terms of \( u \). It may be convenient to write the current in terms of the zero-current phase advance per focusing period for uncoupled motion. When this is done, we obtain

\[ I = \frac{24qu}{\pi Z_0 mc^2 Bf} \left( \frac{\pi a\sigma_0}{L} \right)^2 \]  

(24)

As \( u \) approaches 1, Eqs. (23) and (24) give expressions for the peak current, limited by the focusing. Equation (23) is useful when the peak surface electric field limits \( V/a \), and Eq. (24) is useful if the uncoupled phase advance \( \sigma_0 \) is fixed.

The RFQ Transport Equations

The methods, applied above to the rf octupole transport system, also can be applied to the RFQ system. The analogous equations of motion are

\[ x'' - B \sin 2\pi z x = 0, \]  

(25)

and

\[ y'' + B \sin 2\pi z y = 0, \]  

(26)

where

\[ B = \frac{qV}{mv^2} \left( \frac{L}{a} \right)^2. \]  

(27)

The smooth approximation is

\[ x = X(1 - u), \]  

(28)

and

\[ y = Y(1 + u), \]  

(29)

where

\[ u = \frac{B}{(2\pi)^2} \sin 2\pi z. \]  

(30)

The smoothed variables \( X \) and \( Y \) satisfy

\[ X'' + \sigma_0^2 X = 0, \]  

(31)

and

\[ Y'' + \sigma_0^2 Y = 0, \]  

(32)

where \( \sigma_0 \) is the smoothed phase advance per focusing period given by

\[ \sigma_0^2 = \frac{B^2}{8\pi^2}. \]  

(33)

The space-charge effect is represented by a uniform cylindrically symmetric charge distribution. In this model the smoothed equations of motion, including space charge become

\[ x'' + \sigma_0^2 (1 - u) X = 0, \]  

(34)

and

\[ y'' + \sigma_0^2 (1 - u) Y = 0, \]  

(35)

where

\[ \sigma_0^2 u = \frac{qIZf}{2\pi mc^2 B^3} \left( \frac{L}{a} \right)^2. \]

(36)

The flutter factor \( f \) is given as

\[ f = \frac{1 + \frac{B}{(2\pi)^2}}{1 - \frac{B}{(2\pi)^2}}. \]  

(37)

The quadrupole expressions for beam current, corresponding to Eqs. (23) and (24) for the octupole system, are

\[ I = \frac{qu}{4\pi Z_0 mc^2 Bf} \left( \frac{LV}{a} \right)^2, \]  

(38)

and

\[ I = \frac{2\pi mc^2 B^3}{Z_0 qf} \left( \frac{\sigma_0}{L} \right)^2. \]  

(39)

Multiparticle Simulations

Computer simulations were performed to check the analytical predictions and to help understand the particle dynamics. The matched particle distribution (for zero space charge) for the octupole can be calculated, using the "smooth" Hamiltonian.
The smooth coordinates \((X, X', Y, Y')\) are chosen at random and the Hamiltonian is calculated. If the Hamiltonian is less than a specified value, the smooth coordinates are retained and converted into actual phase-space coordinates at a specified time in the rf octupole period. If the resultant coordinates are transformed through many rf periods, the distribution is indeed observed to be matched.

A matched beam that includes space-charge effects is generated by starting with a matched zero-current beam, and gradually increasing the charge assigned to each macroparticle until a specified value is reached. The charge then is held constant, and the beam is transported through many rf periods to obtain a final transmitted current. The initial size of the beam, and the rate at which the current is increased, are adjusted to find a current limit.

We have chosen a set of parameters for evaluation of the octupole transport formulas. We chose 1-MeV protons, a 1-GHz frequency, a 34-kV intervane voltage, and a ratio of radial aperture to focusing period, \(a/L = 0.1\). The zero-current phase advance, calculated from Eq. (13), is 24.6° at the pole tip. A computer run was made with 360 initial particles.

Table I summarizes the current limits obtained from the computer simulation and from Eq. (23). The current limit from the formula has been obtained by taking \(\mu = 1\).

Table I

<table>
<thead>
<tr>
<th>A COMPARISON OF CURRENT LIMITS FOR THE OCTUPOLE CHANNEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I(A)) (from formula)</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>4.0</td>
</tr>
</tbody>
</table>

The computer simulation value is ~35% lower than the value predicted by the formula. We believe the most likely explanation for the discrepancy to be either (1) a poor approximation for the flutter factor (Eq. 22), which enters in a sensitive way (as the cube) in Eq. (23), or (2) a possible restriction on the zero-current phase advance, related to instabilities, which might affect the computer simulation.

The RFO Accelerator

An RFO accelerator can be described by the following potential function:

\[
U = \frac{V}{2} \left[ \frac{X^4}{a^4} \cos 4\psi + A I_0(kr) \cos kx \right] \sin (\omega t + \phi) \quad . \tag{40}
\]

\[
E_r = \frac{-2XV}{a^4} r^3 \cos 4\psi - \frac{kAV}{2} I_1(kr) \cos kx \quad , \tag{41}
\]

\[
E_x = \frac{2XV}{a^4} r^3 \sin 4\psi \quad , \tag{42}
\]

\[
E_z = \frac{kAV}{2} I_0(kr) \sin kx \quad , \tag{43}
\]

each multiplied by \(\sin (\omega t + \phi)\).

The acceleration efficiency factor \(A\) is given by

\[
A = \frac{m - 1}{m^4 I_0(ka) + I_0(mka)} \quad , \tag{44}
\]

where \(m\) is the vane modulation parameter, shown in Fig. 2. The focusing-efficiency factor \(X\) is given by

\[
X = 1 - A I_0(ka) \quad . \tag{45}
\]

As in the RFQ, the space average longitudinal electric field is proportional to the acceleration efficiency, and is given by

\[
E_o = \frac{2AV}{B} \quad . \tag{46}
\]

We find that for the RFO, there is considerably more accelerating field produced for a given value of \(m\), than for the RFQ.

The pole-tip geometry, which corresponds to the potential function, can be obtained in the same way as for the RFQ.\(^1\) In the middle of the unit cell, where \(z = \frac{\Delta}{4}\) (Fig. 2), there is octupole symmetry in the transverse plane. In this symmetry plane all eight pole tips have radius \(r_0\), and their radius of curvature is \(r_0/3\), where \(r_0 = a/\sqrt{3}\).

Conclusions

We have obtained formulas for an RFO beam transport system and an RFO accelerator and have tested the predictions of a space charge defocusing model against a multiparticle simulation. At high beam currents the simulation shows that the beam will develop a hollow radial distribution, which agrees qualitatively with the model.
Fig. 2. Radio-frequency octupole pole-tip geometry.

Acknowledgments

We thank Rene Mills for her careful work on the computer simulations, and L. J. Laslett for making his work on the octupole available to us.

References


MATCHING THE RF QUADRUPOLE BEAM TO THE DRIFT TUBE SECTION IN THE FMIT ACCELERATOR*

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Summary

The beam produced by the Fusion Materials Irradiation Test (FMIT) radio frequency quadrupole (RFQ) accelerating structure must be matched to the drift-tube linac (DTL) structure that follows. Because minimum beam spill is a primary concern, a matching criterion that considers the beam edges as well as the rms properties is needed.

We flared the RFQ's vanes and adjusted the strengths of the first four quadrupoles in the DTL to achieve optimum performance downstream. Numerical methods used to set the quad gradients, and some experience with various matching criteria are described. The match achieved is compared with matches obtained by other methods.

Introduction

The deuteron beam emerging from the FMIT RFQ must be matched to the following drift-tube section. To save space the match is accomplished by using the first four quadrupoles of the drift-tube section; no attempt is made to improve the longitudinal match. Beam spill is of overriding importance in FMIT because hands-on maintenance is desired. Hence the quality of the match is highly important. The RFQ output beam is not inherently matched to the drift-tube section for two reasons. First, the focusing period in the RFQ is $\beta_x$, while it is $2\beta_x$ in the drift-tube sections. Second, the transverse beam dimensions in the RFQ cannot be expected to be those that produce the best beam in the accelerator's downstream section.

The FMIT DTL design is based on an assumed RFQ output beam having the nominal parameters: 2-MeV energy; 0.006 cm-mrad unnormalized transverse total emittance, in both $x$ and $y$; $\pm 25^\circ$ phase spread; and 0.2-MeV energy spread. The synchronous phase is $0.1^\circ$ and the accelerating gradient is constant at 1.4 MV/m.

Perhaps the most usual matching method would be to match the rms Courant-Snyder $\alpha$'s and $\beta$'s to the requirements of the DTL at a particular point. This was done, but the total beam size obtained was unsatisfactorily large. Using more information about beam performance over a whole section of the downstream DTL resulted in a much smoother match. Also, by including maximum beam size as part of the criterion, we were able, in simulation studies, to achieve a smaller maximum-beam size with little change in the rms properties. The procedure and some observations on experience with it will be presented below.

The Procedure

Of course, the first thing to do is to properly define the "output" beam from the RFQ. This beam should not be the RFQ's entire output but only the part that represents the part of the beam that is "good." We exclude any particles with energy too far off the synchronous energy; that is, particles with no chance to transverse the DTL.

We took the basic assumption that any beam property chosen to make the match must experience a smooth transition, without wide excursions, from the entrance of the DTL to the point in the DTL where the matching may be considered complete. The criterion for matching was based on a group of beam properties in the cells downstream from the matching quads.

A least-squares optimization approach is used. Let there be $m$ properties in a given cell that will be used to determine the match, and $n$ downstream cells in which these $m$ properties are to be optimized. We then have $mn$ properties, $P_{(u)} = P_i, 1 \leq i \leq m$, to optimize. Select a smooth function $f_u(v), (1 \leq u \leq m, 1 \leq v \leq n)$, to which the $t$th beam property is to be fitted. Only the general form of this function is selected, (for example, linear). Its parameters will be determined by the $n$ values of the $t$th property and the function so determined then will be used to determine the desired values of $P_{(u)}$. Thus we first pass the beam through the matching section and through the $n$ downstream cells to find the $mn$ properties, $P_{(u)}$, and the least-squares fit to the target functions $f_u(v)$. From this we derive a set of $mn$ deviations of the properties from their desired values, $\delta_j = P_j - f_u(v)$. Let $w_j$ be the weight to be given to the $t$th property in the $u$th cell.

We define the vector $d$ by

$$d = (\omega_1s_1, ..., \omega_ns_n, ..., \omega_{mn}s_{mn})$$

The beam is then passed through the system repeatedly, each time with a predetermined change in one of the first $m$ quadrupoles in the matching section, to get the partial derivatives.

$$a_{ij} = \frac{\partial P_i}{\partial \alpha_{(u)}} = \frac{\partial P_i}{\partial \beta_{(u)}}; 1 \leq j \leq m, 1 \leq i \leq mn$$

and $a_{ij} = \omega_i a_{ij}$, where $\omega_i$ is the weight to be given the $P_j$ property. Now define the vector of quadrupole gradient changes by $\delta Q = (\delta Q_1, ..., \delta Q_m)$ and the $mn \times m$ matrix $A = (a_{ij})$. Then we can solve the matrix equation $A \delta Q = d$ for the required quadrupole changes in a least-squares sense.

After solution for $\delta Q$, new values of the first $m$ quads are obtained and the entire process is repeated. The iteration continues until suitable convergence is obtained.

The above completes the procedure for finding the input DTL quadrupole settings. However, more

*Work supported by the US Department of Energy.
was done to accomplish the match with the RFQ. We found that some of the matching section quadrupole strengths were higher than desired when the RFQ maintains a constant dimensionless focusing strength, $B$, in its accelerator section. We knew that an increase in beam size between the RFQ and the DTL was required, because of the doubling in the transverse periodicity. To accommodate some of this before the matching quads, we flared the accelerating section of the RFQ slightly and found that the required gradients in the DTL matching quads decreased. Such flaring has become part of the present procedure. Figure 1 shows a plot of $B$ versus the DTL matching quad strengths.

![Graph of range of matching quadrupole gradients versus the dimensionless focusing strength, $B$.]

**Fig. 1. Plot of range of matching quadrupole gradients versus the dimensionless focusing strength, $B$. $B = 5.2$ was chosen.**

### Choice of Fitting Functions and Weights

The chosen set of matching properties consisted of rms waist, rms bust, maximum waist, and maximum bust in 27 cells downstream of the four matching quads. This corresponds to one property for each transverse coordinate; by adjusting the weights assigned to the various properties, the influence of any one property can be emphasized. Several functions were tried to fit the beam properties. The first was a straight line. A straight line violates the smooth change criterion at the end of the set of cells whose properties determine the match and, although this discontinuity should be small, it appeared to be sufficient to affect the beam quality downstream. An exponential taper failed because of numerical difficulties evaluating exponentials with large negative arguments. The final choice, which produced a smooth movement in early stages, $k = 0.001$ is sometimes used if the beam is thought to be close to the minimum size.

The choice of $n$, the number of cells in which criteria are to be met, was also examined over a range of $n = 7$ to $n = 47$. In general, the more cells used, the better the match, as judged by the beam profile; however, the improvement obtained by using more than 27 cells was not great. Because the code running time is a linear function of the value of $n$, we chose $n = 27$.

Weighting was done so that

$$\omega \left( \frac{W_{\text{max}} + B_{\text{max}}}{W_{\text{ave}} + B_{\text{ave}}} \right)$$

was between 0.75 and 1.1. ($W =$ waist, $B =$ bust). Waists and busts were additionally weighted so that each had an equal effect on the problem.

### Experience with the Technique

We compared several possible ways of making the match between the RFQ and the DTL. These cases are described below and summarized in Table I. For brevity in the description and in the table we make use of the following definitions.

**RFQ Input to the DTL** refers to a standard set of 5272 particles generated by passing an initial set of 6000 particles through a numerical simulation of the FMIT RFQ. Particles emerging from the RFQ with energies $>0.09$ MeV below the synchronous energy were excluded. This limit was specifically chosen so that no particles would be lost during the matching. This makes the following comparisons more straightforward. (In our actual FMIT design, we have used a somewhat more elaborate criterion.)

**Uniform Input** refers to a set of random particles generated by PARMILA uniformly in phase space to have the same rms properties as the RFQ beam.

**Cases IA and IB:** In Case IA the RFQ input was used and the match was determined using rms waist, rms bust, maximum waist, and maximum bust in 27 downstream cells. Case IB was the same except that a weight of zero was assigned to the maximum values.

**Cases IIA and IIB:** These two cases parallel Cases IA and IB. A uniform input was used instead of RFQ input.

**Case II:** RFQ input was used to find quadrupole settings that would result in matched values of $a_{x}$, $b_{x}$, $a_{y}$, $b_{y}$ at the end of Cell 4 of the DTL. With intense beams, it is not trivial to determine the ellipse parameters precisely. We started with $a's = 0$ and calculated $b$ values from the envelope equations; then adjusted the $a$'s by trial and error.

**Case IV:** This is the parallel case to Case III. Uniform input was used to find the match to the same $a$'s and $b$'s as Case III.
Particles lost in DTL.

• Cases VA and VB can be compared only with each other.

Table I
DESCRIPTION OF MATCHING CASES

<table>
<thead>
<tr>
<th>Case</th>
<th>Input</th>
<th>Max Weight</th>
<th>Match To</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA</td>
<td>RFQ</td>
<td>1</td>
<td>27 cells</td>
</tr>
<tr>
<td>IB</td>
<td>RFQ</td>
<td>0</td>
<td>27 cells</td>
</tr>
<tr>
<td>IIA</td>
<td>Uniform</td>
<td>1</td>
<td>27 cells</td>
</tr>
<tr>
<td>IIB</td>
<td>Uniform</td>
<td>0</td>
<td>27 cells</td>
</tr>
<tr>
<td>III</td>
<td>RFQ</td>
<td>a's, b's</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Uniform</td>
<td>a's, b's</td>
<td></td>
</tr>
<tr>
<td>VA</td>
<td>Uniform + extra</td>
<td>1</td>
<td>27 cells</td>
</tr>
<tr>
<td>VB</td>
<td>Uniform + extra</td>
<td>0</td>
<td>27 cells</td>
</tr>
</tbody>
</table>

Cases VA and VB: These two cases were used to examine the effect of weighting on a few particles placed well outside the bunch transversely. A uniform input was used, with matching to the rms and maximum busts and waists in 27 downstream cells.

All cases represent possible methods of matching. Case IV is perhaps a standard technique.

We used two criteria to judge the quality of the match. First, the beam must be "smooth," without large changes in size in or after the matching section. Smoothness can be judged by looking at profiles and can be quantized by calculating the standard deviation (σ) of the maximum and rms radii of the beam as it passes through all the cells of the DTL. The second criterion used was beam size. This is quantized by calculating the average maximum radius, r_max, and the average rms radius, r_rms.

For direct comparison of Cases I–IV, we passed the RFQ input beam through the entire DTL and calculated those quantities. In Cases VA and VB, where we were interested only in seeing the effect of weighting the maximums, we used a uniform input supplemented by halo particles.

Table II summarizes the results obtained for the eight cases.

Table II
COMPARISONS OF MATCHING CASES

<table>
<thead>
<tr>
<th>CASE</th>
<th>IA</th>
<th>IB</th>
<th>IIA</th>
<th>IIB</th>
</tr>
</thead>
<tbody>
<tr>
<td>r_max</td>
<td>1.2069</td>
<td>1.2047</td>
<td>1.5507</td>
<td>1.5745</td>
</tr>
<tr>
<td>σ(r_max)</td>
<td>0.1034</td>
<td>0.1024</td>
<td>0.2587</td>
<td>0.2774</td>
</tr>
<tr>
<td>r_rms</td>
<td>0.00472</td>
<td>0.00472</td>
<td>0.00510</td>
<td>0.00515</td>
</tr>
<tr>
<td>σ(r_rms)</td>
<td>0.000598</td>
<td>0.000600</td>
<td>0.000769</td>
<td>0.000829</td>
</tr>
</tbody>
</table>

Comparison of Cases IIA and IIB shows that when uniform input is matched to 27 downstream cells, there is some slight advantage to using the maximum values as well as the rms values. Obviously, a uniform approximation to the RFQ input gives neither as small nor as smooth a beam as true RFQ input. This is true even when the match is made to a's and b's needed at Cell 4, as seen by comparing Cases III and IV; therefore, the distribution shape can be important in achieving the best match.

Comparison of either IA or IB to Case III shows that matching to a single set of a's and e's results in a beam substantially larger in overall size and somewhat larger in rms size. It is also not nearly as smooth.

The effect of using or not using the maximum values when particles are well outside the expected input is examined in Cases VA and VB. From Table II, it appears that using only the rms values (VB) produces a smaller and smoother beam. However, in this case, the "halo" we introduced was lost in the DTL; whereas, when the maxima were used in determining the match, these halo particles were transported through. It has been noted at LAMPF that rms properties alone are insufficient to achieve the lowest beam loss; because this technique handles halo particles, it may prove useful, provided adequate measurements on the DTL can be made.

Conclusions

We have described the least-squares method we used to match the FMIT RFQ beam to the DTL. We have compared this method with other methods that use approximate particle distributions or less information, and we have shown that our method results in a smaller, smoother beam when halo particles are ignored. We have shown that the method is capable of providing a match that may allow halo particles to traverse the DTL.

The most convenient feature of our method is that it is unnecessary to determine, a priori, either the priorities of the RFQ input beam or the necessary properties of a good DTL beam to make the match because the determination of these properties is implicit in the method.

References

For the 1.1GeV-100 mA Spallation Neutron Source SNQ operation costs and beam losses ask for the possible potential of RF control improvements. Two novel methods are investigated.

First, in order to increase the overall RF efficiency, the cavity field is built up as fast as possible in the open loop state of feedback control and in detuned position of the cavity in such a manner that the cavity with beam is matched to the generator. It is shown that this requires the simultaneous application of a generator amplitude and a generator phase step.

Secondly, a feedforward control system is proposed, which reduces the amplitude and phase control error caused by an arbitrary beam transient into the limits of ± 1% and ± 0.1° and maintains these error limits also in the presence of parameter drift. This is done by an adaptive parameter adjustment procedure using a digital model of the control system. The system structure and a promising digital simulation are discussed.

Equivalent circuit

The well-known RF equivalent circuit of a beam loaded cavity in figure 1 a is transformed to the dynamic equivalent circuit in figure 1 b for the complex amplitude (amplitude and phase), which is useful for control applications. Figure 1 b represents a sufficiently good approximation for high Q-values under the assumption: \( \frac{G_i}{Z_L} = 1 \) and \( 1 = n \cdot \lambda / 2 \). The detuning is \( \Delta \omega = - \sqrt{CC} \), \( \beta \) is the coupling factor and \( b \) the beam loading factor defined as ratio of the real beam power to the cavity losses. Because of the particle phase shift \( \phi_0 \) the beam admittance is complex. The decay time of the unloaded cavity is given by \( T_0 = 2 \sqrt{C/G} \).

The condition of power matching of the generator admittance \( \beta \cdot G \) to the beam loaded cavity admittance leads to the equations:

\[
\beta = 1 + b \\
2\omega C = - bG \cdot \tan \phi_0
\]

With the decay time of the loaded cavity \( T_L = T_0/(1 + \beta) \) it is convenient to express the detuning by the transmission phase \( \phi \):  

\[
\tan \phi = - \Delta \omega = T_L = b/(b + 2) \cdot \tan \phi_0
\]

It is obvious, that the generator amplitude \( |I_g_0| \), which produces the field level \( |U| \) in the beam loaded case is larger than \( |I_g_1| \), which is necessary to generate the same field level without beam.

Using the admittance ratio and the formulas above we obtain:

\[
|I_{g_0}/I_{g_1}| = 2(b + 1)/(b + 2) \cdot \cos \phi
\]

Exactly this generator amplitude margin can be used to shorten the filling time of the cavity.

Dead beat filling

Unlike in the resonance case, in the detuned cavity adjustment the forced and the eigensolution have different frequencies. Therefore, a frequency beat occurs and no steady state can be obtained at \( t < \infty \). Is it possible to cancel this beat? From figure 1 b one can conclude that the step response of the first order difference equation with complex coefficients must be an exponential function with complex argument:

\[
U(t) = U_0 (1 - \exp(- t/T_L (1 - j \tan \phi)))
\]

A typical step response is plotted in figure 2 a. At the time \( T_F \) - the filling time - the generator amplitude is switched from \( |I_{g_0}| \) to \( |I_{g_1}| \) and no parameter combination can be found, which makes the steady state at \( T_F \) possible. But, if one adds a certain generator phase step simultaneous to the amplitude step, again like in the resonance case (shown in figure 2 c for comparison) the steady state can be reached at \( T_F \) as it is illustrated by figure 2 b.

Applying the theory of "dead beat response" the following condition holds:

\[
|I_{g_0}/I_{g_1}| = 1/(1 - \exp(- T_F/T_L (1 - j \tan \phi)))
\]

The phase angle of \( I_{g_0}/I_{g_1} \) is the phase step \( \Delta \phi \) in figure 2 b:

\[
\Delta \phi = \phi (I_{g_0}/I_{g_1})
\]

For a given amplitude margin \( I_{g_0}/I_{g_1} \), which depends on the beam loading factor, there is only one possible value for the filling time \( T_F \) and the phase step \( \Delta \phi \), which fulfill the dead beat condition.
Cavity amplitude response to a generator step excitation
a: detuned - amplitude step only
b: detuned - amplitude and phase step
c: resonant

In figure 3 the quantitative relations between filling time, amplitude and phase step and beam loading factor are plotted for a synchronous phase $\phi_s = -30^\circ$. The maximum possible phase step occurs at high beam loading and reaches about 2/3 of the synchronous phase $\phi_s$.

Fig. 2: Cavity amplitude response to a generator step excitation

Fig. 3: Phase step, amplitude step and filling time vs beam loading factor $b$

Typical parameters for the SNQ disk-and-washer structure at $v/c = 0.7$ and $\phi = -30^\circ$ are $b = 0.8$, $T_0 = 57 \mu\text{sec}$, $T_F = 30 \mu\text{sec}$, $|Ig_0/Ig_1| = 1.27$ and $\Delta \phi = 4^\circ$.

Up to now we have considered the cavity in the open loop state of the feedback system. Before the beam enters the cavity the amplitude and phase feedback loops have to be closed, which might cause a minor transient because of misadjustment. Therefore, in practice the total time consumption from rf turn-on is somewhat larger than the calculated filling time.

It should finally be mentioned, that the generator impedance differs from the line impedance $Z_L$ and there might be reasons to choose the line length $L \pm \frac{1}{2}$. This more general case can also be treated with the dead beat response method presented above. The necessary phase and amplitude step will depend then on $G_1$ and $I$, but no fundamental change of the results are expected.

Feedforward control (FFC)

It is state of the art in proton linear accelerators with heavy beam loading to support the amplitude and phase feedback loops by a feedforward signal derived from the beam.

Our concept is based on the assumption of the most severe beam transient, a step function. If the field error in this case can be tolerated, the control system would be even more efficient for all other real beam transients. The feedforward pulse shape can only be a step function, which is simply generated by a pulse generator and is fed to the amplitude/phase modulator. Because the FFC pulse rise time is increased afterwards by the power transmitter, a complete compensation of the transient beam loading is not possible.

A computer simulation for the SNQ amplitude/phase control loop with a PID controller results in a maximum dynamic cavity amplitude error of $-2.5\%$ if only feedback is used. A reduction to $0.6\%$ can be obtained, if a FFC pulse with proper amplitude is fed synchronous to the beam pulse into the modulator. This case is illustrated by the lower curve in figure 4.

Fig. 3: Phase step, amplitude step and filling time vs beam loading factor $b$

Fig. 4: Computer simulation of the dynamic amplitude control error caused by a beam transient for different delay time of the feedforward (FFC) pulse

A further drastic reduction can be obtained, if the FFC pulse and thereby the klystron power is raised before the beam enters the cavity. At an optimum leading time of $0.25 \mu\text{sec}$ the resulting error is within the desired $\pm 0.1\%$ limits (figure 4: middle curve). If the leading time becomes too large, again the error is increasing (upper curve).

The $\pm 0.1\%$ error limits discussed above are achieved in the LAMPF accelerator by slowing down the beam transient.
These digital simulation results had been confirmed also by an analog model of the feedback loop.1

The simulation proves that the combined use of feedback and feedforward stabilizes the rf field sufficiently against the expected beam disturbances. Figure 4 shows on the other hand the large sensitivity of the error on the delay time. A drift of less than 100 nsec causes the error to increase by a factor of 2. Therefore, an absolute condition for an improved feedforward control is the elimination of parameter drift by an automatic adjustment procedure.

Adaptive parameter adjustment

The proposed adjustment procedure is based on two technical developments, the availability of fast transient recorders with sufficient resolution and low cost digital processors.

The solution is outlined in figure 5. The control signal sample is picked up from the "real world" by a transient recorder. The equivalent signal calculated by the computer model of the control system is changed by means of a multidimensional parameter optimization as long as it fits well enough to the real signal.

Fig. 5: Block diagram of the adaptive parameter adjustment procedure

This new parameter set is used either for correction of the FFC pulse generator (delay and amplitude) or for marginal checking (loop gain and stability etc.), if control loop parameters had been changed. The advantage of this scheme is that only one sample of the "real world" is necessary and the adaption takes place completely in the "computer world". Obviously, the quality of the adaption depends on the quality of the computer model, the digital simulation.

Digital simulation

The digital simulation must represent sufficiently the dynamic structure of the control loop, which is here approximately an 8th order system with delay. The execution time of one simulation cycle determines the number of periodic beam bunches, which pass the cavity until the parameter correction takes place. This last requirement favors direct methods against such transformation methods as Fast Fourier Transformation (FFT) or the State Space Transformation or the timewasting method of convolution integrals.

The most appropriate direct method seems to be the transfer of the differential equation system into an approximate system of difference equations that are solved successively. In addition, with this method the time delay can be treated exactly.

In figure 6 a the normalized representation of a Nth order dynamic system with delay and feedback is shown in Laplace notation, where the integration operator occurs as 1/s.

The nominator coefficients are and the denominator coefficients are easily obtained from the time constants of control plant and the PID controller.

There are several well-known approximations of the integration operator12, which can be expressed in terms of the z-transform as follows:

$$f(z) = e^{-mt}H(z)$$

$$\frac{1}{1-z^{-m}}$$

with the definition of the z-transform $z = \exp(-T \cdot s)$, $T$ is the sample time and $m$ the order of approximation. For explanation of (8) two examples are given:

For example 1 the trapezoidal rule with $P_m(z) = \frac{z^{-m}}{m!}$ and $h_m = T/2$, $m = 2$ the Simpson rule with $P_m(z) = \frac{z^{-m}}{m!}$ and $h_m = T/3$.

In order to get a successively solvable system of difference equations, the system of figure 6 a under use of equation (8) must be reorganized in such a way, that the state variable $X_N(z)$ depends only on the state variables of one step before present time. This is performed by the coefficient transformation13:

$$c_k = \sum_{i=0}^{K} h_m \cdot a_i ; 0 < K < N$$

With the condition, that the delay time $T_t$ is a multiple of the sample time:

$$T_t = p \cdot T ; \quad p > 1$$

We obtain the solvable system of difference equations in figure 6 b.

If this program structure is compared with the FFT, it should not be difficult to develop a digital processor like the FFT processor. If a typical 5 usec transient (error or control sample) is sampled with a 10 MHz transient recorder, we have typical 50 sample points. It is estimated, that the execution time of the digital processor for these 50 sample points could be less than 0.5 msec (FFT processors with 1024 sample points have an execution time of 5 msec14). That means, in the interval between two SNQ beam pulses (100 Hz repetition rate) about 20 transients with different parameter sets can be calculated. This should be sufficient, if only one or two fluctuating parameters have to be tracked in the practical accelerator operation. If more parameters have to be tracked or if the parameter deviation between two samples is large (i.e. at first turn-on of the adaptive loop) the time consumption may increase considerably, but the total adaption time should be less than 1 sec.

The simulation method in figure 6 b had been tested with the closed loop response of the SNQ feedback
system. As a next step the digital simulation will be implemented in the adaptive adjustment loop.

Acknowledgement

The stimulating discussions with G. Hochschild and K. Bongardt are appreciated. We thank A. Hornung for design and construction of an analog model of the SNQ feedback loop.

References

1. J.E. Vetter (Editor), The Basic Concept of the SNQ Linear Accelerator, Kernforschungszentrum Karlsruhe, KfK 3180 B (1981)
6. R.A. Jameson, Analysis of a Proton Linear Accelerator RF-System and Application to RF Phase Control, LA-3372, Los Alamos N.M., June 1965
7. B.P. Murin, RF-Field Stabilization and Control for Ion Linear Accelerators (in Russian), Atomisdat Moscow, 1971
**Introduction**

The SNQ consists of a linear accelerator accelerating 100 mA protons with 5% duty factor up to 1.1 GeV and of a rotating heavy metal target.

For the design of the SNQ-linac a conventional electrostatic preaccelerator was proposed as injector into the rf-linac. Before a final decision will be taken, the rf-quadrupole structure will be examined extensively as a possible alternative way of injection. In the following the main design criteria, as suggested in the SNQ-study, will be presented and discussed. In addition, some results of experimental work on ion sources, beam extraction and beam transport of a neutralized ion beam will be given.

**Design of the Electrostatic Preaccelerator**

**Requirements**

The design current for the SNQ-Linac is 100 mA protons with a pulse length of 500 usec and a repetition rate of 100 Hz. In order to achieve a sufficiently low level of activation along the linac, only small beam losses are allowed. It is felt that stable beam conditions are of particular importance to obtain a clean machine. A stability of the beam current in the order of one percent both during a pulse and over long time were therefore specified. All components have to work very reliably and, after shutdown have to deliver reproducible beam conditions in order to guarantee the desired availability of the SNQ.

**Choice of the Injection Energy**

A high injection energy is desirable in order to reduce the problems of beam dynamics at the front end of the accelerator. On the other side, the availability of an electrostatic preaccelerator decreases with increasing accelerating voltage because of high voltage breakdowns. Taking into account the stringent requirements on reliability for the SNQ and considering especially the experiences in accelerating continuous ion beams at CRNL and at LLL a injection energy of 450 keV was chosen. An increase up to 600 or even 800 keV seems to be possible after an adequate development time. Valuable experiences for operation at higher voltages will be obtained from other projects under construction.

**Principle Arrangement of the Preaccelerator**

The electrostatic acceleration takes place in two stages. First the ion beam is extracted out of the ion source at a low voltage (< 50 kV), transported to a high voltage column and then accelerated there to the desired energy (Fig. 1). The two-stage arrangement chosen offers considerable advantages over the more conventional one-stage system where the ion source is directly attached to the high voltage column.

- The extraction voltage can be chosen independently from the total preacceleration voltage. The extracted ion beam current can be appropriately controlled (1A < 1 mA), therefore.
- The beam transport system, which follows the extraction from the ion source can be used to match the beam to the optics of the accelerating column. By removing the beam halo at the entrance of the column, beam spill inside the column can be reduced.
- The pressure in the high voltage columns can be kept low by differential pumping.

However, the extracted low energy (≤ 50 keV) ion beam must be transported with a high degree of neutralization. The transport of a neutralized ion beam, especially through magnetic transport elements, may result in an emittance growth by beam plasma oscillations.

To keep the beam parameters sufficiently constant over the pulse length and to provide short (< 1 usec) rise and fall times, the required pulse of 500 usec will be formed on the 450 keV level by a ultra fast beam deflector. A rough pulse will be preformed by pulsing the ion source. Chopping the beam at 50 keV was excluded, because of the high space charge forces at that energy.

**Description of the Components and Experimental Results**

**Ion Source**

A magnetic multipole ("bucket") source has been chosen, although several other kinds of ion sources are able to generate the required proton currents. The main advantages of the multipole source for accelerator operation are:

- The arc discharge is quiet. The noise level (1 MHz bandwidth) of the extracted ion current was measured to be less than 1% at continuous operation.
- The ion current density is constant over the extraction aperture. Therefore, the beam can be ex-
tracted nearly free from aberrations with reproducible beam properties. The operation of the source is simple and reproducible. The disadvantage of the multipole source is its relatively low proton percentage.

To evaluate the properties of the source, especially for an accelerator application, an experimental program was started. Extensive measurements have been done mainly on the ion source shown in Fig. 2 and 3. The source consists of a cylindrical anode body (diameter = 11 cm, length = 15.8 cm). Twelve rows of cobalt-samarium magnets produce a magnetic multipole field. On the backplate the magnets were arranged either radially or parallel without any significant difference seen in operation of the source. Tungsten filaments were used as cathode. The heating current of the filaments was used to control the discharge current at constant discharge voltage (emission limited mode). The extraction plate was normally kept on cathode potential. The source was operated at pressures between 2 and 20 μbar, mainly, however, around 6 μbar. The maximum discharge power limited by the power supply and by the cooling capability of the source was 10 kW (80 A, 125 V) for continuous operation. The corresponding ion current density \( j_+ \) at the extraction aperture was measured to be \( \sim 500 \text{ mA/cm}^2 \). At constant gas pressure \( j_+ \) is proportional to the discharge current with only a weak dependence on the discharge voltage.

Fig. 2: The tested magnetic multipole source with removed extraction plate

With a movable probe \( j_+ \) near the extraction plate was measured as a function of the radius and was found to be sufficiently homogeneous. Over the extraction aperture with a radius of 6.5 mm \( j_+ \) is constant to better than 1% (Fig. 4).

The lifetime of the tungsten filament consisting of two parallel 16 cm long tungsten wires helically wound was tested at continuous discharge operation. The filament current was controlled to keep the discharge current constant at 40 A at a constant voltage of 90 V. The required filament current decreased from 98 A at the beginning of the test to 85 A after 165 h of operation when the cathode failed. During this operation time the diameter of the tungsten filaments decreased from 1.0 mm to about 0.9 mm. Not only thermal evaporation, but also sputtering through the plasma ions causes a significant reduction of the filament diameter as observed on an additional cold filament, which diameter decreased to about 0.95 mm over the operation time. For a pulsed operation with a low duty factor the effect of the plasma is strongly reduced, therefore a longer lifetime is expected even if the filament is heated continuously.

The proton yield of the extracted beam was found uncomfortably low. The highest proton percentage achieved was 55% at the highest obtainable discharge current of 80 A (Fig. 5). Experiments on modified source geometries as suggested from experiences at UKEA Culham\(^9\) and LBL\(^10\) are underway.

Fig. 3: A schematic view of the tested ion source with a 3-electrode extraction

Fig. 4: A typical plot of the ion current density \( j_+ \) and the azimuthal magnetic field \( B_\varphi \) near the extraction plate as a function of the radius

Fig. 5: Ion species as a function of discharge current \( I_{\text{arc}} \) resp. ion current density \( j_+ \) at \( U_{\text{arc}} = 125 \text{ V} \) and \( P_{\text{arc}} = 10 \text{ μbar} \)
The pulsing behaviour of the ion source was tested by pulsing the arc voltage. The rise time was observed to be about 30 μsec. During a pulse the discharge current respectively the ion current are decreasing by typically 2 or more percent over 100 μsec for pulses of a total length up to 2 msec. An improvement in the stability of the ion current is expected by pulsing with a constant current generator and allowing the discharge voltage to change during a pulse.

**Extraction and Ion Source Beam Transport**

In order to obtain 100 mA of protons at the entrance of the rf-accelerator, a total ion beam of about 250 mA has to be extracted assuming a proton yield of 60 %, a bunching efficiency of 80 % and beam losses on scrapers and due to charge exchange of 20 %. A 250 mA ion beam can be extracted out of a single aperture with diameter of 13 mm at ~ 50 kV. The results of a computer optimization are shown in Fig. 6. The calculations have resulted in a divergence of less than 20 mrad and a normalized rms-emittance of about 0.05 π mm mrad for an ion current of 0.7 μA. The suggested beam transport system between the ion source and the accelerating system is shown schematically in Fig. 1. The extracted divergent beam is matched to the following part of the system by a solenoid. Four quadrupoles and a 90°-bending magnet transfer the beam in a 1:1 scale to the entrance of the acceleration column, where the beam halo will be scraped off. A comparable system was optimized with the TRACE program and it was found that the extracted ion beam can easily be transported if the space charge is neutralized to at least 90 %.

![Fig. 6: Beam forming in an optimized 3-electrode extraction system. J_4 = 200 mA/cm², \Phi aperture = 13 mm](image)

In order to study the behaviour as well of the extraction as of the transport of a neutralized ion beam, some experimental work has been done on a high voltage test stand. An ion beam was extracted with a 3-electrode extraction system (Figs. 3, 6). The performance and divergence were found in good agreement with the calculated values. At 50 kV a total ion current of 240 mA has been extracted at continuous operation resulting in a perrance of 2 \times 10^{-9} A/V²/μm.

In addition to a visual observation of the beam width the beam profile was measured with a movable multi wire scanner consisting of a cooled 0.5 mm slit with an arrangement of tungsten wires behind it. From the thus measured divergence of the drifting beam a neutralization degree for at least 97 % was estimated for a 35 mA beam at 45 keV at a pressure of 2 \times 10^{-8} bar. The focusing effect of a solenoid on the transport of a neutralized ion beam was examined. Within the estimation error of about 5 % the experimental focal length of the solenoid agrees with the calculated value for the space charge free case. When focusing the ion beam (one species) to a spot of a few mm diameter an increase of the amplitude of oscillations by more than a factor of 10 was observed with the multi wire scanner coming presumably from oscillations in the beam plasma. The main frequency of the oscillations is around 30 to 50 kHz. It will be proven, how far these oscillations are causing a modulation of the ion beam current density. The experiences gained with the solenoid demonstrate that a low voltage (< 50 keV) neutralized ion beam can easily be matched with reproducible properties to a high voltage column only with a solenoid, giving thus an alternative to the suggested transport system (Fig. 1).

**The Accelerating Column**

The ion beam will be postaccelerated in a high voltage column up to the desired injection energy. Experiences at LLL² were taken into account for designing the column. The total voltage is distributed over 3 accelerating gaps producing a nearly constant field of 30 kV/cm. The beam transport inside the column was verified with a computer code. The large aperture of the electrodes of 10 cm diameter gives a high pumping speed and reduces beam losses inside the column.

**Conclusions**

Within the present state of the art the preaccelerator for the SNQ-linac can be built reliably. To guarantee the strong requirements on beam properties some development work on the ion source concerning the pulsing behaviour and also the proton yield are necessary. In order to know the beam properties extensive measurements especially of the beam emittance have to be done.

**Acknowledgements**

Discussions with many colleagues working on ion sources and electrostatic injection in different places were very useful. Especially I would like to acknowledge the fruitful collaboration with Dr. A.J.T. Holmes, UKEA, Culham and Dr. M.R. Shubaly, CRNL, Canada, Dr. M. Weiss, CERN, kindly calculated the ion source beam transport with the TRACE-code. Dr. K. Mittag, KfK, calculated the focal length of the solenoid. Dr. J.E. Vetter, KfK, carefully read the manuscript.

**References**

1) G.S. Bauer et al. (ed.): Realisierungsstudie zur Spallations-Neutronenquelle, Teil II, KFA Jülich/ KfK Karlsruhe, Jül-Spez-113, KfK 3175, see also A. Citron, these proceedings
3) J.Ungrin: AECL-6584, CRNL, Canada, Dec. 1979
7) J.D. Hepburn et al.: AECL-6537, CRNL, Canada, May 1978
A computer code BCI was used to calculate the energy loss of beam bunches in two types of cavities being studied in CRNL. The merit of the proposed on-axis coupled structure for CHEER is discussed in terms of beam energy loss. A calculation for a simple structure consisting of two accelerating cells and a coupling cell is performed. The amplitude modulation of the wake field is interpreted as the excitation of the zero and first coupled-resonator modes and coupling coefficients are derived. Beam loading of a cw linear accelerator is studied by calculating the bunch energy loss and cavity energy when a cavity is excited resonantly with a series of beam bunches. Calculations of non-resonant excitation are also presented.

Summary

A computer code BCI was used to calculate the energy loss of beam bunches in two types of cavities being studied in CRNL. The merit of the proposed on-axis coupled structure for CHEER is discussed in terms of beam energy loss. A calculation for a simple structure consisting of two accelerating cells and a coupling cell is performed. The amplitude modulation of the wake field is interpreted as the excitation of the zero and first coupled-resonator modes and coupling coefficients are derived. Beam loading of a cw linear accelerator is studied by calculating the bunch energy loss and cavity energy when a cavity is excited resonantly with a series of beam bunches. Calculations of non-resonant excitation are also presented.

Introduction

The computer code, BCI1 (Beam-Cavity-Interaction), has been used extensively in CERN for calculating energy losses in traversing cavities and various beam line elements by a single beam bunch. These energy losses are important in electron storage rings. The code calculates the electromagnetic fields excited by arbitrarily shaped bunches of charged particles travelling in structures with cylindrical symmetry by numerically integrating Maxwell's equations in the time domain. Transient fields at any instant of time are obtainable. A new version of this code includes options of using an open boundary condition and finite conductivity2.

The Electron Test Accelerator (ETA) group at Chalk River Nuclear Laboratories has been interested in studies of heavy beam loading of accelerator structures during high current cw operation. Experiments have been performed3 where 80% of the rf power was transferred directly to the beam. In order to simulate this cw condition, the BCI code was modified to provide an option called LINAC which performs calculations with multiple beam bunches. For the Canadian High Energy Electron Ring (CHEER) study4, a new on-axis coupling cell structure with iris coupling was proposed. The beam energy loss in this type of structure including the loss in the coupling cell can be investigated using the BCI code.

This paper will describe our experience with this code and calculations using multiple beam bunches.

Energy Loss Parameters

Two types of cavities have been examined. Cavity A is a typical accelerating cavity that has been used in the side-coupled structure5 of ETA. Cavity B is an accelerating cavity of an on-axis coupled structure presently under study to be used in CHEER6. Both of the cavities are designed for a fundamental frequency of 804 MHz. Schematics of these cavities are shown in Fig. 1.

Coupled Resonator Modes

A simple structure consisting of two cavities of cavity B resonantly coupled by a simple cylindrical cavity has been excited using a single bunch with \( \sigma_{\text{rms}} \) of 0.14 m. The long bunch was used to predominantly excite modes around the fundamental frequency \( f_0 \). The wake field of this bunch showed, in addition to the oscillations at the fundamental frequency observed in a single
cavity, modulation on the amplitude of these oscillations. This modulation is shown in Fig. 2a as the scalloping on a roughly exponential curve. The general decreasing trend of the amplitude is a result of field energy leaving the structure through the two open ends. The modulation is more clearly defined with the geometry shown in Fig. 2b where reflective boundary conditions were placed at the two ends to eliminate the decreasing trend of the amplitude. The amplitude modulation of the wake field oscillation for this geometry is very prominent. Since this modulation does not appear with a single cavity, its appearance may be inferred as the excitation and interference of zero and \( \pi \) modes of the simple structure having frequencies \( \pm \Delta \) displaced from the fundamental frequency. The values of \( \Delta \) is then equal to \( f_0 \) divided by the number of wake field oscillation in each modulation period. Furthermore, the values of \( \Delta \) has been found to increase with the radius of the bore hole that couples the cavities together. This is consistent with the proposed interpretation of coupled resonator modes because the frequency splitting of zero and \( \pi \) modes increases with an increase in coupling. Table 1 shows the modulation period, confirmed by Fast Fourier Transform Analysis, and the derived coupling coefficients for three sizes of beam pipe. The coupling coefficients are calculated as:

\[
k = \text{frequency difference of zero and } \pi \text{ modes} = 2\Delta
\]

They are compared to coupling coefficients calculated using SUPERFISH as reported in reference 4. Though good agreement is found for a pipe radius of 0.045 m, there are discrepancies at large apertures and further studies will be required to resolve these discrepancies.

### Table 1: Coupling Coefficients Determined from BCI and SUPERFISH

<table>
<thead>
<tr>
<th>Beam Aperture (m)</th>
<th>Modulation Period (bunches)</th>
<th>( k ) BCI</th>
<th>( k ) SUPERFISH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>19</td>
<td>10.5</td>
<td>6.8</td>
</tr>
<tr>
<td>0.06</td>
<td>29</td>
<td>6.9</td>
<td>4.5</td>
</tr>
<tr>
<td>0.045</td>
<td>102</td>
<td>1.96</td>
<td>2.12</td>
</tr>
</tbody>
</table>

**Multiple Bunches Excitation**

Since an understanding of cw beam loading is necessary for optimum structure design, an option called LINAC has been added to BCI at CRNL. This option will repeat the beam bunches at specified regular time intervals, simulating the cw condition in an accelerator. Using this option, a cavity without external power source was beam excited. The bunch energy loss and total cavity energy were examined as the cavity approached equilibrium. Both resonant and non-resonant conditions were studied.

In these calculations, cavity A was used. The individual bunch had a gaussian shape with a \( \sigma_{\text{rms}} \) of 0.02 m. The fundamental frequency of the cavity was determined as 797.65 MHz (\( \lambda_0 = 0.37585 \) m) by studying the wake field oscillation after a bunch, whose length was large compared to \( \lambda_0 \), had traversed the cavity. Calculations with different conductivities \( \Sigma \) of the cavity wall were performed. This is advantageous because the time required for a cavity to achieve equilibrium is inversely proportional to the wall losses and one can effectively compress the time scale for achieving equilibrium to save computer time by decreasing the conductivity.

Accelerating cavities are usually operated at the resonant condition, when the bunch frequency \( f_b \) is equal to the cavity fundamental frequency \( f_0 \) or its sub-harmonics. Figures 3 and 4 shows respectively the cavity energy and bunch energy loss as a function of bunch number under this condition. Initially, the bunch energy loss increases linearly with the number of bunches and the cavity energy increases as the square of the number of bunches. This shows the increases of bunch energy loss are mainly because of the increase of the beam induced wake field, which has an amplitude proportional to the square root of the cavity energy acting to decrease the beam energy.

Both the bunch energy loss and cavity energy approach constant levels, when the bunch energy loss is equal to the wall loss in the cavity. According to simple electromagnetic theory, this energy loss is proportional to the square of the field strength at the wall surface and the skin depth of the conductor. In terms of cavity energy \( E_c \) and wall conductivity \( \Sigma \), the energy loss is proportional to \( E_c / \Sigma^2 \). This proportionality is approximately followed by the equilibrium energy losses found in Figs. 3 and 4 for conductivity values of 100, 200 and 500 mho/meter.

The non-resonant condition, where the bunch frequency is not equal to the cavity mode frequency or its sub-harmonics, can be realized in any recirculating accelerator when modes other than the accelerating mode of the accelerator are con-
considered. This general case is of great importance when beam line elements are considered. Figure 5 shows the bunch energy losses when these two frequencies differ by various amounts. Because of the difference in frequency between the wake field and beam bunches, the bunches will either lose or gain energy depending on their relative phase with the wake field. With the relative phase between the bunches and wake field continuously shifting, beat patterns in the bunch energy loss (Fig. 5) and cavity energy (Fig. 6) are observed. The bunch energy loss is maximum when the bunch is exactly out of phase with the wake field, and minimum when exactly in phase. The number of bunches, N, in a beat cycle is equal to the ratio of \( f_0 \) and the difference of the two frequencies \( f_B \) and \( f_0 \), i.e.,

\[
N = \frac{f_0}{f_B - f_0}.
\]

Figures 5 and 6: Beat pattern, wall conductivity 10^6 mho/m.

In addition to what are shown in the figures, it is also found that: in the resonant condition, the most negative wake field is calculated for the peak of the beam bunch, showing zero phase shift; in the non-resonant condition, the most negative wake field occurs at a time later than the peak of the beam bunch, corresponding to a finite phase shift. This is again as expected for simple forced oscillation as in observations one to three above.

The higher energy loss in the resonant condition shows that one must be careful to recognize the various excitation modes of the accelerating structure in a recirculating accelerator. One must avoid having the bunch frequency equal to the frequency of any of the higher order modes, or the coupled resonator modes of the accelerating structure, or the mode frequency of any beam line elements.

**Conclusions**

In order to understand beam energy losses in cw linear accelerator with heavy beam loading, calculations using the computer code BCI (Beam-Cavity Interaction) were performed. The total energy loss parameters with a single bunch calculated for the accelerating cells used in ETA (CRNL) and in CHEER were found to be 0.592 and 0.396 W/pc respectively. The additional energy loss in the coupling cells used in the CHEER on-axis coupled structure was calculated to be only 10% of that for the complete structure. The modulation of the wake field of a simple structure consisting of a coupling cell and two accelerating cells was interpreted as the excitation of zero and \( \pi \)-coupled-resonator modes. The derived coupling coefficients agree with those calculated by SUPERFISH for small beam pipes but differ for large beam pipes. A new option in the code for simulating cw operation was used to study the resonant and non-resonant excitation of a cavity. The calculations show that the bunch energy loss and cavity energy follow relations of generalized forced oscillations. The comparison of the resonant and non-resonant results reaffirmed that, in a recirculating accelerator and for beam energy loss considerations, one should avoid situations in which the bunch frequency is equal to any mode frequency (or its subharmonics) of any beam line element except that of the accelerating mode.

**References**

DESIGN AND CONSTRAINTS FOR THE ZEBRA INJECTOR, RFQ AND DTL

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Atomic Energy of Canada Limited
Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario K0J 1JO

Summary

ZEBRA (Zero Energy Breeder Accelerator) is a proposed laboratory test accelerator designed to produce the full accelerator-breeder beam current of 300 mA at only 1% of the final energy of 1 GeV. Being an experimental prototype, it will be heavily instrumented to diagnose performance under conditions typical of the low energy portion of an accelerator breeder. It will consist of 3 sections - a dc injector, an RFQ buncher-preaccelerator, and a drift tube Alvarez linac. Several constraints are introduced by its eventual application as an injector for an accelerator breeder including variable beam current, economic accelerating gradients that will result in reliable operation, frequency choice and frequency multiplication between the RFQ and Alvarez linacs. This paper will discuss the constraints and present the rationale for the current reference design.

Introduction

The first stage of the accelerator breeder development program at CRNL is the ZEBRA accelerator. It is intended to establish the feasibility of a linac to meet high average current requirements and develop the necessary expertise.

It will consist of four components as shown in Table 1.

Table 1

<table>
<thead>
<tr>
<th>ZEBRA Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
</tr>
<tr>
<td>0.075 MeV</td>
</tr>
<tr>
<td>RFQ</td>
</tr>
<tr>
<td>0.075 - 2.0 MeV</td>
</tr>
<tr>
<td>108 MHz</td>
</tr>
<tr>
<td>DTL</td>
</tr>
<tr>
<td>2.0 - 10.0 MeV</td>
</tr>
<tr>
<td>216 MHz</td>
</tr>
<tr>
<td>Beam Dump</td>
</tr>
<tr>
<td>3 MW</td>
</tr>
</tbody>
</table>

The principal requirement of ZEBRA is to deliver an output current of 300 mA at 10 MeV but the frequency choice is restricted by consideration of the entire accelerator system and by the availability of high power tubes. Preferred values are 108 MHz in the radiofrequency quadrupole (RFQ), 216 MHz in the drift-tube linac (DTL), and 432 MHz in the high β linac. The higher frequency would enable the use of klystrons as the rf source, a more efficient amplifier than gridded tubes required for the lower frequency stages. The output energy of the injector was fixed at 0.075 MeV for two reasons. Above this energy the cost of the injector would increase rapidly and its reliability at high current would decrease rapidly, while below this energy emittance growth and beam loss in the RFQ due to space charge effects become excessive. The output energy of the RFQ was fixed at 2 MeV which is below the copper (p,n) threshold to avoid activation in the RFQ and transport line and yet high enough to give satisfactory acceptance of the RFQ output beam by the DTL and to permit an efficient single tank DTL.

Injector

The ZEBRA injector poses a number of design problems not encountered in other accelerators. The most obvious is the high continuous current requirement - 375 mA of protons, but based on ion source development presently underway, this seems readily achievable. The major problem is the requirement for variable current with a restricted range of beam energy. The present reference design calls for a current variation from 0 to 375 mA at 75 keV. A two stage injector could be considered, but it would be expensive and beam transport elements that would likely be required lead to emittance growth; as seen at KfK3 and GSI4. A proposed approach is to have the injector current variable down to 40 mA and spill the remainder in the RFQ. This uses a single stage injector that can operate at variable current by changing gas pressure (to spoil the proton fraction) and a neutralizer tube to convert some of the protons to neutrals5.

Preliminary experiments at Chalk River indicate that a reduction in the proton current by a factor of 4 is readily achievable by a 12% voltage reduction and by varying gas pressure. The remaining factor of 2.5 reduction can be achieved by the neutralizer tube.

Emittance requirements are not overly stringent but require that the phase space volume be filled uniformly to minimize beam loss in the RFQ. Calculations using the beam simulation code BEAM6, and measurements made at Chalk River indicate that this can be achieved, provided no unexpected beam transport problems arise. The proposed design is summarized in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Proposed Injector Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Energy Range</td>
</tr>
<tr>
<td>60 keV - 75 keV</td>
</tr>
<tr>
<td>Proton Current Range</td>
</tr>
<tr>
<td>40 mA - 375 mA</td>
</tr>
<tr>
<td>(fixed source geometry)</td>
</tr>
<tr>
<td>Normalized Emittance</td>
</tr>
<tr>
<td>6 × mm-mrad ± 10%</td>
</tr>
<tr>
<td>(at full current)</td>
</tr>
<tr>
<td>Plasma Source Type</td>
</tr>
<tr>
<td>orthogonal cusp</td>
</tr>
<tr>
<td>duoP1Gatron</td>
</tr>
<tr>
<td>Extraction Column</td>
</tr>
<tr>
<td>tetrode, multi-aperture</td>
</tr>
<tr>
<td>Maximum Extracted Current</td>
</tr>
<tr>
<td>850 mA</td>
</tr>
<tr>
<td>Mass Separation</td>
</tr>
<tr>
<td>90°, n=1/2</td>
</tr>
<tr>
<td>Vacuum Pumps</td>
</tr>
<tr>
<td>turbo-molecular cryopumps</td>
</tr>
</tbody>
</table>
The basic requirements of the RFQ are listed in Table 3. The output current of the DTL must be 300 mA of 10 MeV protons which requires slightly higher current output from the RFQ. The maximum gradient at which a cw device can be operated reliably is not known with any precision. The value in the table is our best estimate for a system with some margin of safety.

Table 3
RFQ Requirements and Constraints

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>108 MHz</td>
</tr>
<tr>
<td>Input Energy</td>
<td>0.075 MeV</td>
</tr>
<tr>
<td>Output Energy</td>
<td>2.0 MeV</td>
</tr>
<tr>
<td>Output Current</td>
<td>306 mA (2 MeV H+)</td>
</tr>
<tr>
<td>Maximum Gradient</td>
<td>1.75 x Kilpatrick limit</td>
</tr>
</tbody>
</table>

Difficult Requirements: High Current

The reference design given in Table 4 was generated according to the procedure of Crandall et al. Although acceptable, the design has an output phase spread that is larger than desired. High current is the most difficult design requirement to be met and because experience with operating RFQ's is limited, a detailed analysis of the factors affecting current limits was made.

Table 4
RFQ Reference Design

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>108 MHz</td>
</tr>
<tr>
<td>Input Energy</td>
<td>0.075 MeV</td>
</tr>
<tr>
<td>Buncher Energy Wb</td>
<td>0.600 MeV</td>
</tr>
<tr>
<td>Final Energy Wf</td>
<td>2.0 MeV</td>
</tr>
<tr>
<td>Final Synchronous Phase φs</td>
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<tr>
<td>Maximum Gradient</td>
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<tr>
<td>Gradient on axis V/r0</td>
<td>15.0 MV/m</td>
</tr>
<tr>
<td>Focusing Parameter B</td>
<td>7.07</td>
</tr>
<tr>
<td>Vane Voltage V</td>
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<tr>
<td>Outer Diameter</td>
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<tr>
<td>Vane Length</td>
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<tr>
<td>Excitation Power</td>
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<tr>
<td>Beam Power</td>
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<td>Total Power</td>
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<tr>
<td>Design Current</td>
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<tr>
<td>Iin</td>
<td>360 mA</td>
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<tr>
<td>Iout</td>
<td>306 mA (2 MeV protons)</td>
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<tr>
<td>Normalized Emittance (90%)</td>
<td>6.0 π mm-mrad</td>
</tr>
<tr>
<td>Input (90%)</td>
<td>7.5 π mm-mrad</td>
</tr>
<tr>
<td>Output (90%)</td>
<td>1.0 π mm-mrad</td>
</tr>
<tr>
<td>Input (RMS)</td>
<td>1.7 π mm-mrad</td>
</tr>
<tr>
<td>Output (RMS)</td>
<td></td>
</tr>
<tr>
<td>Current Limit</td>
<td>430 mA (2 MeV protons)</td>
</tr>
</tbody>
</table>

The transverse and longitudinal current limits in an RFQ are given by Wangler as

\[ I_t = \frac{8}{3\pi^2} \frac{m_0 c^2}{\phi_k} \sin \varphi_s \]

\[ I_L = \frac{4\pi}{3\pi^2} \frac{m_0 c^2}{\phi_k} \frac{1}{f} \frac{r_b^2}{\lambda} \frac{1}{\sigma_{t}} \frac{1}{\sigma_{L}} \]

\[ Z_0 = 376.73 \Omega \]

\[ \frac{\nu_t}{\nu_L} \] ratio of space charge to focusing forces, maximum value 0.84

\[ m_0 c^2/\text{eq} = 938.952 \times 10^6 \text{ volts} \]

\[ f = \text{space charge form factor} = 1/3 \text{ if } r=b \]

\[ r = \text{beam average radius} \]

\[ b = \text{beam bunch half-length} \]

\[ \sigma_{t}, \sigma_{L} \text{ zero current phase advance per period.} \]

For high current \( \sigma_{t} \) should equal \( \sigma_{L} \) and be as large as possible (up to a maximum of \( \pi/2 \))

\[ \sigma_{L}^2 = \frac{-2}{m_0 c^2} \frac{A V}{\lambda} \sin \varphi_s \]

\[ \sigma_{t}^2 = \frac{B^2}{8\pi} + \Delta r f \]

where

\[ B = \frac{-\text{eq} \lambda}{2} \frac{\lambda}{V} \frac{m_0 c^2}{r_0} \]

\[ \Delta r f = -\sigma_{L}^2/2 \]

\[ A = \text{acceleration efficiency} \]

\[ V = \text{vane voltage} \]

\[ r_0 = \text{mean radial aperture} \]

To obtain maximum current we require a design with

\[ \sigma_{t} = \sigma_{L} = \pi/2 \]

i.e., \( A V \sin \varphi_s = \frac{-m_0 c^2}{4} \)

\[ B = \sqrt{3} \pi^2 \]

In practice \( V/r_0 \) is limited by the sparking limit so at small values of \( \lambda \) it may not be possible to reach the optimum value of \( B \). In this region the condition to be met is

\[ \sigma_{t} = \sigma_{L} = \frac{B}{2\sqrt{3} \pi} \]

or

\[ r_0^2 A \sin \varphi_s = \frac{(V)}{\beta^2} \text{eq} \frac{\lambda^4}{r_0 m_0 c^2} \frac{12\pi^4}{4} \]
At a specified frequency, $V/r_0$ is at the sparking limit so the right hand side is a constant. The procedure of Crandall et al. preserves this relation in the bunching section but not in the accelerating section.

In the accelerating section Crandall et al. keep $A$ and $\phi_s$ constant, which results in a reduction in longitudinal stability. This can be prevented by increasing $A$ or $\phi_s$ to keep $(A \sin \phi_s)/\phi^2$ constant. The output phase energy distributions for the reference design and an alternate, which increases $\phi_s$ in the accelerating section, are shown in Figs. 1 and 2. Note the smaller phase spread in Fig. 2.

![Fig. 1 Phase-energy plot of output beam for reference design.](image1)

![Fig. 2 Phase-energy plot of output beam for alternate design.](image2)

**Table 5**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>216 MHz</td>
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<tr>
<td>Input Energy</td>
<td>2 MeV</td>
</tr>
<tr>
<td>Output Energy</td>
<td>10 MeV</td>
</tr>
<tr>
<td>Output Current</td>
<td>300 mA</td>
</tr>
<tr>
<td>Maximum Electric Field</td>
<td>$1.25 \times$ Kilpatrick limit</td>
</tr>
<tr>
<td>Maximum Magnetic Field</td>
<td>1.0 Tesla</td>
</tr>
<tr>
<td>Difficult Requirements:</td>
<td>Low Spill of Beam from RFQ</td>
</tr>
</tbody>
</table>

The DTL reference design parameters are listed in Table 6.

**Table 6**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>216 MHz</td>
</tr>
<tr>
<td>$\omega_{in}$</td>
<td>2 MeV</td>
</tr>
<tr>
<td>$\omega_{out}$</td>
<td>10 MeV</td>
</tr>
<tr>
<td>Number of Drift Tubes</td>
<td>30</td>
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<tr>
<td>$\phi_s$ cells 1-10</td>
<td>$-42.5^\circ$</td>
</tr>
<tr>
<td>$\phi_s$ cells 11-30</td>
<td>$-30^\circ$</td>
</tr>
<tr>
<td>$E_0$ cells 1-10</td>
<td>3.5 MV/m</td>
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<tr>
<td>$E_0$ cells 11-30</td>
<td>3.0 MV/m</td>
</tr>
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<td>Drift tube, ID</td>
<td>40 mm</td>
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<td>OD</td>
<td>167 mm</td>
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<td>Tank Diameter</td>
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<td>Quadrupole Length</td>
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<td>Gradient Sequence</td>
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<tr>
<td>Excitation Power</td>
<td>800 kW</td>
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<tr>
<td>Beam Power</td>
<td>2400 kW</td>
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<td>Total Power</td>
<td>3200 kW</td>
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<tr>
<td>Design Current</td>
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<tr>
<td>Input</td>
<td>$300 , \text{mA}$</td>
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<tr>
<td>Normalized Emittance</td>
<td>$11.1 , \text{mm-mrad}$</td>
</tr>
<tr>
<td>Output (90%)</td>
<td></td>
</tr>
<tr>
<td>Current Limit</td>
<td>$700 , \text{mA}$</td>
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</table>
Conclusions

A preliminary design of an accelerator for the ZEBRA project has been completed based on existing technology. The design meets some of the requirements and constraints as verified by computer calculations using PARMTEQ and PARMILA10. Significant work remains to be completed on tolerances to machining and assembly, on reducing the amount of beam spilled in the structure (and that expected for higher energy sections of an accelerator breeder), on optimizing design parameters, on verification of injector performance, on beam diagnostics and location, on control features that influence the overall design and on suitable specifications for the rf sources.

The design, although preliminary, is not expected to change in a significant manner. Studies have shown that funneling techniques are not necessary for the currents considered. Higher vane fields in the RFQ would lead to reliability problems and would not significantly lower the injection voltage. Lower vane fields do however mean a complete redesign, probably even consideration of different frequency regimes such as 83 and 166 MHz for the RFQ and DTL. A re-examination of fabrication and construction costs may lead to small changes in accelerating gradient but not overall changes in DTL surface fields. Drift tube face angles will be determined not only from efficiency arguments but from break-down effects.

References

Loss Monitors for the Fermilab Linac

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Batavia, Illinois 60510

Abstract

A system of beam-loss monitors has been installed in the FNAL 200-MeV linac. It consists of two-foot long ion chambers installed two per tank and six in the 200-MeV diagnostics area. The loss data are available in the main control room via computer and as real time video signals. A high gain amplifier is required for those monitors near the linac cavities because of the normally low losses. System description results of performance tests and examples of monitor use as a tool to assist in linac tuning are presented.

Introduction

The Fermilab 200-MeV linac has used beam-loss monitoring only occasionally since operation began in 1970. Scintillation-photomultiplier detectors were used during initial operation particularly at the higher energies. Ion chambers of the Hornstra design, which are used in the switchyard areas of the main accelerator, have been used on occasion in the linac 200-MeV beam switching area during the past few years and are now distributed along the linac as well. There has never been an essential need for loss monitoring along the linac itself. Residual radiation levels are typically difficult to detect outside the tanks with a standard survey meter, except at two places. One area is the bending magnet region of the cancer therapy transport line for 66-MeV beam where 100 m on contact is typical. The other point is the straight section between tanks 8 and 9 where a pipe kink sometimes scrapes beam and yields a few m of residual radiation. The advantage of a more extensive loss monitor system, for use in beam tuning and safety, nevertheless, has long been recognized. For the past two years work on an ion chamber system has proceeded on a very low priority basis because of manpower and money constraints. The detector system is now installed and working quite well although some work remains to be done.

The linac, which accelerated high peak current proton beams until late in 1977 and much lower current (20-45 mA) H+ beams since then, delivers time average H+ beam at 66 MeV of 35 pA to produce neutrons for cancer therapy. The 200-MeV H+ beam required for the high energy physics program is less than half as much.

Detector Description and Distribution

The ion chamber is constructed of a two-foot length of 1-5/8-inch RG319 A/U Andrew Heliax cable, which is placed inside a length of conduit.
Because of the high level of rf noise in the linac tunnel, several steps are taken to minimize its effect. A short length of twinline cable runs between the detector and the amplifier, which, for protection against radiation damage, is placed about 15 feet away in a penetration in the shielding wall. Several layers of aluminum foil are wrapped around the detector and grounded at the linac tank. The on-board regulators are preceded by an rf trap. The amplifier is enclosed in a two-wide NIM module which has all joints and openings covered with conductive tape. As a result, high frequency noise levels observed in the main control room at present are in the 5-30 mV range, typically 10 mV.

Gain curves for the amplifier are shown in Figure 2 and are similar at 10 and 100 kHz.

The response of the ion chamber to beam-loss radiation as a function of applied voltage reaches a plateau above 160 volts at atmospheric pressure as shown in Figure 3. The curve was extended to 1500 volts because some testing was done at higher voltages to give increased, though distorted signals when the chamber contained air. The A-CO₂ gas mixture gives a "gain" in signal of 8.

Figure 4 gives the beam loss pulse response of two detector and amplifier channels with differing amounts of loss signals, noise levels and ringing conditions. The time-scan plots from the sample and hold circuits show the variations over very many beam pulses. Beam pulses were short (10 μs) during tests to limit integrated beam loss.

**Beam-Loss Testing**

Creation of a few mA of beam loss for testing was caused by misadjusting quads near the entrance and exit of individual tanks, by turning off quads in the mid-tank region and by changing steering coil settings. Loss occurring at unknown and distributed locations in a tank makes it difficult to obtain precise calibrations of localized detectors. Losses were created for beam energies from 56 MeV (Tank 3) to 200 MeV (Tank 9). We do not plot an energy-response curve because of uncertainties, however, monitor signals varied from tenths of a volt per mA loss at 56 MeV to a few volts per mA loss at 200-MeV, a variation consistent with the nice energy-response curve obtained at Brookhaven with long loss monitors.

To test the loss monitors and to measure the distribution of radiation flux in a vertical plane, we placed a bank of six parallel detectors in a vertical plane perpendicular to the beam line at distances of from 3 to 32 in. from the beam line. This was done at the high end of tank 5 and again at the high end of tank 8. Losses were created near the high energy end of the tanks and also further upstream in the same tank. Uniformity of detector response was confirmed by interchange of positions.

Examples of a few flux distribution curves are shown in Figure 5. One sees the quite steep decrease with distance from the beam line when beam loss is known to occur near the detectors. By contrast one sees the slower decrease (in some cases linear) for attempted loss far upstream. The calculated dashed curves are for an assumed point loss in the straight section below the bank of detectors and an inverse square law decrease in the vertical plane. Integration over the detector length was performed but no correction was made for the finite chamber diameter. In other examples in the high energy end of the linac where there is pronounced forward peaking of neutrons, loss created at the input end of a tank was observed to give low but nearly identical signals at the high end of the tank in detectors separated by a distance of 27 in. These results are not unexpected and exhibit some advantage in using two separated detectors in each straight section.

After distribution of the loss monitors throughout the linac, some useful observations have been made in tuning linac parameters. As examples of loss monitor use, plots are shown in Figure 6 for beam loss as a function of a single quadrupole current. One curve shows a loss minimum while the second curve shows a window outside of which losses appear. As expected the on-set of loss occurs long before the beam-current monitors can show the loss. Similar plots have been obtained by adjusting other linac parameters. There is considerable variation in the width of the loss-free window when intertank rf phases are adjusted. Further study of this situation may prove useful.

Reduction of losses in the 200-MeV diagnostic and beam switching area was quickly made by adjustment of linac focusing and steering magnets. Small vertical beam-loss signals between tanks 8 and 9 could easily be removed but would return when automatic steering adjustments were made to achieve a proper match to the booster transport line. This impasse points to the need for either a change in the match requirements or further upstream steering adjustments. Tune up of the cancer therapy beam line routinely includes reference to the beam-loss monitor placed along the line.

As with many other linac parameters which are continuously monitored by the computer, the beam-loss signal can be used to inhibit linac beam when the loss exceeds some preselected level.

The present loss monitors are an aid to linac tuning. We are considering the addition of long loss monitors, particularly along the lower energy tanks where sensitivity is low. There is one long loss monitor under test at present, which will be used at tank 3.

**Acknowledgement**

The authors gratefully acknowledge the advice on construction of the ion chambers by Rick Janes of the Fermilab Switchyard Group, based on his early experience with similar chambers.

**References**

Fig. 1 Amplifier schematic

Fig. 2 Amplifier gain curve

Fig. 3 Ion chamber plus amplifier response versus applied chamber voltage

Fig. 4 Beam pulse loss signals - 2 μs/div.
   a. 0.1 volt/div.; b. 0.05 volt/div.

Fig. 5 Radiation flux distribution above beam line.
   a. 116 MeV; b. 181 MeV

Fig. 6 Beam loss signal versus quadrupole setting in linac tank 8. Scales are 1 volt/div. and 20 amps/div. a. Input quad varied; b. Next to last quad varied.
A MICROPROCESSOR-CONTROLLED BEAD PULLER FOR RF CAVITY MEASUREMENTS

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Atomic Energy of Canada Limited
Research Company
Chalk River Nuclear Laboratories
Chalk River, Ontario K0J 1JO

Summary

A microprocessor-controlled bead puller is being developed to provide a sophisticated, self-contained bead pull facility with local data analysis. The following features are incorporated: 1) continuous bead travel to minimize lateral vibrations, 2) 0.1 mm (or better) bead position resolution, 3) up to 5 m total pull length, with steps as small as 0.5 mm, 4) local cassette storage of data, 5) all operations controlled by software via a keyboard, 6) provision of a link to the main CRNL computer, and 7) local programs for bead pull control and data analysis. The facility is described and impressions of its operation given.

Introduction

Successful creation of a working accelerator requires, at some stage, measurement of rf fields in the accelerator cavities. Bead pulls are the standard method for determining these fields. The process is based on the fact that insertion of a small object into an rf cavity perturbs the cavity resonant frequency by an amount related to the squares of the local electric and magnetic fields, hence field distributions can be found. Bead pull measurements consist of recording cavity frequency shift versus bead position, as a perturbing bead (supported on a thread) traverses the cavity. The resulting field distribution is used to check the accelerating properties of the cavity.

In its simplest form, a bead pull system consists of a voltage-controlled rf oscillator, an automatic frequency controller to tune the oscillator to the cavity frequency and give an analog frequency output, a chart recorder to plot frequency, and a motor to pull the bead. Digital frequency measurements can only be made using a system capable of reading and storing large amounts of data, quickly.

At the Chalk River Nuclear Laboratories (CRNL), the Accelerator Physics Branch is carrying out a study of the problems associated with designing and building ZEBRA (Zero Energy Breeder Accelerator), a 300 mA, H+ 10 MeV linac facility. At the moment, several experimental structures are being studied with bead pull techniques, so a highly automated bead pull facility satisfying the criteria in Table 1 would be extremely useful to reduce measurement time, improve data handling, and provide immediate data analysis. A microprocessor-controlled instrument can easily satisfy these criteria.

Development of the microprocessor-controlled bead puller suits another area of the ZEBRA study: evaluation of computer control and "smart" instruments. For the bead puller, hardware was bought ready-to-use, with all editing, assembling and

Table 1: Criteria for the Bead Puller

- smallest measurement interval 0.5 mm
- largest measurement interval several mm
- shortest cell 6 mm (50 kv RFQ)
- shortest tank to be pulled 0.1 mm
- longest tank to be pulled 5 m
- fast enough to be convenient 1 min/m
- chart output
- mass storage of data
- local data analysis
- connection to main computer
- easy to use, by many different users
- portable

emulation performed on an available, well-equipped development station.

System Layout and Hardware

Figure 1 is a schematic layout of the system hardware. The rf section consists of a voltage-controlled oscillator feeding the rf cavity via a drive loop, while the oscillator is controlled by an automatic frequency controller fed from a sampling loop. The AFC voltage is read by a 10-bit ADC to provide frequency data. The AFC voltage is fed directly to the chart recorder for bead pulls; the chart can also be driven via an 8-bit DAC from data in memory. The chart is turned on and off by the microprocessor.

The chart recorder response rate (≈ 1 Hz) and the length of the shortest cell in a tank combine to limit the bead pull speed; for this system a range of 10 to 15 mm/s was selected. The data recording process takes ≈ 300 µs, hence the bead can be moved continuously by a dc motor and readings taken "on-the-fly". This minimizes transverse bead vibrations inherent in stepping-motor driven systems. The bead is held on a continuous loop of monofilament nylon line, and is automatically repositioned to "travel limit 1" between runs.

Bead position information is provided by an incremental optical shaft encoder having 1000 encoder pulses and one marker pulse per revolution. The encoder pulses drive the microprocessor non-maskable interrupt, whose service routine increments the previously stored total pulse count, then periodically initiates an AFC voltage reading and stores both the frequency-related voltage and total pulse count. The Z80 CPU uses interrupt mode 1, for which the shaft encoder marker pulse and the two travel limit switches are OR-ed together to drive the interrupt request. These three interrupt signals are also fed to optically-isolated inputs that are pulled by the interrupt service routine to identify the interrupt source. Marker interrupts complement, the chart recorder marker state to give a position reference on the chart output; travel
limit interrupts control bead movement. The keyboard/printer is a Texas Instruments Silent-700 unit. Bulk data storage is on dual ADPI model-1 cassette tape units. Communication with the CRNL main computer is possible via the modem.

The microprocessor system selected for the bead puller uses the STD bus developed by Pro-Log; Table 2 summarizes the boards installed. One board was made locally to interface interrupt and reset signals to and from the bus. All inputs are optically isolated and outputs relay driven.

The method of calling sub-programs and the use of prompts works very well. It also allows, with some foresight in writing the monitor, addition of sub-programs with little or no change to existing ones.

In the chart mode, the data display program MEMOUT complements the marker at the same rate as did the shaft encoder on the original chart display, thus the position scale reference appears on all charts.

Obviously, the data analysis package could take many forms, depending on the actual experiments. For initial experience, PEAKFIND has been configured to suit an experiment measuring field tilts in an Alvarez tank model for various post coupler configurations. For each run it locates each peak, levels the peak baseline relative to that of the first peak, and finds the peak height. Then it normalizes the run by forcing the average of the first four peaks to be a predetermined value, and prints the position, peak height and normalized peak height. The treated data can then be printed or plotted, using MEMOUT.

To date, all programming has been done in Z80 assembly language, but PASCAL may be used in the more complex data analysis routines.

When the distance count available, mass storage on tape is not immediately required. The availability of a development station greatly reduced commissioning time, for several reasons: short programs or code sections to investigate specific system functions could be easily written and operated; software could be edited, assembled and emulated in minutes; and the features of the station greatly surpassed anything that could reasonably have been installed in the microprocessor itself. Developing programs on the emulator means that all programs can be stored in EPROM's, which in turn removes the necessity of loading programs off tape and saves RAM space. This is a convenient feature for occasional system users.

The method of calling sub-programs and the use of prompts works very well. It also allows, with some foresight in writing the monitor, addition of sub-programs with little or no change to existing ones.

In the chart mode, the data display program MEMOUT complements the marker at the same rate as did the shaft encoder on the original chart display, thus the position scale reference appears on all charts.
The analog voltage range of the frequency difference signal must be chosen to be a substantial fraction of the range of DAC's and ADC's in the system, otherwise the ±1 bit noise adds significantly to the data noise (particularly for the 8 bit DAC used to drive the chart recorder when data is plotted from memory).

The capability of plotting and/or printing data from memory (subprogram MEMOUT) at various stages in data analysis allows checks on the necessity for and appropriateness of the data treatment.

The sub-program PEAKFIND was written to facilitate a certain experiment, and illustrates the power and time savings of on-line data analysis.

The general approach to selection of the microprocessor hardware, and hardware and software development, was very suitable in this application. While the microprocessor-controlled head puller is just beginning to be used for experiments, it is already clear that it will provide accurate data quickly, and that the additional powerful feature of local data analysis greatly facilitates data interpretation.

References
2. S.O. Schriber, "The ZEBRA (Zero Energy Breeder Accelerator) Program at CRNL - a 300 mA, 10 MeV Linac" (Proceedings of this conference).
Abstract

A 750 kV Cockcroft preaccelerator is being built for acceleration of polarized H⁺ ions and for injection into the 20 MeV linear accelerator. To stack more particles in the booster synchrotron, H⁺ ions are preferred instead of protons. A new polarized H⁺ ion source is being developed, and a beam intensity of 5 μA was achieved. The accelerating column is similar to the operating column for ordinary protons. At the beginning of a 40 m long beam line, which transfers the 750 keV H⁺ ions from the column to the old LEBT, the proton spin of the H⁺ ions is rotated from parallel to the beam to vertical. An ordinary H⁺ ion source is also being developed for dual mode operation of the polarized and unpolarized beams.

Introduction

In a design of the KEK proton synchrotron, acceleration of polarized protons was studied. However, a strong intrinsic resonance was supposed to occur in the 500 MeV booster synchrotron and no polarization was considered to be kept after the resonance. Recently, it was pointed out that the resonance is so strong that the polarization is substantially kept by spin flip. There are many resonances in the 12 GeV main ring too. Some are strong enough to keep polarization by spin flip, but others are not so strong that depolarization should be avoided by fast passage.

The booster synchrotron was designed for five-turn injection of the 20 MeV protons. It is estimated that an effective 100-turn injection is possible for charge-exchange injection of 20 MeV H⁺ ions. It means that the equal circulating current is obtained by a 200 μA proton beam or a 10 μA H⁺ beam in the booster. A pulsed high current Lamb-shift ion source had been developed at KEK and a beam current of more than 1 μA was achieved. However, it seemed very difficult to increase its beam current drastically by the system, so a new ion source has been studied and it seems promising. Thus the polarized preaccelerator adopts the H⁺ system. When it is completed, the operating proton preaccelerator should be changed to a H⁺ preaccelerator for dual mode operation of the polarized and unpolarized beams.
Although an RFQ linac seems very attractive for acceleration up to 750 keV, the beam will debunch unless it is injected directly from the RFQ linac into the DT linac. Therefore, it was decided to make an open Cockcroft-Walton preaccelerator.

**Layout of Preaccelerators**

As there is no sufficient area to build a Cockcroft preaccelerator for the polarized $\text{H}^+$ ions beside the operating preaccelerator, a new building was built behind the operating preaccelerator building and they are connected each other. The ions will be accelerated and transported to the operating LEBT by a 40 m long beam line as shown in Fig. 1. The floor of the new room is 1.4 m higher than that of the old room because the new beam line must avoid the power line cable tunnel which was already installed between two rooms. This will affect little on polarization of the beam.

**Ion Sources**

A key of the project is a high current polarized ion source and a 5 $\mu$A beam was already achieved. It has following features:

1. The 3-S electron of the sodium atom is polarized by a dye laser which is optically pumped by an argon laser, the polarized electron is transferred to a 5 keV proton, polarization of the electron is transferred to the proton by conventional zero-crossing magnetic fields and the nuclear-polarized hydrogen atom is changed to a $\text{H}^+$ ion by charge-exchange reaction with the sodium vapor. When the polarized electron is transferred to the L shell of the hydrogen atom in a weak magnetic field, the electron of the $p$-state may be depolarized by the LS coupling. To prevent the depolarization, the electron should be transferred in a strong magnetic field of about 1 T. If a proton beam delivered from a duoplasmatron is guided into such a high magnetic field, then the protons have azimuthal velocities and an emittance of the electron-polarization.

---

**Fig. 1** ECR ion source test stand.

**Fig. 2** 6.5 GHz ECR ion source.

**Fig. 3** 6.5 GHz RF Solenoid Coils

Laser

H$_2$ gas

500 l/s

Faraday cup
ed atomic beam deteriorates. Thus an ECR ion source is being developed. Preliminary results are as follows: the achieved beam current is 30 mA with a current density of 25 mA/cm², its proton ratio is 80 % and it is consistent with the measured electron temperature of 14 eV. A 6.5 GHz RF power is supplied by a klystron, and the corresponding magnetic field for electron cyclotron resonance is 0.25 T. Protons are extracted at the region of 0.45 T. A high power argon laser and ring dye laser will be on the ground in the future, and a light beam of 5895.92 Å will be emitted to the ion source in the 750 kV high voltage terminal.

As the injection system is different for protons and for H⁻ ions in the booster synchrotron, it takes too much time to switch from one to the other. For dual mode operation of high-current ordinary protons and polarized protons in the booster, the present proton preaccelerator should be converted to a H⁻ system. A magnetron type surface-plasma source is being tested for high current H⁻ beams. A current of 40 mA was achieved in the cesium mode. It was attained by a higher extracting voltage using a pulse source instead of a DC source. However, the pulse source has insufficient capability, and it is partly responsible for change in beam current during a pulse.

**Fig. 4** H⁻ ion beam of surface-plasma ion source. X: 50 µA/div, Y: 10 mA/div.

### High Voltage Apparatus

The accelerating voltage is supplied by an open symmetric Cockcroft-Walton generator. Its voltage will be stabilized within ±0.1 %. The voltage drop and ripple due to charging and discharging the capacitors are approximately

\[
\Delta V_C = \frac{I}{fC} \frac{N}{3} \left( \frac{N^2}{2} + 1 \right),
\]

\[
\delta V_C = \frac{I}{fC} \frac{N}{2} (p - p),
\]

where N is a number of the stages, I is an output current, C is a capacitance of each capacitor and f is a frequency of the driving AC. Here, N = 4, C = 0.01 µF, f = 350 Hz and the maximum value of I is 5 mA. The voltage drop due to the output current is in some cases much larger than the \(\Delta V_C\), however, it is cancelled by a feedback system. \(\delta V_C\) is also reduced by a stray capacitance of the high voltage terminal and a dumping resistor.

The high voltage terminal must be large enough to contain the polarized source and its auxiliary equipments. Moreover, the ordinary H⁻ source will be tested in it until the operating preaccelerator is changed to the H⁻ system. So its dome is 4 m long, 4 m wide and 3 m high. An electric power of 80 kVA is supplied in it by a generator driven with a FRP shaft.

The accelerating column consists of two big porcelain tubes similar to the operating column, which has run since 1974 and was not disassembled since 1976. There is no indication of deterioration in high voltage characteristics. Its inside diameter is about 1 m, thus it ensures a large conductance for the ion source gas load.

### Low Energy Polarized Beam Transporting System

The beam line must transport properly not only the H⁻ ion but also its proton spin. When the H⁻ ions are extracted from the polarized ion source and accelerated up to 750 keV, their spins are parallel to the beam direction. Immediately after the accelerating column, they are rotated by a 23.7° bending magnet and become perpendicular to the beam in the horizontal plane. Then, the ions pass through a 0.0704 T-m solenoid and their spins are rotated around the beam axis by 90°. After the solenoid, the ions are focused and bent by quadrupoles and dipoles and injected into the linac through the old LEBT as shown in Fig. 1. The spins are vertical except in a region where the ions go down by 1.4 m from the new preaccelerator level to the old one. Beam envelopes were calculated by the computer program MAGIC and TRANSPORT assuming emittances of \(e^0 = e_y = 10^0 \pm 10^0\) mm-rad. All quadrupole magnets were made in a company and delivered to the laboratory with their DC power supplies. They have hyperbolic poles and deviation of dB/dr is expected to be less than 0.2 % within 80 % of the bore radius of 4.6 cm. The maximum design field gradient is 4.34 T/m.

The project started in 1980 and is expected to be completed by the end of 1982 fiscal year.

### References


SUMMARY

A new high-current thermionic gun has been installed on the CID injector at SLAC and brought into operation. The gun and pulser system generate three nano-second pulses of about six amps peak which, when bunched in the subharmonic buncher system, produce in excess of $10^{11}$ electrons in a single S-band accelerated bunch. Preliminary operation of the gun is described, and details of the avalanche cathode drive pulser are presented.

INTRODUCTION

The Collider Injector (CID) has operated successfully accelerating $10^{11}$ electrons in a single S band bunch to 35 MeV. The electron source used for this injector is a thermionic grided gun driven by an avalanche transistor pulser first described in Ref. 1. We have now completed detailed testing of this gun and pulser system, and the results are presented here. Figure 1 shows a cross section of the gun.

GUN DEVELOPMENT

The CID thermionic gun makes use of a special cathode-grid structure developed for us by EIMAC in Salt Lake City.\(^2\) (Fig. 2). The structure is

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* Work supported by the Department of Energy, contract DE-AC03-76SF00515.
mounted on a 3 3/8" Varian Conflat vacuum flange which allows easy replacement of the cathode without demounting or disassembling the gun envelope. The cathode is of the dispenser type which can be let up to air. The emission characteristics as a function of brightness and filament power are shown in Fig. 3. The gun electrode geometry was modeled using the electron trajectory program of W. B. Hermannsfeldt. Figure 4 shows a computer plot of the gun optics at 150 kV. The code predicts a perveance of 0.29 microperv. Figure 5 shows the measured gun characteristics. The average measured perveance is 0.27 microperv. A bias of -60 volts cuts the gun off at 200 kV anode voltage, and a peak pulse drive of +280 volts produces an anode current of 20 amps. Grid interception is about 28%, and the cathode drive active impedance approximates 12 ohms. Rise and fall times of the anode beam pulse have been measured at less than 200 picoseconds.

The first CID gun has been hi-potted to 200 kV in one atmosphere of SF₆, and has been beam tested to 175 kV. Emittance has not been measured as yet, but the beam has been transported, subharmonically bunched, and accelerated to 35 MeV with little beam loss. The first cathode is still in place with close to 1,000 hours of operation, has been let up to air several times, and still shows no signs of degradation.

PULSER DEVELOPMENT

Figure 6 shows a block diagram of the avalanche type pulser developed initially for the CID gun. There was no power source other than filament power available on the gun back deck, so all power for the pulser was derived from the filament source. The pulser trigger is coupled to the high voltage gun deck through a balun type transformer. The pulser system itself consists of four, three transistor avalanche pulsers driving 50 ohm coaxial inversion transformers. The four transformers drive the gun cathode-grid gap and deliver a combined peak current of about 9 amps in a 2.5 nanosecond pulse. With grid interception and other losses, this yields an anode beam pulse of 6 to 7 amps fully contained baseline to baseline in 3 nanoseconds. The whole pulser and power supply system resides within the conical re-entrant portion of the gun body. Figure 7 shows a photograph of the gun with the pulser in place.

REFERENCES

1. R. Koontz, R. Miller, T. McKinney, and A. Wilmunder, "SLAC Collider Injector, RF Drive Synchronization and Trigger Electronics and

2. EIMAC, Division of Varian, Salt Lake City, Utah 84104 (Werner Brunhart).


![Graph 1](attachment:graph1.png)

**Fig. 3**
CID Gun Emission Characteristics
Anode Voltage: 175 kV
Drive: +340 V - 60 V bias
net drive: 280 V
Vacuum: $5 \times 10^{-6}$ Torr

![Graph 2](attachment:graph2.png)

**Fig. 5**
CID Gun Transfer Characteristics
FIL = 9 V
Fixed bias - 60 V
Average Perveance 0.27 $\mu$Pv
THE RACETRACK MICROTRON RADIO-FREQUENCY SYSTEM

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Summary

The design and construction progress of a prototype rf system to drive the Los Alamos-NBS racetrack microtron (RTM) electron accelerator is described. The rf system requires 450-kW cw at 2380 MHz from a single klystron. The output from the klystron is split three ways to drive a capture section, a preaccelerator section, and the main accelerator section. The fields in each section are phase- and amplitude-controlled to tight tolerances. Temperature control of the accelerator sections also is linked to the amplitude-control system, because the system's average power is so high.

Introduction

The overall accelerator is reviewed in Ref. 1, and the rf system is shown schematically in Figs. 1 and 2. The beam goes from a 100-kV injector, through a pair of TM10 chopper cavities, then through a buncher cavity. There is a 2.4-m preaccelerator section and a 1-m capture section in the injection line, and the main acceleration section on the RTM is 8 m long. All three accelerator sections are designed for 1.5 MeV/m and are of the disk-and-washer type described in Ref. 2. The TM10 modes and fields in the square chopper cavities are independent of each other. Thus, a total of eight rf fields must be controlled in amplitude and phase for the system to operate. Three 75-W amplifiers and one 450-kW klystron, aided by four variable-ratio power dividers$^3$ and four high-power phase shifters constitute the high-power rf system. Normally the rf system is operated cw, but the klystron drive may be pulsed to facilitate conditioning of the high-power cavities. The rf system comprises the following subsystems: the low-level rf system, the dc power supply, the waveguide power-distribution system, the klystron, the phase- and amplitude-control system, the watercooling system, and the safety-interlock system. The major design parameters and problems associated with each system are discussed, and the overall progress to date is reviewed.

The Low-Level rf System

The rf source is a voltage-controlled crystal oscillator (VCXO), followed by a 16-times multiplier with a 2380-MHz output frequency. The oscillator may be electrically tuned by ±2.4 MHz. The rf source also includes a 1-W amplifier and an 8-way power splitter. Thus, about 100 mW of power are available at each of the eight outputs. The line to the klystron driver has a 1-kHz, 50- to 500-μs gate that is controlled by an analog signal from the computer. Once a cavity can tolerate 50% duty factor, the gate module remains "on" and the klystron operates cw. Prototypes of the gate and source modules have been built and tested at Los Alamos.

Fig. 1. Low-level rf system schematic.

Fig. 2. High-power rf system schematic.

*Work supported by the US Department of Energy.
The turn-on problem is one of the most difficult in the rf system. The washers will be warmed up by 15°C by the rf fields, and the cavities will change resonance frequencies by about 25 kHz/°C. During cold weather, the inlet water temperature will be low at times when no rf power is being applied; but once the system is operating, the inlet water temperature may be as high as 35°C. The sensitivity of the cavity to changes in waveguide temperature is 40 kHz/°C. Thus, its worst-case frequency change will be about 1775 kHz, which is well within the 2.4-MHz tuning range of the VCXO. Initially, the computer will sweep the VCXO to find the cold resonance frequency, with low power delivered to the cavities. Then the power will be increased, and the frequency will follow the cavity resonance as the cavity and the water system become warmer. A mechanical tuner has been designed as a back-up system, but evidence so far indicates that the VCXO tuning method alone will be adequate.

There are three grided-tube 75-W amplifiers and feedback loops (Fig. 1) that are used to drive the buncher and the two chopper cavities; these amplifiers have 20-dB gain. The three amplifiers and a spare all have been delivered and tested for several hours at full power.

The dc Power Supply

The dc power supply consists of four outdoor units: a fused manual circuit breaker, a vacuum circuit breaker, a linear variable transformer, and the transformer-rectifier unit. The input voltage is 13.2 kV at 52 A, three-phase. The output is 65 kW at 16.5 A, with less than 1% peak-to-peak ripple. The high-voltage transformer has a delta primary, and both delta and wye secondaries to reduce the ripple. The high-voltage transformer, the rectifier stacks, and a one-stage LC filter are all housed in a common oil tank. An ignitron crowbar and its dropping resistors are housed indoors. Neither side of the power supply is solidly grounded, and a single-point ground is established at the crowbar unit. The crowbar fires within 5 μs of a fault, and the vacuum circuit breaker can open in 30 ms.

The linear variable transformer is motor driven, and the output voltage is continuously adjustable from 33 kV to 65 kV. The power supply is now completely installed at Los Alamos and has been tested to full voltage and current. A foil tester has been added to the crowbar, but the crowbar unit has not yet passed this test. We expect the power-supply to be completely operational by November 1, 1981.

The rf Power-Distribution System

The 450-kW cw rf power from the klystrons will be delivered to the main accelerator and the preaccelerator and capture sections. The phase and amplitude in each of these cavities must be controlled independently. The system uses a WR-430 waveguide that is water cooled for phase stability. A schematic of the system is shown in Fig. 2. The use of a circulator at this very high power level would not be required if the waveguide length between the cavities and the generator were constant, but the variable-ratio power divider changes this length as the ratio changes. Thus, the klystron may see a high load impedance, which can damage the klystron. The klystron could have been designed to operate stably into a higher mismatch, but this design traded off the overall efficiency for the matched condition. Therefore, a high-power circulator has been ordered, but it is uncertain that the circulator is necessary for different methods of distributing the rf power. The phase shifters and power dividers in Fig. 2 all are controlled by stepper motors and feedback systems. All waveguide components, except the circulator, have been delivered to Los Alamos; the circulator is scheduled for delivery in February 1982.

The two TM110 chopper fields in each chopper cavity are derived through a variable-ratio power divider and phase-shift system that are coaxial, rather than waveguide, components. A single 3-dB hybrid would suffice if the coupling loops and all other physical attributes of the two modes were identical; but the actual method used will have to be very tolerant of asymmetry in the system.

Klystron

The klystron to be used is a VKS-8270 klystron, which has five fixed-tuned cavities. The tube is rated 450 kW cw at 2380 MHz. The collector is dc-isolated from the klystron body, so that the body current may be easily monitored. Two complete amplifier packages, each consisting of a klystron, solenoid, and socket tank, have been ordered and are now at Los Alamos. In their factory tests, both tubes delivered 500 kW, had 57-dB gain, and +20-MHz bandwidth. One complete klystron amplifier is set up at Los Alamos and will be tested in early November, this year.

Phase and Amplitude Control System

The phase- and amplitude-control system achieves control by electronic and mechanical methods. The buncher control loop is an exception: it has only electronically controlled phase shifters and attenuators. The chopper cavities have a mechanically controlled, variable-ratio power divider and phase shifter; these control the amplitude and phase of the second field, while the electronic loop controls the primary field variables. The electronic control on the klystron system controls the field in the capture section, and two waveguide variable-ratio power dividers and phase shifters are used to control the fields in the preaccelerator and main accelerator tank. Rapid beam-loading transients will be avoided, and the slow mechanical system keeps the average errors in tuning temperature under control.

Water Cooling System

The total water-system requirements are 390 gpm at 65 psi of deionized water; the waveguide cooling system requires 5 gpm at 30 psi of
tap water. A schematic of the deionized water system is shown in Fig. 3. The accelerator cavities require up to 320 gpm, but these have their own pumps and deposit heat only into the main water system. The temperature of the accelerator cavities must be controlled to ±0.5°C; this control will be accomplished by a three-way mixer valve. The klystron and water loads are quite tolerant to water temperature, but the circulator requires ±2°C input water; thus it is also on an auxiliary loop, connected to the main water system by a three-way mixer valve.

Safety-Interlock System

A Kirk-key system is used on the 65-kV dc power supply to prevent personnel access to the input and output of this supply. The rf waveguide distribution system has a single air inlet and outlet. The inlet is pressurized with a small blower, and a moving-air detector is used at the output to ensure that there are no openings in the waveguide system.

The ignitron crowbar is activated by the rate of rise of the klystron cathode current. When the crowbar fires or misfires, it is automatically reset by the computer, but if a second crowbar occurs within 1 min, it shuts down the entire system.

The minor faults in the rf system (bursts of body current, a waveguide arc, excessive reflected power to any cavity, excessive control-loop error signals) cause the rf drive to be removed from the klystron. After 1 ms, a lesser rf drive is reapplied. One such fault per second is allowed, but if 10/min occur, the system is shut down.

The major faults usually involve a diminished water flow or excessive temperature. Thus, manual control of the water system is required. The klystron drive is removed and the 65-kV power supply is shut down. Other major faults include excessive klystron average-body current, klystron filament or magnet current being out of range, and high voltages or klystron vacuum too high.

Whenever any fault is detected, a signal is sent to the injector to shut off the beam injected into the accelerator. The beam is not turned on until the rf system has stabilized.

References


Fig. 3. Line diagram of water-cooling system.
CONSTRUCTION OF A HIGH-POWER RF RESONANT TEST LOAD

Accelerator Physics Branch
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Summary

A high-power resonant load has been constructed at Chalk River as part of a program to develop high-current cw linacs. The aluminum load designed to dissipate 400 kW cw is resonant at 270 MHz to be compatible with an existing rf amplifier. It has been designed for high-power testing of accelerator components such as coupling loops, loop windows and tuners. Eleven ports have been built into the cylindrical geometry to test flexible drift-tube and post-coupler suspensions as well as several types of metal-vacuum seals. Mechanical and rf design details are discussed.

Introduction

A program is underway at the Chalk River Nuclear Laboratories (CRNL) to study high current cw linacs that could be used for breeding of fissile-fuel for nuclear power stations. Present estimates indicate that a 1 GeV proton accelerator with a 300 mA average current will be required to produce fuel at a viable cost. Detailed studies of the first 10 MeV of such an accelerator are underway at CRNL and are described elsewhere\(^1\). An Alvarez accelerating section will be used in the 10 MeV linac to accelerate the beam above 2 MeV and will require rf drive loops and vacuum windows individually capable of coupling cw power levels in the 500 kW range. A high power resonant load is being built at CRNL to provide a test facility for loop and rf window development as well as to test cavity components such as post-couplers, drift-tube suspensions, and tuners; all of which are subjected to much higher average power densities than are normally encountered in low-duty factor accelerators.

Basic Design Criteria

Existing rf equipment dictated a load frequency in the range 265-275 MHz and a maximum load power of \(\approx 400\) kW. A cylindrical geometry with a diameter of 83 cm (\(d = 0.766\) ) was chosen corresponding to a frequency of 276.5 MHz. Cavity openings for pump ports, tuners, etc., and the addition of a drift-tube test assembly reduce the frequency to approximately the middle of the tuning range. Aluminum was selected as the shell material for fabrication reasons and a 1 m cavity length was selected as a suitable compromise between acceptable power density and compact size. A nominal 1.25 cm wall thickness is used for the cavity for vacuum and mechanical stability.

A cross-sectional view of the resonant load is shown in Fig. 1. The axis of the cylindrical load is vertical to allow easy access to numerous ports.

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A cross-sectional view of the resonant load is shown in Fig. 1. The axis of the cylindrical load is vertical to allow easy access to numerous ports.
Cooling jackets have been welded around the tuning plunger sleeves where past experience with cw accelerator operation indicates heating can occur. The vacuum pumping aperture is formed by seven 17 mm diameter aluminum pipes that are welded into the pumping port parallel to the cylindrical axis and through which water is passed.

**Seal Test**

Electrical seals for removable cavity end plates and components such as drift-tubes have provided many problems for the operation of accelerator cavities. These problems are particularly acute for cw operation due to the high average power loss that occurs across ohmic joints. Girder suspension designs for drift-tubes such as developed at CERN would decrease or perhaps even eliminate the need for removable end plates. However, the rf contact seal problem is then transferred to one of sealing the girder-to-tank interface.

The lower end plate on the resonant load is welded to the cylinder walls with a full penetration external weld to test the possibility of this construction technique for an Alvarez end wall. The upper end plate seal is shown in Fig. 2. An 83 cm diameter, 6 mm cross-sectional diameter Helicoflex seal is used to provide both the vacuum and rf seal. The current density (6000 A/m) value across this interface will be at least as high as that expected across a girder-to-tank joint and the experiment will serve as a rigorous test of the seal. Provision has been made to copper plate the seal contact areas if required and both copper and aluminum seals have been obtained. An 'O' ring groove has been machined in the tank flange and an elastomer seal can be used as back-up should the Helicoflex seal vacuum properties degrade due to mechanical problems or high rf power.

Helicoflex seals are also being used for both the tuner and coupling loop vacuum seals. In both these cases the groove in the flanges has been designed to allow substitution of an elastomer seal. One additional test port has been specifically designed to test Helicoflex seals of various diameters and at two rf field levels by suitable location of the joint.

A simple method of joining aluminum to other metals has recently been developed for the Aladdin rf accelerator cavities. This method, based on an inexpensive commercially available aluminum Mott gasket, will be used on the remaining nine cavity ports that are exposed to rf fields. The seals will be used to attach standard stainless steel conflat flanges to the aluminum cavity. Several techniques of depositing a copper layer on the stainless steel flange surfaces to reduce rf heating are being investigated.

**Rf Drive**

Power for the resonant load will be supplied from a cw amplifier using a RCA2054 VHF triode capable of delivering in excess of 400 kW. Details of the rf system are published elsewhere. The rf is coupled to the load via a nominal 23 cm (9 in) diameter drive loop located at the midplane of the cylinder. The drive loop with vacuum window located 5/12x from the loop end has been designed to allow numerous loop and window tests. Details of the coupling loop are the subject of a separate paper at this conference.

**Tuners**

Two ports capable of accommodating nominal 15 cm diameter slug tuners have been provided to allow adjustment of the load frequency and field tilt. These ports for testing tuner construction techniques are centred at 25 cm from each end plate and are arranged at a +90° and -90° axial orientation with respect to the drive loop.

A cross-sectional diagram of the tuner design is shown in Fig. 3. The plunger outside shell made of copper has an outside diameter that is 2 mm smaller than the sleeve inner diameter. There is sufficient thickness in the shell wall to decrease this diameter by 2 or 3 mm should multipactoring or sparking problems require. The plunger has a stroke length of 10 cm and at maximum penetration extends 8 cm into the cavity.

Experience with drift tube stems on a cw Alvarez accelerator shows that major effort is required to reduce the rf currents that can reach thin walled items such as bellows. Spring contacts on finger stock can be used to short rf fields but
at high duty factor a large rf field attenuation is first required. The 1 mm thick annular space between the plunger head and the cavity sleeve has a minimum length of 8 cm and should greatly reduce the rf fields beyond the plunger. A second attenuating path is provided in the opposite direction between the inside wall of the plunger and a central support tube. Both of these surfaces are made of stainless steel to spoil the Q of any inadvertant resonances that may occur in the region with rf harmonics. These two high resistivity surfaces should further attenuate the rf field. The plunger inner wall is water cooled while air cooling (not shown in the Figure) is provided for the support tube and bellows exterior. Grooves have been machined into the outside of the support tube to test two different types of contact springs.

One end of the stainless steel bellows (Fig. 3) is welded to a conflat flange which is sealed to the central support tube. A cuff attached to the other end of the bellows is welded to the central water cooling channel. The conflat flange can be unbolted from the assembly and the cuff weld can then be ground off allowing a relatively easy method of repairing or replacing the bellows.

Thermocouples (not shown) have been attached to the inside of the support sleeve to monitor the sleeve temperature. The outside of the aluminum tank port sleeve is cooled by a cooling jacket welded to the structure.

Experimental Ports

Eight additional ports exist in the rf cavity. The locations and purposes of all ports are summarized in Table I. Axial positions are referenced to the top end plate while orientation is clockwise relative to the rf drive line as viewed from the top.

A number of drift tube tests, primarily related to drift-tube stem suspension and bellows heating, are planned. A rigidly suspended 16.5 cm diameter drift-tube with a length appropriate to a 100 MeV accelerating cell has been constructed for the initial tests. Post-coupler to drift-tube coupling effects and sparking tests are other experiments planned. A viewing port has been provided to allow remote viewing of the drift-tube and post-coupler during high power operation.

<table>
<thead>
<tr>
<th>Distance from Top (cm)</th>
<th>Orientation</th>
<th>Diameter (cm)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>45°</td>
<td>5</td>
<td>Drift-tube tests</td>
</tr>
<tr>
<td>&quot;</td>
<td>90°</td>
<td>3.8</td>
<td>Field probe</td>
</tr>
<tr>
<td>&quot;</td>
<td>135°</td>
<td>5</td>
<td>Post-coupler tests</td>
</tr>
<tr>
<td>&quot;</td>
<td>225°</td>
<td>6</td>
<td>Helicoflex tests</td>
</tr>
<tr>
<td>&quot;</td>
<td>255°</td>
<td>3.8</td>
<td>Drift-tube and post-coupler viewport</td>
</tr>
<tr>
<td>&quot;</td>
<td>270°</td>
<td>15</td>
<td>Tuner</td>
</tr>
<tr>
<td>&quot;</td>
<td>315°</td>
<td>5</td>
<td>Spare</td>
</tr>
<tr>
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<td>0°</td>
<td>25</td>
<td>V.F. drive loop</td>
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<tr>
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<td>135°</td>
<td>3.8</td>
<td>Drive loop viewport</td>
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<tr>
<td>&quot;</td>
<td>180°</td>
<td>32</td>
<td>Vacuum manifold</td>
</tr>
<tr>
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<td>90°</td>
<td>15</td>
<td>Tuner</td>
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<tr>
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<td>225°</td>
<td>3.8</td>
<td>Field probe</td>
</tr>
<tr>
<td>&quot;</td>
<td>270°</td>
<td>3.8</td>
<td>Tuner viewport</td>
</tr>
</tbody>
</table>

Status of Construction

The cylindrical load and its end plate are 75% complete. Vacuum blanking flanges will be used on the tuner, post-coupler, and drift-tube ports for initial measurements. One tuner is now partially assembled and construction of the second will await initial test results of the first unit. The coupling loop is essentially complete and initial low power testing of the load is expected shortly.

References

1. S.O. Schriber, "The ZEBRA Program at CRNL - 300 mA-10 MeV Proton Linac", proceedings of this conference.
7. J.C. Brown and R.M. Hutcheon, "Design Considerations for a Developmental High Power Coupling Loop to Drive a Resonant Load", proceedings of this conference.
**Summary**

The success of the radio-frequency quadrupole (RFQ) proof-of-principle (POP) tests conducted in 1980 at Los Alamos have essentially guaranteed that the RFQ linac will be used in many accelerator projects soon. Several RFQs are already under construction at Los Alamos, and we expect to be designing and machining the vanes for several RFQs to be built at other installations.

The technique for machining the vanes for the POP RFQ was developed by Williams and Potter. While retaining their basic approach, we have modified their technique for generating the data required by the milling machine from the parameters defining the vane shapes. The objective of this exercise has been to develop a generalized fabrication procedure that could be used in commercial machine shops.

**Computer Numerically Controlled (CNC) Machine**

The ideal cross section for RFQ vane tips is pseudohyperbolic, a shape that is difficult, even for the most advanced milling machines, to reproduce. Typical CNC mills do, however, have linear and circular interpolation capabilities. For this reason, the ideal cross sections are approximated by straight and circular milling cuts.

For machining RFQ vanes, AT Division has leased a MAZAK V-10 three-axis vertical mill equipped with temperature control and a FANUC 7-M controller. The controller memory contains the generalized software for machining vane tips, and specific vane-tip data are read from punched paper tape. By taking advantage of certain advanced features of the controller (cutter size compensation, stored subroutine capability, internal arithmetic operations, etc.), the required data set has been reduced to a minimum.

**Cutting-Tool Path**

To describe the vane-tip geometry in the milling machine reference frame, we use a left-handed cartesian coordinate system; the x-axis being in the longitudinal direction, increasing with particle velocity, y positive to the right and z positive upwards. The origin is defined to be in the center of the vane-tip's base at its upstream end. In some cases, the vertical origin is taken to be a horizontal reference surface, machined into the vane blank, to be used for inspection and alignment measurements. The finished vane tip has left-right symmetry about the y=0 plane.

At discrete longitudinal positions spaced $\Delta z$ apart, the tool makes one transverse path as shown in Fig. 1. The mill is programmed to cut a straight-line segment up one side, cut a circular arc across the top, and cut a straight-line segment down the other side.

Except in the radial matching section, the vertical height, B, remains fixed throughout the length of the vane. At points (Y,Z) and (-Y,Z) in Fig. 1, the straight-line segments are tangent to the circular tip. The radius, $\rho$, and the location of the center of the circle, C, vary continuously along the length of the vane. In the radial matching section, $\rho$ may be larger than the half-width, A, of the part, in which case the tool path is a single circular arc.

**Machining Procedure**

A vane is usually machined in two passes. The first pass is a rough cut that removes most of the metal. The second pass is the finishing cut. When the rough cut is made, the machinist can set a switch on the control panel that causes only one out of three transverse cuts to be made. If the same-diameter tool is used for both the rough and finish cuts, then the same paper tape can be used for both operations. It is desirable in some cases to use a larger tool for the rough cut, in which case a special tape generated for that tool size is required.

In the rough-cut mode, the mill cuts metal on both the clockwise and counterclockwise pass to shorten the machining time. For the finish cut however, where surface finish is an important consideration, this technique causes an irregular surface because of the backlash inherent in the milling machine. This effect can be tuned out numerically for individual parts and is a standard feature of the controller.

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*Work supported by the US Department of Energy.*
feature of the controller. We find it more satisfactory in general to cut metal only in the clockwise direction. This eliminates transverse backlash and requires compensation in only the vertical direction. At the completion of one cutting pass the tool moves away from the part and returns rapidly to the other side of the vane for another clockwise cut.

Because the machining procedure is so repetitive, the instructions governing the motion of the mill are programmed into subroutines that are loaded into the memory of the controller. There are subroutines for clockwise and counterclockwise passes for both the radial matching section and the general case. Some additional coding is used to determine whether a rough or final cut is desired. The paper tape itself is considered to be the main program but contains only work-surface coordinates and subroutine calls, plus an occasional longitudinal coordinate to allow the machinist to restart in the middle of a vane if necessary.

From Desired Vane Shape to Cutter Path

The equation defining the circular portion of the vane surface is

$$f_s(x, y, z) = (z - z_0)^2 + y^2 - R^2 = 0$$

where $z_0$ is the center of the circular tip and $R$ is its radius; both $z_0$ and $R$ are known functions of longitudinal position, $x$. The radius vector $\mathbf{r}_c$, specifying the center of a spherical cutter of radius $R$, when the cutter is in contact with the vane surface at $\mathbf{r}_s$, is

$$\mathbf{r}_c = \mathbf{r}_s + R\mathbf{n}_s$$

where $\mathbf{n}_s$ is the unit vector normal to the vane surface at $\mathbf{r}_s$, and is obtained by taking the gradient of $f_s(x, y, z)$.

For each longitudinal position along the vane surface at the midplane, $(x_s, 0, z_s)$, one can calculate the corresponding location of the center of the cutter $(x_c, 0, z_c)$. Because we wish to make the cuts at discrete longitudinal intervals, separated by a constant value of $\Delta x_c$, we must use an iterative procedure to determine the $x_c$ corresponding to each $x_s$. Having found $x_c$, then the radius of curvature $R$ at the tip is known, and one can calculate the quantities $\rho$ and $C$ (refer to Fig. 1) required by the milling machine.

Milling-Machine Data

By taking advantage of its symmetry, the vane-tip shape can be uniquely described for any value of $x$ by only four parameters, two of which ($A$ and $B$) are constants. If the program capability of the milling-machine controller were powerful enough to calculate the tangency points, then two parameters, $\rho$ and $C$, would be sufficient to describe each longitudinal cross section. The 7-M controller does not have this capability; however, it is sufficient to specify $C$ and the point of tangency $(Y, Z)$. Only three parameters are required, therefore, to describe each unique cross section to the controller: $Y, Z$, and $C$. The data for a single step requires only 3.7 in. of paper tape.

The data punched on tape are for the finished surface. When the part is actually cut, the tool path is calculated by the controller based on the surface coordinates and on the radius of the cutter. During the rough cut, typically 10 mils of excess material is left uniformly on the surface by entering into the tool compensation register a tool radius 10 mils larger than the actual radius. This excess material is removed during the finish cut. If the surface is given a 2 mil copper plating, then an additional 2 mils is removed by entering into the register a tool size 2 mils smaller than the actual radius.

From the Cutter Path to the Actual Vane Shape

The above procedure ensures the finished vane's having the correct $z_s$ and $R$ at all points along the midplane. But, because of the finite cutter size, the actual cross sections of the vane tip will deviate slightly from the desired circles. However, knowing the complete cutting-tool path, it is possible to calculate the resultant vane shape.

The coordinates of the tool's center are known for the entire vane. The locus of points swept out by the center of the cutting tool can be thought of as defining a surface, which we will call the cutter surface. Unless the cutter tool is too large, there is a one-to-one correspondence between points on the cutter surface and points on the resultant vane surface

$$\mathbf{r}_s = \mathbf{r}_c - R\mathbf{n}_c$$

where $\mathbf{n}_c$ is the unit vector normal to the cutter surface.

Choosing Size of Tool and Longitudinal Step

Some compromises are necessary in choosing the cutter size and the step size. The cutter should be as large as possible so that a good surface finish can be achieved with a large step size. This means reduced time and cost for machining a vane. On the other hand, a cutter that is too large will distort the surface or gouge out material. The radius of the cutter must be less than the minimum radius of curvature of the "valleys" along the vane tip. However, the vanes usually have more curvature at the side, and it is not clear where one should set the limit.

Cutting Tool

Using the generalized software written for the milling machine, RFQ vanes could be machined with either a ball end mill or a circular cutter having radiused teeth and mounted on a right-angle tool holder. Experience has shown that end mills in this application have some limitations. Even carbide tools tend to wear out during the finish cut,
leaving at least an esthetically unpleasing surface. This effect is different on either side of the part because in one case the tool is climb cutting, whereas on the other it is cutting conventionally. In addition, cutting speed is slow because of the limited ability of the tool to cut well near its tip. A circular cutter would have substantially longer life, higher cutting speed, and should produce a better surface finish. This technique has not been tested to date, because most of our development has been aimed at 440-MHz structures where the vanes are small, relative to a right-angle tool holder, and interference with holding fixtures has been a problem.

**Practical Experience**

To date, vane tips have been machined for four different projects at three different frequencies: 80, 200, and 440 MHz. Each vane tip has been machined using ball end mills in copper, steel, or aluminum. The paper-tape capacity of the machine is only about 800 ft, or the equivalent of 1.3 m worth of vane assuming a cut were made every 0.5 mm. In some cases, multiple tapes were required. Machining tolerances have been held within ±0.0015 in. over a length of 1.3 m. Primarily, errors have been caused by tool wear and misjudgments in repositioning the part when its length exceeded the stroke of the bed. The surface finish is determined by tool size and step size. On vanes that are to be electroplated, the surface finish has been totally satisfactory. We have experienced no catastrophic errors from tape errors, programming, or procedural errors. We feel that vane tips could be produced in industrial shops equipped with this type of milling machine.

**References**


A scale model of the Fusion Materials Irradiation Test Facility (FMIT) 80-MHz drift-tube linac (DTL) was constructed to investigate the tuning procedure. Figure 1 shows this structure: a post-coupled Alvarez with couplers located on alternate drift tubes. The model DTL has 16 cells and was constructed to have the accelerating mode at 367 MHz. The mode spectrum was measured for various post penetrations, and field profiles of the modes were recorded. The field profiles were measured by using a beadpull apparatus, together with an automatic data-acquisition system. Tilt-sensitivity measurements were performed to find the optimum post penetrations for stabilizing the accelerating mode.

Fig. 1. Photograph of the FMIT scale-model DTL.

Introduction

Optimum stabilization of the field distribution against tuning errors for a resonantly coupled accelerator structure is obtained when all the resonant couplers are tuned to the same frequency as that of the accelerating mode. This tuning is achieved in biperiodic structures by adjusting all the couplers in a systematic way so that the stop band is closed. For a quasi-periodic structure, like a post-coupled DTL, closing the stop band results in the post-coupler frequencies being too high at one end of the structure, too low at the other end of the structure, and correct only at some intermediate locations. The result is that the structure is optimally stabilized in only the central region. Because the purpose of the post couplers is to stabilize the field distribution against the effects of tuning errors, a practical tuning technique is to adjust the post couplers until the field distribution is sufficiently insensitive to deliberately introduced tuning errors.

For a structure with post couplers every nth drift tube, the post couplers must be placed starting at the nth drift tube and ending on the nth drift tube from the other end to insure correct boundary conditions for the coupling mode. This implies that there should be a multiple of n accelerating gaps in the structure.

Field Ratio Method for Post-Coupler Tuning

In a truly biperiodic structure, coupled-circuit-model calculations show that if one end cell is perturbed by \( \Delta f_1 \), and the other end cell is perturbed by \( -\Delta f_1 \), the resonant frequency is unchanged to first order; and the field distribution is tilted linearly with a slope proportional to \( \Delta f_1 \times \Delta f_{sb} \), where \( \Delta f_{sb} \) is the stop band width. Reversing the sign of the perturbation reverses the sign of the tilt. Further calculations show the cell-to-cell amplitude error to be proportional to \( \Delta f_1 \times \Delta f_{cc} \), where \( \Delta f_{cc} \) is the tuning error of the coupling resonator between the two cells under consideration. This makes it possible to tune structures such as the post-coupled DTL, where the stop band is not a useful measure of the coupling-resonator frequency.

There are two components to the field distribution error: a geometrical part resulting primarily from errors in the position of drift-tube stems and post couplers with respect to the drift tube, and a tuning-related part that depends on accelerating cell frequencies and post-coupler frequencies. The geometrical part of the field distribution error may be cancelled by measuring the field distributions from two different sets of end-cell perturbations. One field distribution corresponds to the perturbation obtained by decreasing the drift-tube gap on one end of the structure and increasing the gap on the other end to restore the operating frequency. The other field distribution corresponds to a perturbation of similar magnitude but opposite direction. Forming a cell-by-cell ratio of these two field distributions cancels the geometrical part, leaving only the tuning-related part. When the post couplers are adjusted so that this ratio is equal for all cells, the field distribution is stabilized. Field measurements with no end-cell perturbations will now reveal the geometrical part of the field distribution errors. These errors are removed by rotating the post-coupler tabs until the desired field distribution is achieved.

*Work supported by the US Department of Energy.
Post-Coupler Tuning Procedure

1. Set each post coupler to the same length, and orient it so that it is symmetric about a vertical plane through its axis.
2. Keeping all post couplers the same length and, without rotating them, set their penetration either to close the stop band or to noticeably reduce the tilt sensitivity in some portion of the structure.
3. Adjust the penetration of each post coupler in proportion to the measured tilt sensitivity at its location, until it has been stabilized.
4. Adjust the rotation of the post coupler until the stabilized field distribution fits the desired theoretical pattern.
5. Recheck the tilt sensitivity to verify that rotating the post couplers did not appreciably affect the structure stability.

Tilt-Sensitivity Measurement Procedure

1. Detune one end cell by some predetermined amount, as measured by observing the change in the accelerating-mode frequency, or by some mechanical means, such as counting turns on a screw adjustment of the end drift-tube's longitudinal position.
2. Detune the other end cell, so as to restore the accelerating-mode frequency to its original value.
3. Measure the field distribution by the beadpull technique. Either the peak amplitude or the average amplitude may be used, as desired. For consistency, the field amplitudes should be normalized for unity average value.
4. Reverse the perturbation of Step 1. If the size of the perturbation is determined by observing the accelerating-mode frequency, restore both end cells to the unperturbed condition before setting up the new perturbation.
5. Restore the accelerating-mode frequency as in Step 2.
6. Measure and normalize the field distribution by the same technique as that used in Step 3.
7. Form the ratio of the amplitudes measured in Steps 3 and 6 on a cell-by-cell basis.
8. If the same end-cell perturbation is used consistently, the tilt sensitivity at each post coupler is proportional to the difference in amplitude ratio of the two cells on either side of the post coupler. This definition applies, whether the post couplers are located at every drift tube or at every nth drift tube.

Mode Spectrum

The mode spectrum for both the post-coupler modes and the TMQ1 modes were recorded as a function of the spacing G—the gap between the drift-tubes and the post-couplers. In each case, all the post couplers were set for the same spacing G. Mode identification was done using beadpulls. The plot of the mode spectrum is shown in Fig. 2. The curves show how the post-coupler passband is very sensitive to the value of G. The curve for G = 1/2 in. seemed to close the stop band and this value of G then was used as a starting place for the next step in the tuning procedure—the tilt-sensitivity measurements.

Tilt-Sensitivity Measurements

The tilt-sensitivity measurements were performed, using the previously described procedure. In our case, the detuning was done using adjustable end drift tubes that were movable by a screw adjustment. Peak fields were measured in each cell, using a beadpull apparatus, and then were normalized for unity average value. A ratio then was made on a cell-by-cell basis for the cases of perturbation in each direction. Figure 3 shows a computer printout for the measured normalized peak field in each cell. The first list is for a tilt in one direction, the second for a tilt in the opposite direction, and the last is the ratio of the first two. This is the case for G = 3/8 in. All post couplers had this same value. The plot of the ratio is shown in Fig. 4. This measurement was done for values of G ranging from 0.1 to 1.0 in. No significant improvement in the tilt sensitivity could be found in this range of G.

Conclusion

The difficulty in obtaining a satisfactory adjustment of the post couplers is believed to be caused by the structure's shortness and its low beta. With only 16 accelerating gaps, the structure's field distribution is already fairly insensitive to perturbations or tuning errors. In low-beta structures, the cell-to-cell variations are such that correct adjustment for each post could require a different value for G. Coupled-circuit analysis shows that the tuning of the coupling resonator is more critical when the accelerating-cell to accelerating-cell coupling is much stronger than the coupling-cell to accelerating-cell coupling. Figure 5 shows a simple coupled-resonator...
Fig. 3. Computer printout of normalized peak-field amplitudes for each cell, and ratio for tilt-sensitivity measurement.

Fig. 4. Plot of normalized peak-field-amplitude ratio on cell-by-cell basis (G = 3/8 in.).

Fig. 5. Coupled resonator model for post coupler and accelerating cell.

model having some of the basic features of the DTL. The resonators labeled \( \omega_1 \) - 6 and \( \omega_1 + 6 \) represent two accelerating cells and \( \omega_2 \) represents a post coupler. The coupling coefficients are \( k_1 \) and \( k_2 \). For this model the tilt-sensitivity reduction factor \( r \) as a function of \( \omega_2 \) is given by

\[
r = \frac{1 - \frac{\omega_2^2}{\omega_1^2} \frac{k_2^2}{k_1^2}}{1 - \frac{\omega_2^2}{\omega_1^2}}.
\]

where

\[
\omega_2 = \frac{\omega_1}{1 + k_1}.
\]

Thus, with \( k_2 < k_1 \), the resonant coupler is effective for only a small range of \( \omega_2 \).

References

BRAZING TECHNIQUES AND ALLOYS FOR ACCELERATOR RF COMPONENTS

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Summary

Techniques have been developed for brazing thin flat sheets and for using electron beam heating to provide braze melt temperatures in situations where furnace brazing is not possible. These techniques are discussed and the results of a survey of braze alloy resistivities are presented.

Introduction

High power rf structures capable of operation at 100% duty factor are being designed at the Chalk River Nuclear Laboratories as part of a program to develop high current accelerators. These structures are usually made of OFHC copper to provide both good electrical and thermal conductivity. They generally consist of several components that must be joined by brazing. For structures such as the relatively thin vanes of a radiofrequency quadrupole (RFQ) accelerator, large areas of thin copper plate must be brazed over the cooling channels needed to remove the high average heat load introduced by cw operation. Satisfactory brazes require joint spaces less than 40 \( \mu \)m thick and it is very difficult to keep thin plate adequately flat unless it is held with mechanical connectors. A braze technique using mechanical connectors has been developed.

High electrical conductivity must be maintained in a brazed structure for areas conducting high rf currents. Although electrical resistivity in thin joints may not appear significant, braze alloy frequently flows out over adjacent surfaces. If it is impossible to remove surface coatings after brazing, the alloy chosen must have a low resistivity. When a structure requires several successive brazes at decreasing temperatures it is difficult to find enough high conductivity alloys. Most suppliers do not have resistivity figures for their alloys. Resistivity measurements have been made for alloys covering a wide range of melting points.

Mechanical Connector Selection

Although dead weight loading may be adequate in some cases, it is difficult to apply accurate uniform loading in relatively small brazing furnaces. Most mechanical connectors - screws, clips, rivets, etc. - must be removed after brazing. If they cannot be removed they must be made of OFHC copper and become an integral part of the structure. Near the centre of large plates only screws and rivets appear suitable. Screws and screw clearance holes would have to be manufactured to tight tolerances to assure good brazing. Although OFHC copper rivets are not readily available they can easily be made by heading bar stock. Rivet holes do not require close tolerances because the riveting operation expands the shank. In normal practice the hole may be up to 3% oversize. To obtain good electrical conductivity the rivet heads and shanks should be brazed. Rivet head brazing requires either sheet or wire braze alloy inserts.

A convenient stock size for brazing wire is 0.76 mm. When this wire size is used under the head, the head diameter must be about 3.2 mm larger than the shank, i.e., a diameter ratio of 2.0:1 for the small rivets and 1.67:1 for the larger rivets. Most head shapes are designed for 1.5 to 1.9:1. Only the flat head shape has a 2.0 diameter ratio. Countersunk heads have a 1.85 ratio. This means that conventional heads are satisfactory on the larger rivets but the smaller rivets need slightly oversize heads.

Sufficient rivet shank must project beyond the plate to form a proper head and fill the slightly oversize hole. When rivets with a 25 mm grip (total plate thickness) are used the excess length needed to form a head is shown in Table 1.

<table>
<thead>
<tr>
<th>Rivet Size</th>
<th>Head Type</th>
<th>Head Dia</th>
<th>Head Length</th>
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<tr>
<td>3.2</td>
<td>button</td>
<td>6.4</td>
<td>4.8</td>
<td>1.5</td>
</tr>
<tr>
<td>3.2</td>
<td>countersunk</td>
<td>6.4</td>
<td>9.6</td>
<td>3.0</td>
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<tr>
<td>4.8</td>
<td>button</td>
<td>8.0</td>
<td>5.6</td>
<td>1.77</td>
</tr>
<tr>
<td>4.8</td>
<td>countersunk</td>
<td>8.0</td>
<td>4.0</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Rivet Tests

Two tests were made. Each contained two rivets of the above four types. One assembly used 0.0076 mm thick braze alloy washers under the heads and sheet alloy between the plates. The second assembly used 0.76 mm braze wire rings under the heads by countereboring the holes 1.5 mm oversize. These recesses were flat bottomed and 0.9 mm deep. The plate-to-plate braze used 1.27 mm wire. In all cases the alloy was 72 Ag 28 Cu.

After brazing, the braze wire assembly was leak tight. The braze shim assembly did not leak around the rivets. It did have serious leaks between the plates in the spaces between 4.8 mm rivets. Unless parts are heavy and free to move together when the alloy melts, it appears sheet braze alloy should be avoided.

The wire braze piece was machined to remove the rivet heads. About 0.25 mm was removed from the plate where there were countersunk heads. Approximately 1 mm was removed where there were button heads to get below the wire insert counterbores. Following head removal both pieces were...
### Table 2

**BRAZING ALLOY RESISTIVITIES**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Composition (%)</th>
<th>Trade Name</th>
<th>Liquidus °C</th>
<th>Solidus °C</th>
<th>Form mm</th>
<th>*Resistivity (μΩ-cm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>50 Au 50 Cu</td>
<td>50-50 (WG)</td>
<td>970</td>
<td>955</td>
<td>1.27 wire</td>
<td>9.7</td>
</tr>
<tr>
<td>2</td>
<td>82 Au 18 Ni</td>
<td>Nioro (WG)</td>
<td>950</td>
<td>950</td>
<td>0.051 x 12</td>
<td>31.2 (29.3)</td>
</tr>
<tr>
<td>3</td>
<td>81.5 Au 16.5 Cu 2.0 Ni</td>
<td>Permabraze 130 (H&amp;H)</td>
<td>925</td>
<td>910</td>
<td>1.27 wire</td>
<td>17.2</td>
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<tr>
<td>4</td>
<td>80 Au 20 Cu</td>
<td>80-20 (WG)</td>
<td>910</td>
<td>908</td>
<td>0.76 wire</td>
<td>12.3</td>
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<tr>
<td>5</td>
<td>65 Ag 20 Cu 15 Pd</td>
<td>Palcusil 15 (WG)</td>
<td>900</td>
<td>850</td>
<td>1.14 wire</td>
<td>6.0</td>
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<tr>
<td>6</td>
<td>58 Ag 32 Cu 10 Pd</td>
<td>Palcusil 10 (WG)</td>
<td>852</td>
<td>824</td>
<td>0.76 wire</td>
<td>4.2</td>
</tr>
<tr>
<td>7</td>
<td>60 Au 20 Cu 20 Ag</td>
<td>Silcoro 60 (WG)</td>
<td>845</td>
<td>835</td>
<td>1.27 wire</td>
<td>13.0</td>
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<td>8</td>
<td>68 Ag 27 Cu 5 Pd</td>
<td>Palcusil 5 (WG)</td>
<td>810</td>
<td>807</td>
<td>0.76 wire</td>
<td>3.8</td>
</tr>
<tr>
<td>9</td>
<td>71 Ag 28 Cu 0.75 Ni</td>
<td>Nicusil 3 (WG)</td>
<td>795</td>
<td>780</td>
<td>1.27 wire</td>
<td>2.6</td>
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<tr>
<td>10</td>
<td>72 Ag 28 Cu</td>
<td>Cusil (WG)</td>
<td>780</td>
<td>780</td>
<td>0.76 wire</td>
<td>2.3 (2.2)</td>
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<tr>
<td>11</td>
<td>71.8 Ag 28 Cu 0.2 Li</td>
<td>Lithobraise 720 BT (H&amp;H)</td>
<td>760</td>
<td>760</td>
<td>1.57 wire</td>
<td>4.2 (3.39)</td>
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<tr>
<td>12</td>
<td>63 Ag 27 Cu 10 In</td>
<td>Incusil 10 (WG)</td>
<td>730</td>
<td>685</td>
<td>0.076 x 25</td>
<td>7.1</td>
</tr>
<tr>
<td>13</td>
<td>61.5 Ag 24 Cu 14.5 In</td>
<td>Incusil 15 (WG)</td>
<td>Permabraze 615 (H&amp;H)</td>
<td>705</td>
<td>630</td>
<td>1.27 wire</td>
</tr>
</tbody>
</table>

*WG — Western Gold and Platinum Company  
H&H — Hardy and Harman Company  
Bracketed values are manufacturers' listing.*

split through one set of rivets. A chronic and sulphuric acid mixture was used to etch the surface and make the braze alloy visible. All 3.2 mm rivet shanks were tightly brazed. Most 4.8 mm rivet shanks showed some porosity remote from the outer surfaces and this suggests insufficient braze alloy. All countersunk rivet heads showed some porosity. Apparently riveting did not fill the countersinks and the braze alloy was unable to bridge all gaps. The 3.2 mm countersunk rivets using brazing wire were relatively good. Button head rivets were excellent once the surface was machined.

**Resistivity Measurements**

A survey of manufacturers' data and metal handbook showed very little resistivity data for the brazing alloys commonly used. Readily available foil and wire samples, approximately 0.7 to 1.6 mm diameter by 200 to 500 mm long, were used for resistance measurements. A 2.5 A dc power supply and a high impedance (10 MΩ) digital voltmeter were used for the measurements. At 2.5 A the measured voltage drops were 15 to 500 mV. The error in resistivity is estimated to be less than 10%.
Voltage contact points were sufficiently far removed from the current contacts to eliminate end effects. No attempt was made to measure a series of points along the samples to independently establish the voltage gradient.

Where possible the measurements were checked against tabulated values. Because small changes in alloying element concentrations can produce large changes in resistivity, the apparent errors were sometimes as great as 25%. The measurement technique was checked by using samples of solid copper hook-up wire and Chromel-A heating element ribbon. The largest disagreement between the measured and tabulated values for these samples was 3.3%.

The composition and resistivity of the braze alloy may change during an actual braze depending on the metals joined and on the braze temperature. This composition may be further altered if the joint undergoes several temperature cycles near its melt point. The dc resistivity measurements must therefore be considered only as a guide in choosing a suitable alloy. Where tabulated values differ, the differences must be attributed to alloy composition difference. In Table 2, alloys 10 and 11 differ only in the small amount of Li in alloy 11. Clearly a small change in Li (manufacturer's listed range is 0.15 to 0.30%) can easily produce large changes in resistivity. Alloy compositions were not checked. Because the Li is consumed as a deoxidizer or flux a brazed joint may have a lower resistivity.

Electron Beam Welding

There are some copper structures, like drift tubes using permanent magnets, which cannot be sealed by brazing. Such magnets will not tolerate the braze temperature. Unfortunately, conventional welding techniques suffer because copper is a good thermal conductor and readily oxidizes. Such welds tend to be porous and rarely penetrate more than 3 mm. Electron beam welding was investigated because the heating is very localized and there is no risk of oxidation.

An attempt was made to improve the weld penetration by inserting a 72 Ag 28 Cu, 1.27 mm braze wire in a groove located 2.4 mm below the surface. Although the electron beam could not fuse the copper below this depth, the residual energy might melt the alloy and form a brazed joint to a much greater depth. One leak tight joint was formed with a 25 kV beam. The braze wire did not melt and only the outer 0.25 mm was tight (Fig. 1). Without a braze wire and using a 27.5 kV beam the outer 1.2 mm of the weld were leak tight (Fig. 2). At 30 kV the braze wire melted but the joint leaked (Fig. 3).

All welds were made with two revolutions of a circular disk traveling at 38.1 mm/s. Temperature sensitive tapes on the inner surface indicated peak temperatures near 300°C. One successful test at 27.5 kV included a small permanent magnet. With a magnet in place, an iron ring and disk were used to shield both edges of the weld. Without this shielding the beam did not follow the weld surface. Further modifications may still permit combined electron beam welding and brazing.
EFFECTS OF RADIAL SUPPORT STEMS ON THE DISK-AND-WASHER STRUCTURE

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Summary
Measurements of the Q value have been done on the disk-and-washer cavities of \( \beta = 1 \) that were made by copper at 2856MHz for the test of electron linear accelerator structures. The washers are supported by the radial stems. In the present study, materials (copper and Teflon) and number of the stems are changed. Linear relations between number of the stems and the values of 1/Q's and resonance frequencies are found using the Teflon stems. For linear extrapolation to the case of no stem, the 1/Q and resonance frequency are close to the values calculated by using the computer program SUPERFISH. For the copper stems, no systematic relations are found for the ir/2A mode.

Introduction
Several types of the support systems are considered for the DAW structures: radial support, T-type, TO-type, etc. Considering the fabrication and field symmetry along an axis, probably the radial support is the best. Unfortunately, negative results were reported by S.O.Schriber and J.M.Potter. We have performed the similar experiment of the radial support. This paper reports the preliminary results. Measurements are carried out on single cavity with two half disks and one washer which is supported by the radial stems. Parameters of the cavity are optimized by using the SUPERFISH. Diameter of the stems are all 9.5mm.

The Teflon stems
Resonance frequencies and 1/Q values change linearly with the number of stems (Fig. 1): the fewer the stems, the lower the 1/Q values and the higher resonance frequencies. These results show that the Teflon stems do not disturb strongly a field distribution, and dielectric losses are proportional to the number of stems. The value extrapolated to no stem should be equal to the calculated one without any stem. The extrapolated resonance frequency well agrees with calculated one. However the Q value is lower about 20% from calculated one. It may be caused by rather rough inner surface and/or residual RF coupling effect between the cavity and measurement tools.

The copper stems
The conductive stems deform an axisymmetry of the boundary condition. The modes which are excited in the cavity without any stem are therefore no longer eigenstates of the cavity with the stems. The states which are coupled between the TE-like and TM-like modes are the eigenstates of the cavity with stems. A dominant mode coupled with ir/2A mode may be the TE{11}-like mode, which is the lowest TE-mode. If the coupling between the two modes is stronger, two resonance states which partially has the accelerating electric field should be appeared near 3GHz. In fact, we have measured two states near 3GHz on a cavity with two stems placed at an angle of 180°.

In both states, the electric field on centers of short plates of both ends of the cavity where the transverse electric field should not exist is stronger than peripheral one. One state of them is lowered from the calculated accelerating mode frequency while the other is raised. Though the Q value is relatively high, the longitudinal electric field is not so strong as in the others mentioned below.

A structure of four stems have the highest resonance frequency and the lowest Q value. So, this should not be adopted as an accelerating structure.

Structure of a single stem and two stems placed at an angle of 90° show similar characteristics for the Q values and resonance frequencies. Since from a geometrical consideration, they have different symmetry from the TE{11} mode, then mixing of this component may be avoided. The measured Q values of them are about 70% of the value without any stem which is mentioned above.

Beam Break-up (BBU) is one of serious problems for the electron linear accelerator, especially, a high current one. To avoid BBU, the transverse electric field should be reduced. For this purpose and making the field distribution uniform, rotating the stems from washer to washer will be helpful. Experiments of multi-cell structures with a beam are now in preparation.

Acknowledgments
We wish to thank Y.Kawarazaki and K.Mashiko for useful discussions and criticisms.

Reference
A RFQ CONCEPT USING CIRCULAR RODS

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Summary

Although the RFQ principle was suggested in 1969 already, a first successful test did not happen until 1980. In this paper emphasis is taken on a RFQ configuration, which differs from the one used in Los Alamos however, consisting of modulated circular rods, as figs. 1 and 6 indicate. Of course the zero mode operation does not necessarily require such plain rods, profiles as investigated at Los Alamos can be used as well. The simplicity of manufacture seems evident. Considerations of rf properties and technical aspects are dealt with in another paper. Here we present our way of generating the linac with respect to a maximum beam current and demonstrate the method by three examples, namely a 50 mA fusion preaccelerator for $^{133}$Cs$^+$-ions (4.5 - 100 keV, 10 MHz, 10 mA), a 390 mA proton injector linac (0.115 - 2 MeV, 100 MHz) and a study model for protons (10 - 300 keV, 108 MHz, 10 mA), being under construction in Frankfurt, which is designed for experimental tests of beam behaviour and rf investigations.

Beam Dynamics and Design Considerations

The electrical potential may be represented by a Fourier expansion

$$
\Phi(x,y,z,t) = V \sin(\omega t - \phi) [C_0 x^2 - y^2] + \sum_{M=1}^{\infty} A_{2M-1} \cos(2M-1)kz(ch(2M-1)kx + ch(2M-1)ky)]
$$

(1)

where we have omitted terms with even Fourier coefficients $A_{2M}$ in (1), thus restricting ourselves to electrode profiles uneven with respect to points $P$ (s. fig. 1). As a consequence a simple expression for $C_0$ results

$$
C_0 = \frac{4a^2}{(a + b)^2}.
$$

(2)

In general all Fourier coefficients are related to the electrode shape represented by $a$, $b$ and $\alpha$ in a rather complex manner. A certain profile is characterized by the omission of all Fourier coefficients except $A_1$ with the consequence of losing the above symmetry, which led to (2). In this case closed expressions

$$
A_1 = 2 - b^2(1 + chka) + a^2(1 + chkb)
$$

(3)

$$
C_0 = a^2 \frac{b^2(1 + chka) + a^2(1 + chkb)}{2 + chka - chkb}
$$

(4)

can be deduced from (1). This course is taken at Los Alamos, although equations (3) and (4) do not agree precisely with (5) and (6) in $^4$, due to slightly different boundary conditions, they correspond to a high degree in all practical cases however. From (1) and (2) conventional linear equations result for certain particle motions that are the transversal motions of synchronous particles

$$
\begin{align}
\frac{d^2x}{dt^2} + \frac{e}{m} \left( \frac{4V \sin(\omega t - \phi) + VA_1 \pi^2 f^2 \sin \phi_s}{(a + b)^2} \right) &= \frac{3QF_x}{2V^2} \\
- \frac{3QF_y}{4\pi \epsilon_0 a_x a_y a_z} y &= 0
\end{align}
$$

(5a)

and the longitudinal motions of particles on the axis

$$
\begin{align}
\frac{d^2u}{dt^2} + \frac{e}{m} \left( \frac{VA_1 \pi^2 f^2 \sin \phi_s - 3QF_u}{V^2} \right) &= \frac{a_x a_y a_z}{4\pi \epsilon_0} u = 0
\end{align}
$$

(5c)

Space charge is expressed by the usual K.V. setting $^{5,6}$ (extended to three dimensions), where the beam bunch is understood as an ellipsoid with semi-axes $a_x$, $a_y$, $a_z$ uniformly filled with a total charge $Q$ corresponding to the mean beam current $I = f Q$. As long as these envelope functions $a_x(t), a_y(t), a_z(t)$ have the linac period $1/f$, any $\beta$-section is optically matched to its predecessor. So the goal of our computations is to match the electrode profile such that this envelope period is maintained as long as possible. But this is settled by the tuneshifts $\mu_x, \mu_y, \mu_z$ of the motions ($5a, b, c$) respectively. In order to determine those tuneshifts the three equations ($5a, b, c$) and simultaneously the three envelope functions have to be calculated within all $\beta$-sections, after the three acceptance ellipses of the first section have been taken as initial beam emittances. Computations show that matching is satisfying, when the tuneshifts $\mu_x$ (or $\mu_y$) and $\mu_z$ are kept constant along the accelerator. For the longitudinal motion (5c) this means

$$
\frac{A_j \sin \phi_j}{V_x} = \text{const.}
$$

(6)

As maximum semi-axes $a_x, a_y$ we take the minimum aperture radius $a$ of the linac (fig. 1), as the axial one we use an expression

$$
\frac{a_x a_y a_z}{4\pi \epsilon_0} u = 0
$$

Fig. 1 Cross sections of RFQ rods

a) x-y intersection at z = 0, $\beta \lambda$

b) x-z and y-z intersections

Space charge is expressed by the usual K.V. setting (5a, b, c) respectively. In order to determine those tuneshifts the three equations (5a, b, c) and simultaneously the three envelope functions have to be calculated within all $\beta$-sections, after the three acceptance ellipses of the first section have been taken as initial beam emittances. Computations show that matching is satisfying, when the tuneshifts $\mu_x$ (or $\mu_y$) and $\mu_z$ are kept constant along the accelerator. For the longitudinal motion (5c) this means

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$$

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As maximum semi-axes $a_x, a_y$ we take the minimum aperture radius $a$ of the linac (fig. 1), as the axial one we use an expression

$$
\frac{a_x a_y a_z}{4\pi \epsilon_0} u = 0
$$
\[ a_u = \frac{V}{\pi} \sqrt{1 - \phi_S^2 c_0^2} = \text{const.} \]  
(7)

which can be derived by approximating the separatrix by an ellipse and taking its angular semiaxis \( s^2 \).

We start our linac considerations in this paper with the gentle buncher section omitting the preceding shaper as well as the transverse matcher. For a more detailed discussion of these elements we refer to 9. Usually the initial synchronous phase \( \phi_0 \) together with the velocity \( v_0 \) are given at the input of the buncher. Further fixed data are the final synchronous phase \( \phi_f \) and the final aperture radius a both being kept constant after gentle bunching is finished. As a first step the velocity \( v_S \), which corresponds to \( \phi_S \), is calculated using (7). Now an arbitrary tuneshift \( \mu x,S \) not yet depressed however and \( Q = 0 \) are taken for a zero approach. A corresponding \( \beta \lambda \) accelerator section for this \( v_S, \phi_S \) pair is determined bringing about a parameter combination \( A_{1,0} C_{0,0} S \). Then (1) gives an acceleration parameter \( A_{1,0} \) for the first buncher section with given \( v_0, \phi_0 \) and the condition \( \mu x,0 \) = const., corresponds to a certain \( A_{1,0} C_{0,0} S \) combination. Now by switching on and increasing space charge \( Q \) stability limit is reached either axially or transversally. Since stability boundaries correspond to depressed tuneshifts with \( \cos \mu x + 1 \) or \( \cos \mu u = 1 \) and \( A_{1} \) appears in (5a) or (5b) but with opposite sign in (5c) corresponding current limits have a scope that fig. 2 exemplarily demonstrates. Then iterating the undepressed \( \mu x,0 \) a maximum current \( I_{\text{max}} \) as well as an optimum undepressed tuneshift with unique parameter combinations \( A_{1,0} C_{0,0} S \) for the first buncher section and \( A_{1,0} C_{0,0} S \) for the first accelerator section are obtained. Using this parameter set a "nominal" beam current of about 0.5 \( I_{\text{max}} \) is defined. By keeping the optimum undepressed tuneshift \( \mu x,0 \) constant the buncher part is successively generated using conditions (6) and (7). Later on in that accelerator part however, where the degree of freedom in the synchronous phase is exhausted and the inner aperture is kept constant only the outer radius \( b \) is left as a free parameter. Here matching proved satisfactory, when we adjusted the outer \( b \) such that still the undepressed tuneshift \( \mu x,0 \) was kept constant. The following examples illustrate matters.

Two linac designs we present as examples, a 50 mA \( ^{133} \text{Cs} \) fusion injector and a 390 mA proton system. Fig. 3 sketches the electrode profile of a 13.5 MHz Cs sample with beam envelopes. In fig. 4 the proton injector is outlined. It should be noticed that the correct fast oscillations of the beam envelopes in figs. 3 and 4 correspond to the structure period, while the slow oscillations are either caused by a tiny mismatch frequently occurring with the sensitive K.V. model. This seems negligible however, when more realistic space charge distributions are considered as can be learned from 11, table 4, and 12, table 4, where similar linac examples are discussed.

A preliminary description of our proton study model was given in 11. Meanwhile we inserted some modifications favouring a design principle, where not the transversal tuneshift is kept constant but the outer radius \( b \). This makes manufacturing much easier, since any of the four rods now consists of an inner uniform copper pipe (outer diameter 6 mm) and a proper sequence of short copper cylinders (inner diameter 6 mm) being shoved and soldered on it. Along the buncher the outer diameter of these cylinders increases, while in the accelerator part the modulation remains constant. Fig. 5 sketches geometrical dimensions, beam envelopes and relevant parameters. Of course mismatch is important however, since any of the four rods now consists of an inner uniform copper pipe (outer diameter 6 mm) being shoved and soldered on it. Along the buncher the outer diameter of these cylinders increases, while in the accelerator part the modulation remains constant. 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Fig. 3 Electrode profiles and beam envelopes of 0.6 - 13.3 MeV Cs Fusion injector
In nominal = 50 mA, a = 1.6 cm, $\phi_0 = 30^\circ$, $\mu/\mu_0 = 0.71$, length 24 m,
150 sections, vane voltage 300 kV, 13.5 MHz, $\cos \mu_0 = 0.96$

Fig. 4 Electrode profiles and beam envelopes of 0.115 - 2.28 MeV proton injector linac
In nominal = 393 mA, a = 1 cm, $\phi_0 = 83^\circ$, $\psi = 30^\circ$, $\mu/\mu_0 = 0.72$, length 2.60 m,
31 sections, vane voltage 306 kV, 100 MHz, $\cos \mu_0 = 0.51$

Fig. 5 Electrode profiles and beam envelopes of study model 10 - 313 keV, I = 0,
a = 0.25 cm, b = 0.55 cm, $\phi_0 = 60^\circ$, $\psi = 300^\circ$, length 76 cm, 19 sections,
vane voltage 25 kV

Fig. 6 Photo of zero mode RFQ structure
A VARIABLE STRENGTH PERMANENT MAGNET DIPOLE

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Abstract

The design strategy that has been successfully applied to segmented permanent magnet quadrupole lenses can equally well be used to produce dipole field configurations [1]. The use of homogenizing spaces between segments to produce beam optics quality fields over 80% of the magnet gap is described. The use of counter rotating dipole rings to vary the dipole bending strength and the effects of fringing fields are described.

Dipole Description

A permanent magnet dipole is diagrammed in Figure 1. It takes the form of a ring assembled from eight trapezoidal samarium-cobalt pieces with magnetic vectors oriented so as to lead the return flux around the aperture almost entirely within the permanent magnet material. The central field is an increasing function of b/a and can be as much as 10 kilogauss. The dipole field uniformity can be maximized by incorporating homogenizing gaps (s in Figure 1) between the magnet segments as suggested by Halbach [2]. We will use a dipole with a = 1cm, b = 2cm and a field strength of 5 kilogauss as an example. Figure 2, top, shows the error at 80% of the aperture for values of s to 0.2cm. The bottom graph gives the radial field error for values of s near the optimum, showing a possible uniformity better than 10^{-3} for 85% of the aperture.

Adjustable Strength Dipole Characteristics

The effective strength of a permanent magnet dipole for particle beam steering can be varied in a manner similar to that used for adjustable quadrupoles. This is done by counter-rotating successive rings so that there is a reduction, approximately proportional to the cosine of the rotation angle, of the net impulse received by the particles as the beam traverses the dipole. Figure 3 illustrates the configuration in which three identical dipoles are placed in series with the length of the center ring equal to twice the length of each end ring. By rotating the rings around the beam axis...
in the rotation senses shown, the effective bending strength of the dipole is reduced with no vertical displacement or impulse.

The vector diagram in Figure 4 shows the orientation of each dipole field, $B_j$, and the resulting impulse, $J_j$, on a particle beam resulting from each ring. The net impulse is reduced as the angle $\alpha$ is increased.

Beam Transport Through Three Dipoles in Series

Following the particle trajectory through each dipole, the entrance parameters of the downstream dipole are made equal to the exit parameters of the upstream one. Fringe field effects will be considered below. We will consider each ring separately.

For a proton passing through a dipole oriented along the $x_1$ axis, the momentum vector $p$ is rotated through an angle $\omega t$ where $\omega$ is the cyclotron frequency and $t$ is the time required to pass through the dipole. The new momentum vector is given by

$$p_1 = E_0 \rho_0 R_0 \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega t & -\sin \omega t \\ 0 & \sin \omega t & \cos \omega t \end{bmatrix}$$

The displacement of the particle is given by

$$\Delta x_1 = \int_0^t E_0 \rho_0 R_0 dt = E_0 \rho_0 \delta_0$$

If the dipole is rotated around $x_2$ by an amount $\alpha$, a new rotation matrix results:

$$R_2 = A \rho \delta_0$$

where

$$A = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

And $A$ is the transpose of $A$. Now

$$E_1 = E_0 \rho_0 R_0 A = E_0 \rho_0 \delta_0$$

and

$$\Delta x_1 = \int_0^t E_0 \rho_0 R_0 dt = E_0 \rho_0 \delta_0$$

The second dipole is twice as long (so that the particle stays in the field for a time $t'$) and is rotated about $x_3$ in the opposite sense:

$$E_2 = E_0 \rho_0 R_0 A$$

where $R_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \cos \omega t' & -\sin \omega t' \\ 0 & \sin \omega t' & \cos \omega t' \end{bmatrix}$

$$\Delta x_2 = \frac{1}{2} \int_0^{t'} E_0 \rho_0 A dt = E_0 \rho_0 \delta_0$$

Finally, the third dipole is identical to the first so that

$$E_3 = E_0 \rho_0$$

The integrations are easily done to yield

$$\int_0^{t'} E_0 \rho_0 dt = \frac{1}{2}$$

The rotations are applied to give

$$R_1 = \begin{bmatrix} \cos^2 \alpha + \cos \omega t \sin^2 \alpha & \cos \alpha \sin \omega t \sin \alpha & \cos \omega t \sin \omega t \\ \cos \omega t \sin \alpha & \cos \alpha \cos \omega t \sin \alpha & \cos \omega t \cos \alpha \\ 0 & \cos \omega t \cos \alpha & 1 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} \cos^2 \alpha + \cos \omega t' \sin^2 \alpha & \cos \alpha \sin \omega t' \sin \alpha & \cos \omega t' \sin \omega t' \\ \cos \omega t' \sin \alpha & \cos \alpha \cos \omega t' \sin \alpha & \cos \omega t' \cos \alpha \\ 0 & \cos \omega t' \cos \alpha & 1 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} \cos^2 \alpha + \cos \omega t \sin^2 \alpha & \cos \alpha \sin \omega t \sin \alpha & \cos \omega t \sin \omega t \\ \cos \omega t \sin \alpha & \cos \alpha \cos \omega t \sin \alpha & \cos \omega t \cos \alpha \\ 0 & \cos \omega t \cos \alpha & 1 \end{bmatrix}$$

The exact phase space equations of motion are

$$E_1 = E_0 R_1 \delta_1$$

$$E_2 = E_1 R_2 \delta_2$$

$$E_3 = E_2 R_3 \delta_3$$
Fringe Field Effects

The forces due to fringing fields on a particle traversing a dipole aligned along the \( x \) axis can be represented by:

\[
\vec{f} = \frac{e}{m} \vec{p} \times \vec{B}
\]

The three independent matrix elements are, to second order:

\[
f_x = \frac{-x_1^2 + x_2^2}{8} \frac{dB}{dx} \quad f_y = \frac{-x_1 x_2}{4} \frac{dB}{dx} \quad f_z = \frac{x_1}{4} \frac{dB}{dx}
\]

To get the impulse due to the fringe fields integrate over the time required to go from the uniform field part of the magnet to infinity:

\[
\vec{j} = \frac{e}{m} \int_0^\infty \vec{p} \times \vec{B} \, dt
\]

Assuming the fringe region to be sufficiently short so that \( \vec{p} \) is not deflected significantly along the \( x_3 \) axis gives

\[
\vec{j} = \frac{e}{m} \int_0^\infty \vec{p} \times \vec{B} \, dt = \int_0^\infty \frac{dB}{dx} \vec{x}_B \, dx
\]

For \( 10 \text{ MeV protons} \) \( 1 \text{ cm} \) above the axis of a 5 Kg dipole and moving at an angle of 6° from the dipole axis, this gives a deflection of about 1 milliradian. For a particle entering the dipole, the limits of integration change:

\[
\vec{j} = \frac{e}{m} \int_{-\infty}^{\infty} \vec{p} \times \vec{B} \, dt = \int_{-\infty}^{\infty} \frac{dB}{dx} \vec{x}_B \, dx
\]

The matrix \( \vec{x}_B \) has the property \( \vec{x}_B \vec{x}_B = \vec{2} \). Therefore

\[
\vec{j} = \frac{eB}{m} \left[ (x_1 \cos\alpha + x_2 \sin\alpha) \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \right]
\]

For a rotation in the opposite sense

\[
\vec{j} = \frac{eB}{m} \left[ (x_1 \cos\alpha - x_2 \sin\alpha) \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \right]
\]

Thus, if the particle leaves a dipole rotated by \( + \alpha \) and enters a similar dipole oriented at \( -\alpha \), the total impulse is

\[
\vec{j} = \frac{eB}{m} \left[ (x_1 \cos\alpha + x_2 \sin\alpha) - (x_1 \cos\alpha - x_2 \sin\alpha) \right] \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \left[ p_2 - p_1, 0 \right]
\]

For a rotation in the opposite sense

\[
\vec{j} = \frac{eB}{m} \left[ (x_1 \cos\alpha - x_2 \sin\alpha) - (x_1 \cos\alpha + x_2 \sin\alpha) \right] \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \left[ p_2 - p_1, 0 \right]
\]

Adapted from an expression for the field values in the permanent magnet dipole geometry developed by R Gluckstern for NEN

Conclusion and Design Example

An adjustable permanent magnet dipole can be constructed from three counter-rotating sections, the middle section being twice as long axially as the first and last sections to make \( t' = 2t \). To first order, assuming both the deflection in the first section \( (\alpha) \) and rotation \( (\alpha) \) angles are small, a beam entering the dipole on axis with a momentum of \( [0, 0, \vec{p}] \) exits on axis with a momentum of \( \vec{p} = [0, 4\cos\alpha \sin\omega t, \vec{p}] \)

the characteristic time \( (t) \) can be calculated using the formula

\[
t = \frac{ML}{p}
\]

where \( L \) is the axial length of the first section.

For a beam entering off axis, the fringe fields introduce some aberrations. The following table illustrates the magnitude of this effect.

<table>
<thead>
<tr>
<th>BEAM PARAMETERS</th>
<th>MAGNET PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_0 = [1 \text{ cm}, 1\text{ cm}, 0] )</td>
<td>( B = 0.5T )</td>
</tr>
<tr>
<td>( p_0 = [0, 0, \sqrt{2}\mu \text{m}] )</td>
<td>( \alpha = 0.1 \text{ radian} )</td>
</tr>
<tr>
<td>( K = 10 \text{ MeV protons} )</td>
<td>( \text{Total length} = 36 \text{ cm} )</td>
</tr>
</tbody>
</table>

Beam Deflection = \( 23^\circ \)

Fringe field aberrations = \( 4.3 \text{ milliradian} \)

ACKNOWLEDGMENT

We wish to acknowledge the contributions at New England Nuclear of Ronald Holsinger* and Robert Lown** to the initial development of a permanent magnet dipole. The work reported here is derived from the fundamental magnetic analysis of Dr. Robert Gluckstern*** and the original contributions of Klaus Halbach [2,3].

References

2. K. Halbach, Design of Permanent Magnet Multipole Magnets with Oriented Rare-Earth Cobalt Material, Nuc. Inst. & Meth., 169, 1-10, June 1979
3. K. Halbach, Strong Rare-Earth Cobalt Quadrupoles, IEE Trans. on Nuc. Sciil, June 1979

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FIRST RESULTS ON BNL H- MEQALAC

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INTRODUCTION

The MEQALAC (Multiple-Beam Electrostatic Quadrupole Array Linear Accelerator) concept and its first experimental test have been described previously[1]). The test verified that a MEQALAC can transport and accelerate multiple, high brightness beamlets starting at very low initial B^10^q in the test). The six-dimensional phase space density per beam, (T/fez)/(e^NL^£&) (ref. 2) was 3.3x10^29/m^3-rad^3). This paper will describe initial results of a second MEQALAC test which explored higher frequency operation with smaller bore size. The current density was higher by up to a factor of seven. This MEQALAC was a four beam H- accelerator[3]). Conceivably, it could lead to a replacement for relatively bulky and expensive Cockcroft-Walton pre-injectors.

ACCELERATOR CONSTRUCTION

A BNL Mark III magnetron[4]) with a grooved cathode supplied the H- ions. Beam was extracted with a double gap geometry. The first gap, at 2 mm, held off 15 kV DC and the second gap, at 21/2 mm, held off 25 kV DC.

Figure 1 shows the four channel accelerator. It consists of a transport section in front (LEBT), followed by the linac section sitting on top of its resonator. The ground shield in front protects the LEBT insulators from DC corona coming from the source. In operation, this shield was pushed flat against the ground extractor on the source. The main purpose of the LEBT was to simulate the effect of the bunching length required by the eventual addition of a buncher (see Fig. 6). The linac section consists of ten accelerating gaps with a quadrupole inside each drift space. Figure 2a shows some dimensions at the transition from the LEBT into the linac, and Figure 3 shows the resonator design[5]). The BNC connectors to the drive and pick-up loops can be seen on the side of the resonator in Figure 1.

Table 1 summarizes the design.

<table>
<thead>
<tr>
<th>TABLE 1. 4 Beam H- MEQALAC Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Section</td>
</tr>
<tr>
<td>cell length, Lcell</td>
</tr>
<tr>
<td>quad radius, rq</td>
</tr>
<tr>
<td># of cells</td>
</tr>
<tr>
<td>rq/Lcell</td>
</tr>
<tr>
<td>(quad length)/Lcell</td>
</tr>
<tr>
<td>Linac</td>
</tr>
<tr>
<td>input B/A/2</td>
</tr>
<tr>
<td>output B/A/2</td>
</tr>
<tr>
<td>quad radius</td>
</tr>
<tr>
<td># of accel. gaps</td>
</tr>
<tr>
<td>gap width</td>
</tr>
<tr>
<td>frequency</td>
</tr>
</tbody>
</table>

RESULT

For the first test of this MEQALAC, done in mid-February, 1981, a 1 1/4" ID x 1" long tube was placed near the exit of the linac. When biased to >40 kV, only accelerated particles in the four beamlets could punch through. About 100 µA was observed.
Fig. 2a. Geometry and dimensions of a. the LEBT to Linac transition and b. the buncher region of the new LEBT of Fig. 6. Figures drawn to scale in longitudinal direction only.

Fig. 3. The resonator is basically a resonant section of ridged waveguide. Inductance per unit length decreases in inverse proportion to a particle velocity. Therefore, capacitance per unit length is made to increase by increasing the tab overlap area (not explicitly shown). Tabs (not shown) added to each end of the ridge reduced the voltage variation in the gaps from 15% to 5% by adjusting their capacitance to ground. E and H represent electric and magnetic fields.

A crossed-field mass analyzer verified that it was all $H^-$, and then, by electrostatically deflecting a slice of the beam, the energy spectrum was measured. Figure 4a. shows the result. The high energy peak was still too low in energy. It was felt that rf was being capacitively coupled into the drift space via the quad plates, so the transit time factor was actually lower than that given at the end of the introduction. By improving metal-to-metal contacts in the tank, and by eliminating tracking at the drive loop (the connector was changed from BNC to type N), the tank Q was improved, so the rf voltage could be pushed up to 18 kV.

Fig. 4a. Energy spectrum with low rf.

b. Energy spectrum with correct rf, which was about 25% higher than expected. Abscissa is deflector voltage, proportional to beam energy as shown.

At these higher rf levels, electrons were observed streaming out of the linac. Their energy spectrum was taken, and was found to tail off at an energy corresponding to the peak rf voltage as expected, thereby providing an interesting check on the rf calibration. The magnitude of this electron current was comparable to the accelerated $H^-$ current, but a 200 gauss permanent magnet easily swept them away.

The plot of the amplitude of the 120 kV portion of the energy spectrum versus rf level, Figure 5, shows that about 16.5 kV peak rf voltage was actually needed to reach design energy. The accelerated current increased to 400 pA for an input of about 4 mA. Relevant operating conditions are given in Table 2.

In the experiments, sparkdowns made data collection difficult for source voltages greater than about 37 kV or for LEBT quad voltages above ±3 kV. A spark in the source region caused LEBT to spark even if the LEBT quad voltages were under ±3 kV, and vice versa. Both areas were sources of DC corona. Furthermore, the corona increased as operating hours accumulated on the source, perhaps due to deposition of Cs from the source or sputtered Mo from the cathode. Enough power was involved to result in serious thermal loading in some cases. The corona current returned to its original level after cleaning the metal surfaces involved with Alkonox and an alcohol rinse. Pulsing the source and LEBT voltages essentially eliminated the sparking problem. LEBT was pulsed from ground, and the source and intermediate electrode were pulsed from DC values of 25 kV and 10 kV respectively, where almost no corona was ever observed. The linac was not used in these tests.
Fig. 5. Accelerated current, relative units, versus gap voltage in relative units. Absolute gap voltages are marked in two places.

TABLE 2. 4 Beam H-MEQALAC, Initial Results (no buncher)

<table>
<thead>
<tr>
<th>Input energy</th>
<th>40 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output energy</td>
<td>peaked at ~ 120 kV</td>
</tr>
<tr>
<td>Total output current</td>
<td>0.4 mA</td>
</tr>
<tr>
<td>Current out/ current in</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Rf power</td>
<td>6 kW</td>
</tr>
<tr>
<td>Rf pulse width</td>
<td>50-100 us</td>
</tr>
<tr>
<td>Peak rf voltage/gap</td>
<td>~ 16 kV</td>
</tr>
<tr>
<td>Quad voltage, transport section</td>
<td>limited to ±3 kV DC by sparking</td>
</tr>
<tr>
<td>Quad voltage, linac</td>
<td>± 4 kV, pulsed</td>
</tr>
<tr>
<td>Ave. vac. pressure</td>
<td>(2-4) x 10^-5 Torr, pulsed gas</td>
</tr>
<tr>
<td>Rep rate</td>
<td>2 pps</td>
</tr>
</tbody>
</table>

**CONCLUSION**

Accelerated beam was observed at design energy, but the current was low compared to that required from the BNL 750 keV Cockcroft-Walton pre-injector. The LEBT capture efficiency, 25%-30%, could not have been improved too much without a lower source emittance. The linac efficiency, ~10%, should have been around three times better. One reason it was low was that the beam emerging from LEBT was probably not optimally matched into the linac. Another reason may have been rf and DC aperture defocussing effects. An experimental indication of DC aperture defocussing turned up in tests of the new LEBT without the linac. A new LEBT (Figure 6) with independent quads was made, but never tested with the linac. Another reason may have been rf and DC aperture defocussing turned up in tests of the new LEBT without the linac. Namely, the voltage on the quad in the buncher was consistently low, and the subsequent quad voltages were high, as if a disruption occurred at the buncher where DC ground planes are inserted (see Figure 2b).

With the new LEBT, 1.5 mA per channel was obtained. Combined with its greater flexibility for matching, 2 mA total accelerated current should be achievable with the buncher on. A further factor of 5 and a second linac tank would be needed to compare with the present BNL Cockcroft-Walton. The second tank would be about two feet long, operate at 50 kV peak rf voltage, and require about 30 kW. However, there are no plans now to continue work on this project.

**REFERENCES**

1. R. Adams et. al., "Description of the MEQALAC and Operating Results", BNL 27128, LBL 10301.

**Discussion**

The MEQALAC quads are not excited by rf, but by dc voltage supplies.

We believe the xenon accelerator operated at the space-charge limit of the channels because the source could provide five times the channel limit current, so most of this was lost. In the new accelerator, the injector provides about one-fourth of the space-charge limited current, but at an emittance about three times the channel acceptance. The matching is also not accurate, and again much of the input beam is lost.

We changed the resonator design (used for the xenon machine) for the new device because a different frequency was used. From gap to gap, the H-MEQALAC is a $\beta\lambda/2$ Wideröe structure.
The Pulsed Proton Prototype of a High Current Ion Linac

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The using of the spatial uniform quadrupole focusing at the initial stages of acceleration proposed approximately 10 years ago turned out to be rather fruitful for linac techniques. The accelerators of such type are being designed in several scientific centers, where they are being called RFQ. That abbreviation is fairly convenient, though it is not completely strict because it may include general structures of other types.

The practical application of the RFQ accelerating structure in the ITEP is tightly connected with design of a new proton synchrotron injector to replace the obsolete linac I-2 which was put into operation as long ago as 1966. This will allow placing in the same building an injector with output energy of 40-50 MeV instead of the old 24.6 MeV injector and also improvement of the parameters of the proton synchrotron beam. There will be some more improvements in the new injector besides RFQ structure: Alvarez structure will operate with doubled frequency, permanent magnets will be used in drift tubes, linac control will be automatized, and will be connected with the synchrotron computer.

The program of the new injector preparation may be subdivided into stages. The first stage is the experimental study of the linac initial part (RFQ structure) and has some pure scientific purposes besides the construction of the injector.

Construction of an ion linac with average beam current more than 100 mA is a very important link in up-to-date program of alternative energy sources study. Three directions were defined in foremost scientific laboratories: deuteron linac to the energy 30-35 MeV, proton or deuteron linac about 1 GeV, and a low-charged heavy ion linac to approximately 10 GeV.

The two to three order increase of average beam current in comparison with that achieved at the existing machines makes serious demands on the linac design and parameters. The high cost of the project and a lot of technical unsolved questions require carrying out bench tests and full examination of a prototype. The new ITEP synchrotron injector may serve as such a prototype.

Especially serious difficulties in increasing the linac beam intensity must be overcome at the initial part of acceleration, where the influence of space-charge repulsion forces due to its own beam field is maximum. The use of RFQ structure ensures the most effective solution of this problem both for the new injector and for all three above-mentioned new prospective directions. This is connected with the fact that electric quadrupole focusing in such a high frequency structure can be realized, and besides there is a possibility to vary the parameters of the acceleration period in rather wide and flexible bounds. The possibility of a sizeable injection energy reduction, particle capture broadening, and maximum accelerated particle-current increase also arises.

The maximum accelerated particle current may be estimated from the expression

$$I = \frac{m_0^2}{2}\beta^3 \gamma^3 \left(\frac{\alpha}{\beta}\right)^2 \beta I_0,$$

where: $I$ - the radial oscillation phase change per period of the focusing field; $\gamma$ - nondimensional instant frequency of radial oscillations; $\alpha$ - a drift tube aperture radius; $\beta$ - bunching factor;

$$I_0 = \frac{4\pi\varepsilon_0 m_0 c^3}{e}$$

- a constant characteristic for every type of accelerated particle with dimension of current; for protons $I_0 = 3.14 \cdot 10^7 \, \text{A}$;

$$\varepsilon_0 = \frac{10^7}{4\pi^2 c^2 \beta^2}$$

- dielectric constant of the medium;

$m_0$ and $\beta$ - mass and relative velocity of particles;

$\gamma$ - Lorenz-factor.

The quadrupole channel parameters $I_0$ and $\gamma$ of different accelerators with polarity reversal electric focusing may be chosen approximately equal notwithstanding a concrete type of focusing (static of high frequency quadrupoles, phase alternating focusing), but the factors $I_0$ and $\gamma$ greatly depend on the focusing type and turn out to be maximum when RFQ structure is used. Just this very feature allows obtaining the intensive particle beams of different ions with rather low injection energies. It is shown that the proton and deuteron beams with currents up to 200-300 mA may be accelerated with injection energy 70-100 keV. RFQ structure has also rather important advantages when accelerating super-heavy particles, as the possibility of practically 100% capture extremely simplifies the problem of heavy ion sources construction, and the use of electric focusing forces allows achieving a relatively big acceptance for ions with very low velocities.

The first operating linac using spatial uniform focusing is the 30 MeV proton injector which was put into operation in ITEP in 1977. In 1980 a proton beam of 30 mA was achieved in Los Alamos at the pulsed prototype of the deuteron linac at operating frequency 425 MHz. The beam was accelerated from energy 100 keV to 640 keV along the length 1.1 m. The use of RFQ structure raises many grave theoretical and technical problems for designers. Firstly the question of the most optimum shape of
electrodes to ensure high effectiveness of acceleration and focusing, high electric strength and simple manufacturing arises. Hitherto, the electrodes in the form of cylindrical rods with conic modulation of diameter or electrodes of an intricate, variable, approaching the "ideal" configuration were used. In ITEP the decision was made to use half-cylindrical electrodes with invariable section thickness and with sinusoidal modulation of the distance between the electrodes and the axis (under continuously lengthening period). As calculations show, the fifth harmonic of the quadrupole field may be suppressed when such electrodes are used. The electrodes are simple to manufacture. The transit-time factor and focusing effectiveness are close to the values defined by the "ideal" electrodes.

Secondly the question of choosing the optimum RF cavity type to create necessary field configuration has not yet been decided. In the ITEP double H-resonators were used and in Los Alamos - four chamber resonators of separate sectors (clover leaf type). It may be considered that four chamber resonators are most convenient to create the required quadrupole fields. The main field mode of these resonators is quadrupole and the high frequency field is concentrated inside a single closed cavity. This fact considerably simplifies the cooling of the resonator.

Thirdly the scheme of high frequency power feeding, methods of tuning, adjusting and measuring of required field distribution must be chosen. The ITEP four chamber resonators are being excited by means of loop couplers placed in each chamber and phased in a proper way.

In the ITEP the experimental examination of calculations and chosen technical decisions are being carried out on the assemblies of the new injector.

The main parameters of this prototype are listed below:
- injection energy 88 keV;
- output energy 3 MeV;
- operating frequency 148,5 Mhz;
- maximum current 240 mA;
- resonator length 4,9 m;
- a single quadrant diameter 0,2 m;

An Alvarez-type resonator operating with doubled frequency 297 MHz and provided with permanent magnet quadrupole lenses for focusing will be installed after the initial RFQ. The gradient of 6 kG/cm was achieved in these permanent magnet lenses of 20 mm aperture diameter. To get the best conditions of transition from RFQ to Alvarez resonator the energy of transition was taken to be 3 MeV. To match the beam along the longitudinal and transversal coordinates the adiabatic alteration of parameters along the channel between the initial part and the Alvarez resonator is provided. The output tubes GI-27A are used in RF system. These tubes operate very well in the linac-injectors I-2 and I-100. High vacuum pumping is done by turbomolecular and sputter-ion titanium pumps. The ion source of a duoplasmatron type with heated or cold cathode will be used.

The RF tuning and preparation for putting the RFQ structure into operation is going on at present. The general view of the resonator partially in the vacuum tank is shown in Fig. 2. The resonator is assembled in 8 separate sections. The length of each of the sections varies from 574 to 602 mm. The beginnings and the ends of the electrodes of each section coincide with places where the electric strength at the electrode surface is minimum. Each of four chambers has tuning plates, coupling and measuring loops, a device for electrodes shifting in transverse directions. The electrodes parameters adiabatic alteration along the input section of the initial part assures the injector beam matching with linac. Real electrodes are shown in Fig. 3. The optimization of matching is supposed to be verified on this prototype.

The electrodes were produced by hand and by program-controlled milling machines, in accordance with the data received from correspondingly programmed computers. The main dimensions of the sections were defined by means of modelling.

Before being mounted, all the sections were adjusted to get given distances between all the electrodes, and to equalize section areas of the chambers. Then with the aid of the tuning plates, the fields were leveled to achieve equality of the magnetic fields amplitudes. The distributions of the magnetic fields in each of the 4 chambers along the whole resonator before and after tuning are shown in Fig. 4. There are certain difficulties for tuning due to the first overtone of the dipole types of oscillations which have the magnetic field node in the middle of the resonator, and their frequency is near the frequency of the working type of oscillations.

Now, suppressing of parasitic types of oscillations in resonator and preparations for the examinations with proton beam are going on.

The authors are thankful to V. S. Artemov, A. I. Balabin, V. I. Bobylev, L. V. Kartsev, A. A. Kolomletz, S. B. Ugarov and V. I. Edenskij for their active participation in designing of different parts of this accelerator.

References
5. J.C.Brown et al., ABCL-7102, Chalk River, 1980, p.51
6. I.M.Kapchinskij, V.I.Bobylev, Proc. 5th All-Union Conf. on Particle Accelerators, 1977, V.1, p.237
8. B.L.Toffe et al., ITEP-118, Moscow, 1977
9. E.W.Pottmeyer, Jr., Proc. 6th All-Union Conf. on Particle Accelerators, 1979, V.1, p.264
11. P.Grand et al., BNL-50838, 1979
17. V.A. Teplyakov, Proc. 5th All-Union Conf. on Particle Accelerators, 1977, V. 1, p. 298
20. A.I. Balabin, ITEP-54, Moscow, 1980
22. V.S. Skachkov, ITEP-76, Moscow, 1979

Fig. 1 a) Transverse sections of modulated electrodes, b) The schematic view of an electrode.

Fig. 2 The initial part of accelerator - RFQ structure.
Fig. 3 Electrodes of the final section of the RFQ structure.

Fig. 4 Magnetic field distribution along the quadrants of the RFQ structure. The upper curves - fields in quadrants 1 - 4 before tuning, the lower curves - after tuning.
PROPERTIES OF A $\pi$-MODE RFQ STRUCTURE AND RECENT EXPERIMENTAL RESULTS

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Summary

For low frequency operation of RFQ linacs a new rf scheme has been developed. The linac consists of a chain of resonators, electrically excited in the $\pi$-mode, the fields being generated by four modulated rods. The construction allows direct cooling of the electrodes and therefore cw operation.

RF properties like $R_p$ values, resonant frequencies, field distributions for systems with 4 and with 12 electrodes are presented.

With a coaxial $\lambda/4$ resonator sparking tests have been done at different pulse lengths and duty cycles. Finally the status of our RFQ proton model, which uses the split coaxial structure as resonant cavity, is reported.

$\lambda/2$ RFQ Structure

The RFQ structure, which has been developed in Los Alamos, is very well suited for various applications like Pigm, FNII, proton injectors into storage rings and ion accelerators. This design using the four chamber H-cavities is especially favourable for all cases, in which relatively high frequencies can be used. For the acceleration of heavy ions the corresponding RFQ structure must be run at low frequencies. Such a low frequency RFQ resonator is the coupled $\lambda/2$ structure, which has the advantage of small dimensions, simple construction, good rf properties with high duty cycle. Each pair of quadrupole electrodes consists of two copper rods connected to two radial stems forming a $\lambda/2$ oscillator. A front view of such a structure is shown in fig. 1. Two such resonators are placed at an angle of $90^\circ$ and excited in $\pi$-mode produce the RFQ field. For the electrodes a design using circular rods with coni-

* Work supported by the Bundesministerium für Forschung und Technologie

Fig. 1 Front view of the RFQ $\lambda/2$ structure

Fig. 2 shows the voltage distribution along the quadrupole electrodes for a single $\lambda/2$ and $2\lambda/2$ resonator in the $\pi$- and $\pi\pi$- mode respectively in the $\pi\pi$-mode. While the $\pi\pi$-mode shows the expected linear dependence on the distance from the middle stem, for both other modes a nearly flat distribution could be measured. Measurements have been done by bead perturbation method using a drift tube arrangement displacable on the electrodes. This well known method can be applied despite strongly varying fields in a narrow electrode system.

The $R_p$ value, which is defined as the square of the electrode voltage divided by the rf power, was determined as a function of the electrode length (fig. 3). Although the $Q$ value is only about 2000, the efficiency is very good. The resonator of our proton linac
e.g. has a $R_p$ value of 75 kΩ, the design value of 25 kV electrode voltage can be achieved with only 10 kW. The low Q value facilitates rf control and cooling problems.

Fig. 4 Resonance frequencies of $2\lambda/2$ quadrupole resonators as function of the electrode length

Fig. 4 shows the resonance frequencies for two coupled $\lambda/2$ RFQ resonators as function of electrode length. The lowest frequency always belongs to the $\pi$-mode. The eigenfrequencies of the $\pi$-mode, for which the voltage has a node in the middle of the structure (s. fig. 2, lower curve), and the $0\pi$- and $00\pi$-mode, for which the four electrodes have the same potential, are more than 100 MHz higher. This mode separation indicates the large tolerances with respect to rf properties. The length of both coupled resonators can be varied as much as 20% without a significant change in field distribution. Several $\lambda/2$ RFQ high power resonators have been built and operated successfully up to 72 kW corresponding to voltages between the electrodes of up to 97 kV (duty cycle 1-25%). For lower frequencies a RFQ resonator using the $\lambda/2$ principle has also been built, consisting of twelve unmodulated rods (length 1300 mm, diameter 13 mm) forming an array of 5 independent RFQ channels (fig. 5). With

![Diagram](image)

Fig. 5 Front view of twelve electrode RFQ

this high capacitive load a resonance frequency of 28 MHz was measured (tank diameter 35 cm, length 130 cm). The $R_p$ value is 30 kΩ, Q value $Q_0 = 1000$. For an electrode voltage of 50 kV an rf power of 84 kW is needed. In spite of very long electrodes the voltage is almost constant being only 3% greater in the middle of the resonator than near the radial stems. This array allows simultaneous acceleration of several beams, which might be important for the first part of a fusion accelerator; furthermore the funneling may be easier. Similar principles of funneling are discussed at Los Alamos.

Sparking Experiments

As discussed in 3, the design and the capabilities of RFQ structures depend strongly on the maximum achievable field strengths. Therefore our sparking experiments have been continued. With the $\lambda/4$ coaxial resonator ($R = 610$ kΩ, gap width 1 cm, 108 MHz) voltages up to 350 kV can be produced. Fig. 6 shows the breakdown voltage as a function of the duty cycle and pulse length.
variation by a factor of 10 shows only a little effect. For a duty cycle of more than 5% the breakdown voltage stays nearly constant. Varying the pulse width at constant duty cycles the steep increase in breakdown voltages for pulse widths smaller than 0.3 msec should be remarked. The measured values are by a factor of 2 to 3 higher than the Kilpatrick limit. Experiments with a λ/2 RFQ at 108 MHz have been made. Results of sparking tests are shown in Fig. 7. The maximum voltage between the electrodes has been 97 kV corresponding to a surface field of 26.2 MV/m.

Status of the Proton Model

At the 81 Washington conference we have presented the general properties of the split coaxial RFQ structure and the layout of the proton model. In the meantime several improvements have been made on the proton model: major parts of the injection system were modified, RFQ sections 2 and 3 were added and are running satisfactorily. The beam current was increased from 10 nA to 5 µA behind the third section. The measured (normalized) emittances behind sections 2 and 3 range from 0.1 to 0.4 mm mrad.

Fig. 9 shows calculated and measured spectra behind sections 1, 2 and 3. The proton currents had to be normalized due to different analysing methods. The calculations were done for a dc beam (Δφ = 3600°) and an energy spread of 2% corresponding to the width of the calibration peak. The current distribution over the calibration peak was used to weight the number of particles per energy deviation of the calculated spectra.

Fig. 10 shows theoretical and experimental beam currents behind the 2nd section as function of the rf voltage. The current increases with the transversal acceptance due to lower phase shifts and the axial capture efficiency. For the future this offers a possibility to study space charge effects at high tune depressions (cosω2 can experimentally be varied between 1 and 0). Fig. 11 shows the measured energy spectra behind section 3. The transmitted current again rises steeply towards higher electrode voltages. The 2-3 mA beam extracted from the source contains 35% H+, 50% H2 and 15% H3 with a proton current behind the bending magnet of roughly 300 µA. This current is already sufficiently high to observe space charge effects (116m predicted: 0.5-1 mA), but the beam emittance is still much larger than the RFQ acceptance. Consequently the source extraction system has to be modified to achieve a higher brilliance.

Computations have been done at the Hochschulrechenzentrum.

References

4. P. Junior et al., this conference
SUPERFISH

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Summary

The computer code SUPERFISH was developed to calculate various parameters associated with rf fields in axially symmetrical cavities of arbitrary shapes. The development of the code has been well described. Since the introduction of the code in 1976, it has been in continuous use at Los Alamos National Laboratory. Over the intervening years there have been numerous utility improvements, and several technical additions to the program. This paper describes these modifications and additions, and reviews the basic capabilities of SUPERFISH.

What SUPERFISH Is

SUPERFISH is a computer code that determines the electromagnetic resonance frequency of, and evaluates the electromagnetic fields in, rf cavities with axial symmetry. Recently an intensive effort has been undertaken at Los Alamos to develop a computer code that will extend the capabilities of SUPERFISH to azimuthally asymmetric modes. This code is called ULTRAFISH and is described elsewhere in this conference.

There have been a number of computer codes that deal with the rf cavity problem. These early programs used an overrelaxation method to solve a set of homogeneous linear-field equations. For large diameter-to-length ratios, or for modes other than the fundamental mode, the convergence rate is small; or in some cases, the solution may not converge at all with typical methods for overrelaxation-factor optimization. SUPERFISH, on the other hand, uses a direct, noniterative method to solve a set of inhomogeneous field equations.

The details of the method used are well described and only a brief summary will be presented here. The fields, inside the structure, are described by the azimuthal magnetic-field strength, $H$. Maxwell's equations are represented by one difference equation for $H$ at each mesh point on the surface of, and inside, the structure. One of the mesh points is arbitrarily chosen and $H$ is set equal to 1. The difference equation for that point is thus eliminated. The resulting set of inhomogeneous linear equations is solved with a noniterative Gaussian block-elimination and back-substitution process.

At the point previously chosen, $H$ is calculated from the known values of $H$ at the neighboring mesh points. In general, this value of $H$ will be different from the original value of 1. This difference can be interpreted as the current $I$ of circulating magnetic charges necessary to drive the cavity to the field value of 1 at the chosen point. The coefficients of the original set of difference equations depend on frequency. As a result, $I$ also depends on frequency and on the coefficient $k$. Resonance is characterized when $I = 0$.

To find resonance, $I$ is not used directly, but the normalized quantity, $D = 2 \pi R_1 k I / H^2 d\nu$, is used. The quantity $R_1$ is the distance of the arbitrarily chosen point from the axis, and $k$ is the angular frequency divided by $c$. This technique simplifies the root-finding procedure because it can be shown that, at every resonance, $D = 0$ and $dV/dk^2 = -1$. Between every two resonances, $D = 0$ once and $dV/dk^2 = +1$.

Using SUPERFISH

SUPERFISH is the major program in a series of four programs with pre- and postprocessors that enable the user to input data in a reasonable fashion and to get answers in a usable format. The initial program is AUTOMESH. AUTOMESH understands the physical dimensions of the cavity and generates the cavity outline. The program can draw straight lines between points and can draw arcs that are tangent to straight lines. An AUTOMESH-generated plot of one quadrant of a drift-tube linac cavity is shown in Fig. 1.

AUTOMESH generates a file that is read by the next program in the series, LATTICE. This file fills the cavity outline with a series of interconnected triangles, as shown in Fig. 2. By proper choice of input data, it is possible in AUTOMESH to specify the size of the triangle and to have several areas of different mesh density within the cavity. This feature has obvious impact on computation time. It also enables the user to do the initial calculations with a gross matrix and then to complete them with a more exact approximation.

A recent addition to LATTICE is the ability to put materials into the cavity with relative permeability and relative permittivity other than 1. This new capability allows standard cavity values (resonant frequency, power dissipation, etc.) to be calculated. Test cases have been run, but the capability has not been tested extensively.

LATTICE generates a file that can be fed into the program SUPERFISH. From this file, SUPERFISH calculates the various cavity parameters by the methods previously described. A typical output from SUPERFISH is shown in Fig. 3.

Although several output options are available, the summary shown in Fig. 3 has proved to be the most useful. Several points are noteworthy:

- The power dissipated, energy stored, etc., all are normalized to an electric field of 1 MeV/m. All SUPERFISH numbers must be adjusted to the operational level of the resonant system.

*Work supported by the US Department of Energy.
Fig. 1. One quadrant drift-tube-linac cavity with electric fields, as drawn by AUTOMESH.

Fig. 2. Mesh configuration around drift-tube-linac nose, as drawn by LATTICE.

• Typically, one quadrant of the cavity is drawn because of axial symmetry. Hence, the calculated power dissipation must be multiplied by 2.
• The cavity losses are calculated assuming copper in all cavity walls.
• Experience has shown that good rf assembly practices can achieve only about 85% of the theoretical value of Q calculated by SUPERFISH.
• SUPERFISH divides the cavity boundary into segments and calculates the power dissipation in each segment, which is very useful when determining water cooling, temperature gradients, etc.; the length and number of segments of the cavity boundary can be specified.

Unconventional Uses

SUPERFISH, in its present form, also can be used with an arbitrary cross section in the x-y plane assuming infinite length in the orthogonal z direction. A radio frequency quadrupole (RFQ) for example, with a cross section as shown in Fig. 4, does not lend itself to cylindrical coordinates; therefore modifications in the program have been made to enable the user to specify rectangular coordinates. In effect, these modifications make the cavity straight and infinitely long. Note that in cases such as RFQs, where the cavity's resonant frequency is critically dependent on the spacing between vane tips, extreme care should be taken in selection of mesh size and beginning point of the mesh construction.

Another special case is that of a cavity partially loaded with dielectric material. In this case, it is
assumed that the material is isotropic; that is, the permittivity and permeability is independent of the field orientation in the material. It is possible to specify the region that contains the dielectric and to have several regions, each containing a material with a different dielectric constant.

### Conclusion

The computer code SUPERFISH has been used for several years at Los Alamos. Improvements in the utility and capability of the code have been made, the most notable of which is the ability to calculate the cavity parameters with a dielectric or ferrite material in the cavity, and the ability to set the problem up in \( x - y \) coordinates. The problem of adding azimuthally asymmetric mode capability has recently been completed and is described elsewhere.\

It is anticipated that work will continue on updating and modifying SUPERFISH. Among the planned activities is further test-case work on ULTRAFISH, modification of the field-normalization routine, extensive testing of the dielectric capability, and updating of the user's manual. Baseline SUPERFISH, on magnetic tape suitable for running on either VAX or a large computer Fortran-based operating system such as LTSS can be obtained from Los Alamos National Laboratory. Further details may be obtained from the authors.

### Acknowledgments

The authors would like to acknowledge the contributions of Dr. R. L. Gluckstern, University of Maryland, to this work. The Los Alamos authors, from the point of view of code users, have intended this article to serve as a user status report and outline of the technical contributions, made by others, that constitute the present form of this valuable tool.

### References


ULTRAFISH -- GENERALIZATION OF SUPERFISH TO m > 1*

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Summary
The present version of the SUPERFISH program computes fundamental and higher order resonant frequencies and corresponding fields of azimuthally symmetric TE and TM modes (m=0) in an electromagnetic cavity which is a figure of revolution about a longitudinal axis. We have developed the program ULTRAFISH which computes the resonant frequencies and fields in such a cavity for azimuthally symmetric modes (cos mφ with m > 1). These modes no longer can be characterized as TE and TM and lead to simultaneous equations involving two field components. These are taken for convenience to be rEφ and rHφ, in terms of which all four other field components are expressed. Several different formulations for solving the equations are being investigated. The resulting matrix consists of tridiagonal blocks of twice the dimension of SUPERFISH, but the matrix inversion and root finding procedures are the same. Care must be taken to remove the spurious singularity at ω/2πc = m which appears in the formulation. We have also generalized SUPERFISH to obtain resonant frequencies of two dimensional cavities of arbitrary cross section. In addition, we have generalized SUPERFISH and ULTRAFISH to include regions of different permeability and dielectric constant. The programs have been tested on cavity shapes with analytically obtainable resonant frequencies.

I. Introduction
With the advent of high speed computing, techniques were developed for solving partial differential equations numerically by approximating the equations by difference equations involving the values of the function at mesh points. Iteration schemes were then used to solve these difference equations by "relaxation." For the calculation of azimuthally symmetric modes in azimuthally symmetric electromagnetic cavities, various codes were developed and applied to the design of cavities for linear accelerator sections.1

The next major step in the numerical approach to the cavity mode problem is described in SUPERFISH.2 Specifically, this program used the more versatile triangular mesh and directly inverted the matrix using the driving point and root finder technique described in Section D.

The present paper describes the extension of the SUPERFISH program in the following ways:

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1) Two dimensional cavities of arbitrary cross section.
2) Regions of different permeability, μ, and permittivity, ε.
3) Azimuthally asymmetric modes in azimuthally symmetric cavities.

We have designated the new program as ULTRAFISH.

The first two modifications are relatively simple and will only be described briefly. The bulk of the paper addresses the generalization to azimuthally asymmetric modes.

II. Two Dimensions
The existing SUPERFISH program is easily extended to two dimensions by letting r → ∞ in all relevant terms. In the operating program the result is the elimination of one of the two terms in each of the coefficients in the difference equations. The modified program has been tested in cavities in the shape of a 45°, 45° right triangle and found to agree with the known analytic results for the frequencies and fields.

III. Regions of Different Permeability and Permittivity
The existing SUPERFISH program is easily extended to include regions of different ε and μ. The mesh must be drawn so that the border between regions of different ε and μ coincides with mesh lines, in which case the coefficients can be identified as having terms from the individual triangles. Thus, the ε and μ can be introduced as factors in Maxwell's equations corresponding to their values in each triangle of the mesh. The modified program has been tested in cylindrical cavities with two different radial regions of ε and μ, and with two different axial regions of ε and μ. In each case the numerical results agreed with the known analytic results for the frequencies and fields.

IV. Azimuthally Asymmetric Modes
A. Field Components -- Maxwell's Equations
We shall assume that Eφ, Eρ, Hρ all contain the factor cos mφ that Hz, Hφ, Eφ all contain the factor sin mφ. We further assume that all electric field components have a factor e−iωt, and that all magnetic field components contain the factor iε0/μ0 e−iωt.

As a result, Maxwell's equations for the cylindrical components can be written as

\[ \begin{align*}
\frac{dE_\phi}{d\rho} + \frac{m\rho E_\phi}{\rho} &= -\frac{\partial H_\phi}{\partial z}, \\
\frac{dE_\rho}{d\rho} + \frac{m\rho E_\rho}{\rho} &= -\frac{\partial H_\rho}{\partial z} \\
\frac{dH_\phi}{dz} + \frac{m\rho H_\phi}{\rho} &= -\frac{1}{\rho} \frac{\partial (\rho E_\phi)}{\partial \phi},
\end{align*} \]

where

\[ \begin{align*}
\frac{m\rho^2 E_\phi}{\rho^2} &= \frac{\partial}{\partial \rho} \left( \frac{\rho^2}{\rho} \right) E_\phi, \\
\frac{m\rho^2 E_\rho}{\rho^2} &= \frac{\partial}{\partial \rho} \left( \frac{\rho^2}{\rho} \right) E_\rho.
\end{align*} \]

As a result, Maxwell's equations for the cylindrical components can be written as

\[ \begin{align*}
k_0 H_\phi + \frac{m E_\phi}{\rho} &= \frac{\partial H_\phi}{\partial z}, \\
k_0 E_\rho + \frac{m H_\rho}{\rho} &= \frac{\partial E_\rho}{\partial z},
\end{align*} \]

where

\[ \begin{align*}
k_0 + \frac{m}{\rho} &= \frac{\partial}{\partial \rho} \left( \frac{\rho}{\rho} \right), \\
k_0 + \frac{m}{\rho} &= \frac{\partial}{\partial \rho} \left( \frac{\rho}{\rho} \right).
\end{align*} \]

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where \( u \) and \( \varepsilon \) are the ratio of the permeability and permittivity to that of free space. It is well known that the TE, TM designation of wave guide or cavity solutions applies to very special geometries, and that with azimuthally asymmetric modes one finds it necessary to use a combination of TE and TM modes, that is all six cylindrical components at the same time. This leads to the requirement that two functions must be specified at all mesh points in order to determine all field components. For reasons of simplicity, we shall use the two functions

\[
f(r,z) = r E_\phi (r,z) \\
g(r,z) = r H_\phi (r,z)
\]

This choice of variables also guarantees \( f = g = 0 \) for \( r = 0 \), as is the case for the choice of \( E_\phi, H_\phi \) in SUPERFISH \((m=0)\). These functions are continuous in the cavity, even if \( \varepsilon \) and \( u \) vary with position. Moreover, they satisfy the boundary conditions

- \( f = 0, \ \frac{\partial g}{\partial n} = 0 \) on a metallic (electric) boundary
- \( g = 0, \ \frac{\partial f}{\partial n} = 0 \) on a "magnetic" boundary

We now can solve Equation (1) for all field components in terms of \( f \) and \( g \) \((E_\phi \text{ and } H_\phi)\). The result is

\[
E_z = \frac{k_0 \omega \varepsilon \frac{\partial g}{\partial z} + m \frac{\partial f}{\partial z}}{k_0^2 \varepsilon_0^2 \mu_0 m^2} \\
E_r = \frac{-m \frac{\partial f}{\partial r} - k_0 \omega \varepsilon \frac{\partial g}{\partial z}}{2 k_0^2 \varepsilon_0 \mu_0 m^2} \\
H_z = \frac{k_0 \mu \frac{\partial f}{\partial r} - m \frac{\partial g}{\partial z}}{2 k_0^2 \varepsilon_0 \mu_0 m^2} \\
H_r = \frac{-m \frac{\partial g}{\partial r} - k_0 \mu \frac{\partial f}{\partial z}}{2 k_0^2 \varepsilon_0 \mu_0 m^2}
\]

where \( k_0^2 = \omega^2 \mu_0 \varepsilon_0 \). It appears that we have found a singularity at \( r^2 = z^2 = m^2/k_0^2 \mu_0 \). However, since the fields are finite, the singularity must be spurious, and the numerators in (6) and (7) will vanish identically at \( r = 0 \). This poses a numerical obstacle however, since in our mesh calculation, the values of \( f \) and \( g \) are not exact, and the cancellation may not be precise. Various smoothing techniques must be used in the triangles close to \( r = 0 \).

B. Difference Equations

We shall obtain two difference equations for \( f \) and \( g \) by integrating Equations (2) and (3) over the dodecagon surrounding each point, as constructed from the triangular mesh in SUPERFISH. Specifically, there are six triangles surrounding each mesh point. The dodecagon connects the centroids of these six triangles alternately to the midpoints of the sides of the triangles which form the spokes of the hexagon, as shown in Figure 1.

![Fig. 1 Triangular mesh and corresponding dodecagon region of integration.](image)

Using Stokes Law, we obtain

\[
k_o \oint \frac{dr}{r} dz \ v = \oint (H_r dr + H_z dz)
\]

\[
k_o \oint \frac{dr}{r} dz \ u = \oint (E_r dr + E_z dz)
\]

where the left sides are integrals over the area of the dodecagon, and where the right sides are line integrals over the perimeter of the dodecagon.

Using Equations (6) and (7), we write

\[
k_o J_f = k_o L_f - m J_g
\]

\[
k_o J_g = k_o L_g + m J_f
\]

where

\[
J_f = \oint \frac{dr}{r} dz \ v
\]

\[
J_g = \oint \frac{dr}{r} dz \ u
\]

\[
L_f = \oint \left( \frac{m \frac{\partial g}{\partial z} - m \frac{\partial f}{\partial z}}{k_0^2 \varepsilon_0^2 \mu_0 m^2} \right)
\]

\[
L_g = \oint \left( \frac{-m \frac{\partial f}{\partial r} - m \frac{\partial g}{\partial z}}{k_0^2 \varepsilon_0 \mu_0 m^2} \right)
\]

After extensive algebraic manipulation one obtains

\[ K_f = \int \frac{\rho_f \, dr + \phi_f \, dz}{k_0^2 u_e - m^2} \]

\[ K_g = \int \frac{\rho_g \, dr + \phi_g \, dz}{k_0^2 u_e - m^2} \]

(15)

The quantities \( J_f \) and \( J_g \) are obtained by replacing \( f \) by \( g \) and \( \epsilon \) by \( u \). Here \( A_n^e \) and \( \epsilon_n \) are the area and permittivity of triangle \( n \) in Figure 1, \( f_n \) is the value of \( f \) at the vertex \( N \) (Roman numerals), and \( f_0 \) is the value of \( f \) at the "hub" of the hexagon. The parameters \( a_{ij}^k \) are defined as

\[ a_{ij}^k = a_{ji}^k = \frac{r_{ij}}{(r_i - r_j)(r_i - r_k)} + \frac{r_{kj}}{(r_i - r_k)(r_j - r_k)} \]

(17)

with

\[ \sigma_{ij} = \sigma_{ji} = \frac{1}{r_{ij} - r_k} \ln \frac{r_{ij}}{r_k} \]

(18)

In these expressions \( r_{ij} \) is the value of the radial coordinate at the dodecagon vertex, \( i \), as shown in Figure 1. Clearly all running indices are modulus 12, that is

\[ r_{13} = r_{1}, \ r_{14} = r_{2}, \ \text{etc.} \]

(19)

\[ r_{-1} = r_{11}, \ r_{-2} = r_{10}, \ \text{etc.} \]

The quantities \( K_f \) and \( K_g \) are given by

\[ 36J_f = \sum_{N=n}^{N=n} f_N [\epsilon_{n+1}^e A_{n+1}^e (3a_{n+1}^{o,n+1} + 2a_{n+1}^{o,n+1} + 2a_{n+1}^{o,n+1})] \]

\[ + \epsilon_{n-1}^e A_{n-1}^e (3a_{n-1}^{o,n-1} + 2a_{n-1}^{o,n-1} + 2a_{n-1}^{o,n-1})] \]

\[ + f_0 \sum_{n=1,n \text{ odd}}^{N=n} \epsilon_n A_n (3a_n^{o,n} + 2a_n^{o,n} + 2a_n^{o,n} - 6a_n^{o,n}) \]

\[ + 3a_n^{o,n} + 2a_n^{o,n} + 2a_n^{o,n} \]

(16)

where \( J_g \) is obtained by replacing \( f \) by \( g \) and \( \epsilon \) by \( u \).

Equations (10) and (11), supplemented by the expressions for \( J, K, L \) in Equations (16), (20) and (23), are then the coupled difference equations for \( f \) and \( g \) at the mesh points.

C. Boundary Conditions

The boundary conditions on a metallic (electric) surface are clearly that both tangential components of \( \vec{E} \) must vanish. This clearly implies

\[ f = 0 \] , "electric" boundary

(25)

\[ E_z \, dz + E_r \, dr = 0 \] , "electric" boundary

(26)

where \( dz \) and \( dr \) are taken along the boundary. From Equation (6) one can immediately deduce that Equation (26) is equivalent to

\[ \frac{\partial \phi}{\partial n} = 0 \] , "electric" boundary

(27)

where the derivative is in a direction normal to the boundary in the \( r,z \) plane.

Equation (25) can be directly applied as a boundary condition for each mesh point along the boundary. However, as an alternate the Equation
(27), we shall use Equation (9) or (11) over that portion of the boundary dodecagon which lies within the active region. Operational this corresponds to setting \( \varepsilon = 0 \) and \( f = 0 \) in triangles outside the active region.

For "magnetic" boundaries, the corresponding boundary equations are obtained by interchanging \( \varepsilon \), \( f \) and \( u, g \).

Both \( f \) and \( g \) are set equal to zero at the mesh points along the axis of rotation \( (r = 0) \).

D. Driving Point and Root Finder

As in all eigenvalue problems the solution of the homogeneous difference equations corresponding to Equations (10) and (11) requires obtaining the correct frequency. We shall proceed as in SUPERFISH to assume that either Equation (10) or (11) is driven by an external current element at one mesh point, and then search for the value of the frequency at which the left side of the corresponding difference equation at that point vanishes. In ULTRAFISH it is essential that we allow for such a driving point in either Equation (10) or (11). In this way we will be able to include modes which have either \( E \), or \( H \) identically zero through the cavity for some special geometries.

The root finder has also been taken from the successful experience in SUPERFISH. Specifically, we define

\[
D(k^2) = -\frac{k g_0 I_d u_d}{\int_{r}^{d} \frac{r}{r} [g r^2 + (H_z^2 + H_r^2 + H_p^2)]}
\]  

(28)

where \( I_d \) is the equivalent driving current at mesh point \( d \), given by

\[
I_d = -m k g + k_0 (L_E - J_p) \quad \text{(at mesh point d)}
\]  

(29)

It can be shown, using the method of SUPERFISH, that

\[
\frac{d}{dk^2} D(k^2) = -1 \quad \text{at resonance.}
\]  

(30)

so that a rapidly convergent search method can be used to find the eigenfrequency.

Once again, it is necessary to use the expression corresponding to Equation (30) with \( g \) replaced by \( \varepsilon \) and \( u \) by \( E \) in order to handle special modes for which \( g \) may be identically zero.

E. Matrix Inversion

The matrix inversion process is similar to that used in SUPERFISH, except that the blocks now have twice as many columns and twice as many rows. And the initial matrix is still mostly sparse with the non-vanishing elements concentrated around the diagonals. Because of the increased matrix size the inversion time for a given mesh size is approximately 8 times that for SUPERFISH.

F. Spurious Singularity at \( r = \hat{r} \)

As mentioned in Section TVA, there is a spurious singularity in the expressions for \( E_z, E_r \), \( H_z, H_r \) at \( r = \hat{r} \). This makes its appearance in \( K_E, K_G \), \( L_E, L_G \), where \( Q_{ij}^1 \) and \( P_{ij}^1 \) become singular in Equations (21) and (24) whenever

\[
r_1 = \frac{m}{k} = \hat{r}
\]

For this reason, the dodecagon vertices must avoid direct cancellation of \( r_1 \) and \( \hat{r} \), which may be difficult to guarantee as \( k \) changes in the eigenvalue search. We are presently exploring the best way of selecting the mesh points near \( \hat{r} \) in order to minimize the effect of this singular behavior.

The spurious singularity also enters into the calculation of \( H_z, H_r \) in the normalization integral in the denominator of \( D(k^2) \) in Equation (28). Smoothing techniques are required in order to avoid the singular behavior at \( r = \hat{r} \).

V. Test Cases

The program ULTRAFISH has been run on a cylindrical cavity in order to locate several of the TE and TM modes. We have chosen a cavity of radius 10cm and length 2.5\( \pi \)cm = 7.85398cm and have used a triangular lattice with approximately 600 mesh points. We have located the following modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>ULTRAFISH Freq.</th>
<th>Analytic Freq.</th>
<th>( \hat{r}/a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE111</td>
<td>2102.1 MHz</td>
<td>2101.0 MHz</td>
<td>.23</td>
</tr>
<tr>
<td>TE211</td>
<td>2409.1 MHz</td>
<td>2401.3 MHz</td>
<td>.20</td>
</tr>
<tr>
<td>TM122</td>
<td>5105.9 MHz</td>
<td>5076.9 MHz</td>
<td>.19</td>
</tr>
<tr>
<td>TM010</td>
<td>1147.49 MHz</td>
<td>1147.43 MHz</td>
<td>-</td>
</tr>
</tbody>
</table>

Plots of constant \( f = r E_\phi \) and \( g = r H_\phi \) are shown for the TE111, TE211, TM121 modes in Figures 2a, 2b, 2c respectively. These plots show no visible discontinuity near the spurious singularity at

\[
\hat{r} = \frac{m}{k} = \frac{mc}{2\pi fa}
\]

It should be noted that the program also works for the azimuthally symmetric modes such as TM010. For comparison, SUPERFISH predicts a resonant frequency 1147.41 MHz.

The program has also been tested on a spherical cavity with about 500 mesh points in order to find the mode designated as TE111 (no radical electric field). In this case the frequency found by ULTRAFISH for a radius of 10cm is 2141.8 MHz while the correct frequency is 2142.0 MHz. The plots of \( f = \text{const} \) and \( g = \text{const} \) are shown in Figure 3 and have the expected behavior. Further tests are being pursued in order to determine the accuracy of the frequency and field determinations as a function of mesh size.

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VI. Possible Program Improvements

Many persons have suggested possible improvements in the SUPERFISH and ULTRAFISH programs. Clearly, one can improve frequency and field accuracy by using more mesh points, but this can lead to unreasonable storage and time requirements for the computation. Recent interest in Finite Element Methods also suggests using quadratic behavior in the triangular panels as a means of improving accuracy. This of course leads to more complicated difference equations for the field values, but may be the most practical way to achieve greater accuracy.

Other possible improvements might be obtained by the following:

1) Modify the analysis and procedure in such a way that the spurious singularities are removed analytically. (Note: One can have several values of if one has regions of different e and y.)

2) Use as the functions $r^m f$ and $r^m g$ for $m \neq 1$ in order to obtain greater accuracy for modes with high $m$.

3) Use $r^2$ and $z$ as the variables in a radial plane. This simplifies some of the integrals in the coefficients $J$, $K$, $L$, and approximates more accurately the field dependence near $r=0$.

4) Multiply Equations (2) and (3) by a suitably selected weighting function before integration over the dodecagon. This technique is one of the options discussed in the Finite Element Method and may lead to more accurate fields and frequencies.

5) Use a variational formulation for the eigen-frequency and smooth the linear panel behavior after the matrix inversion but before the calculation of the eigen-frequency. This should lead to more accurate frequency determinations.

There are many other possibilities which have been raised and which also deserve further consideration.

VII. Conclusion

We have developed the program ULTRAFISH to calculate azimuthally asymmetric modes in an electromagnetic cavity which is a figure of revolution about a longitudinal axis. This represents a generalization of the program SUPERFISH for azimuthally symmetric modes, and requires determining the values of two field components ($rE$ and $rH$) at mesh points from coupled difference equations and boundary conditions. The program has been successfully tested for various TE and TM modes in cylindrical and spherical cavities.

The program also permits including regions of different $\mu$ and $\epsilon$. In addition, the program can be used for $m=0$, to solve the 2-D problem with an arbitrarily shaped boundary.

VIII. Acknowledgment

We would like to express our appreciation to Robert A. Jameson for encouragement, moral support, and patience.

Fig. 2a Lines of constant $f$ and $g$ for a TE$_{111}$ mode in a cylindrical cavity.

Fig. 2b Lines of constant $f$ and $g$ for a TE$_{211}$ mode in a cylindrical cavity.

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Discussion

The asymmetries seen in the present spherical test case will be studied further, for example by considering adaptive meshing. We could force symmetry by computing only a quarter of the sphere. Also, a production calculation would use many more mesh points than we used in the test case.

QUESTION: How were these calculations done in the good old days?

ANSWER: (Gluckstern): Well, if Lloyd Smith were here, he could probably comment more. I think actually he did most of those calculations in the MIT himself and I think he did most of them with a hand calculator; I'm not even sure it was electric. But it was a solution of the Bessel functions given boundary conditions and there were approximations made, but the big difference was that the people who were doing the calculating worked very closely with a whole host of people who were not programmers, but were modelers and who built copper models of the half cells that were calculated. They put in conductors in the places where there would be perturbations due to loops or to stems, or what have you, and made measurements and then corrected the calculations by an iterative process until there was a series of cells calculated for a linac and verified by a model. Then, they went ahead and built it.

(Livdahl): I can add a little bit to that. The method that was used for the first analytic calculations that I'm familiar with was developed by Walkinshaw and a number of others at Harwell. It corresponded to assuming a drift-tube geometry that was cylindrical, then matching the fields at the outer radius of the drift tube. In the gap, the first assumption was that you had a TM_{122} mode and in the outer region you also allowed for a sum of terms with different Z dependence. You matched the electric field at this boundary; that allowed you to express each of the terms in the outer region's sum in terms of a single parameter that is the electric field magnitude on the axis in the gap. Then you calculated the magnetic field and equated the average magnetic field in the gap at the boundary and that gave a single transcendental equation for the frequency that you could solve by hand computation. Christofolous also contributed to the progress in that field by starting to press for drift tubes of stranger shapes than just the usual with the rounded corners, because he was able to demonstrate that those would have a higher shunt impedance, and would be more efficient. I think that gave the impetus to the next generation of computer programs, which were the MESSYMESH iterative procedures that were developed at MURA, and the LALA iterative programs that were developed at Los Alamos.
BEAM DYNAMICS IN HEAVY ION INDUCTION LINACS*

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Summary

Interest in the use of an induction linac to accelerate heavy ions for the purpose of providing the energy required to initiate an inertially confined fusion reaction has stimulated a theoretical effort to investigate various beam dynamical effects associated with high intensity heavy ion beams. This paper presents a summary of the work that has been done so far; transverse, longitudinal and coupled longitudinal transverse effects are discussed.

Introduction

An inertial fusion power plant would require the delivery of some megajoules of energy to a target a few millimeters in diameter in a time measured in tens of nano-seconds. These numbers imply particle energies of 5-10 GeV and currents of ten kilo-amperes for atomic weights greater than 200. While it might be possible to achieve such performance with conventional r.f. linacs and a system of storage rings, an induction linac is also attractive because it provides good electrical efficiency at high current and would avoid the complex beam handling necessitated by the use of a large number of accumulator rings. However, in order to capitalize on the potential efficiency the current must be kept as high as possible throughout the accelerator without degradation in either transverse or longitudinal beam quality as determined by the need to focus the beam, or beams, on a small target several meters in from a reactor wall. The central question in beam dynamics is thus the effect of high intensity on momentum spread and emittance.

Induction linacs have been used to accelerate electrons for some time; recently, with currents up to 10 kiloamperes. That application is simpler to analyze than for heavy ions since the electrons are soon ultra-relativistic; space charge effects are relatively small and differential longitudinal motion negligible. A better comparison is with an r.f. ion linac; the tune depressions contemplated are similar to those encountered at the front end of an r.f. linac but must be maintained during the entire length of the machine, the instantaneous current being increased by suitably ramping the voltage on the accelerating modules. There is nothing analogous to r.f. defocussing and a good match is more easily achieved at the front end, but neither is there an automatic phase stability, so that small positive and negative fields would be provided at the ends of the bunch to counteract longitudinal self-fields and thermal drifting.

Scaling Laws

It can be shown from the structure of Vlasov's equation that the electric current transported in a magnetic quadrupole channel is related to the r.m.s. emittance by an expression of the form:

\[ I = K_1 \left( \frac{A}{q} \right)^{1/3} B^{2/3} (\beta_Y)^{1/3} \epsilon^{2/3} \] (1)

and to the beam radius, a, by another expression

\[ I = K_2 (\beta_Y)^2 B a, \] (2)

where A and Z are atomic weight and ionization state and B is the quadrupole field strength at the beam edge. The constants \( K_1 \) and \( K_2 \) depend on details of the lattice, the phase space distribution function and the tune depression. As the tune goes to zero, \( K_1 \) approaches infinity but \( K_2 \) is finite; in that limit, equation(2) is the quadrupole analog of the Brillouin flow formula for solenoidal focusing.

Equation(1) was first given by Maschke2 with a value of \( K_1 \) corresponding to a tune depression of about a factor of two, a formula which became known as the Maschke limit. Because the two expressions are so different in functional form, there was early confusion concerning scaling, particularly since atomic weight and charge state are additional free parameters for this application. The confusion was largely laid to rest by Reiser3 in a paper which spelled out the reasons for the differences and presented a smooth approximation version which exhibited emittance and channel acceptance simultaneously:

\[ I = \frac{1}{2} I_0 (\beta_Y)^3 \sigma_0 \frac{\alpha}{\epsilon} \left[ 1 - \left( \frac{\epsilon}{\alpha} \right)^2 \right] ; \left( \frac{\epsilon}{\alpha} \right)^2 = 1 - \nu \] (3)

where \( I_0 = 3.1 \times 10^7 \) A/Z amperes, \( \sigma_0 \) is the channel acceptance and \( L \) is the lattice period. Even so, care is required in using these formulas because important practical parameters do not appear explicitly.

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Transverse Stability

In 1970 Gluckstern\(^6\) investigated the possible modes of a perturbed K-V beam, infinite in longitudinal extent with constant external restoring force. In connection with the study of induction linacs, a generalization to the case of quadrupole focusing was carried out\(^6\). Since the bunch in an induction linac is typically 10-20 meters long and 10 cm in radius, an infinite beam is a reasonable first approximation. In both models, one finds a great number of modes that become unstable and grow rapidly at sufficiently high intensity (or tune depression). The quadrupole analysis shows in addition the occurrence of “structure resonances”; that is, instabilities which occur at lower intensity when a mode frequency approaches a low order rational relation to the quadrupole period. A striking fact that has not been explained is that, as a function of tune depression, the thresholds and growth rates beyond threshold appear to be identical in the two models, to a precision beyond what one might expect from a smooth approximation to quadrupole focusing. Concurrent with the analytic quadrupole work, simulation programs were developed to attack the problem\(^6\). Early runs were in qualitative agreement with theory and further indicated that non-KV distributions were also unstable and that emittances grow by factors of two or three before saturating. In one run, a low-order structure resonance appeared in isolation from other unstable modes; a quantitative comparison with theory showed excellent agreement and lent credence to both theory and simulation.

On the basis of this work a criterion was established that maximum current could be transported by a quadrupole lattice with zero intensity phase advance less than 60° (to avoid the structure resonances) and a tune depressed to 24° (to avoid the intrinsic resonances). There is, however, a later development. According to linear theory, there is no growth in r.m.s. emittance and it was assumed that the observed growth in simulation work was a non-linear effect. Haber then discovered for a continuous solenoid, and Hofmann\(^7\) for a quadrupole array of 60° zero intensity phase advance, that a great rearrangement occurs in phase space (instability) but that the r.m.s. emittance does not change even for tune depressions as low as the simulation technique permitted reliable results. There now appears to be no limit on current if r.m.s. emittance is the sole criterion for hitting a target since \(\kappa_j\), in equation(1), becomes infinite. However, equation(2) indicates that the aperture must then increase also so that, for practical reasons, there is not much room for improvement over the 60°-24° criterion.

Hofmann\(^8\) has extended Gluckstern’s work to the case of unequal restoring forces and emittances in the two planes, leading to a further proliferation of modes and possible instabilities. These results, however, are of more interest to the question of equipartition and the ultimate stable distribution\(^9\) than to the performance of induction linacs.

Finally in the category of transverse stability, a calculation was made\(^10\) for the beam break-up mode, the coherent transverse instability which has been so bothersome to electron linac performance. The accelerating modules were represented for this purpose as a cavity with a single, low Q, mode. Because of the low Q and strong transverse focusing for coherent motion, the beam break-up mode does not present a problem for a heavy ion induction linac.

Longitudinal Stability

The single bunch in an induction linac differs from a bunch in an rf linac in several ways. It is very long compared to its diameter, rather than almost spherical. In order to exploit the maximum current criterion obtained from the considerations of the previous section, the instantaneous current should be constant along the bunch and in order to achieve maximum acceleration the voltage on the modules should be constant during the passage of the bunch except for a slight increase during passage to compress the bunch in time. The confining potential is a square well defined by the auxiliary modules which prevent the ends of the bunch from deteriorating. To first approximation, the ions see a d.c. field all the way from source to final energy — what, then, is the source and magnitude of momentum spread in the bunch? We believe it will be due to errors in timing and wave shape of the module voltage pulses — estimates indicate an average value of \(10^{-4}\) to \(10^{-3}\). At that level, individual particles would move from front to rear and back at most one or two times in several kilometers of acceleration. At the same time, the characteristic velocity of space charge waves for a perturbation in charge density is at least an order of magnitude larger than the thermal spread, so that a good approximation for stability analysis is to neglect energy spread altogether — a cold beam in plasma physics jargon.

The principal worry concerning longitudinal stability arises from the fact that if the module parameters are selected to give good electrical efficiency in transferring energy to the beam, then the beam sees a module as an L-C circuit with a resistive component of several hundred ohms,\(^11\) though there appear to be ways to modify the module circuitry to reduce the impedance. In the CERN PS, primarily, there has been observed a micro-wave instability; i.e. one at wavelengths short compared to bunch length which leads to a damaging increase in momentum spread but for which no satisfactory theoretical explanation existed. According to a semiepipirical criterion used by CERN, an induction linac bunch would be highly unstable and so an urgent need arose to understand the phenomenon, at least in the parameter range of interest. Kim\(^12\) has
made a perturbation analysis for a bunch in a square well potential and concludes that the system is stable for a monotonically decreasing momentum distribution. Channell et al. considered a parabolic density distribution with no momentum spread and find stability, provided that the resistive component is sufficiently small. An estimate of the convergence of their expansion procedure by Bisognano suggests that the e-folding distance for a density perturbation moving along the bunch must be small compared to the bunch length.

Computational work has been done by Neuffer using a code developed by Neil et al. and by Haber and Sternlieb using a modified NRL simulation code. These codes have been applied only to parabolic charge distributions, the more realistic model analyzed by Kim being more difficult to deal with computationally. The results appear to corroborate Bisognano's speculation; a ten percent density bump propagating from the center and growing more than one e-folding chews the bunch apart, starting from the disturbed end, while one with less growth causes some disturbance but then reflects and dies out. In a square bunch, the bump would reflect more quickly and, we hope, with less disruptive effect — clearly more work must be done.

In Haber's simulation work, various fascinating phenomena appeared, such as soliton formation — the Vlasov equation for a cold beam with dispersion at short space charge wavelengths in fact closely resembles the Korteweg-deVries equation but such effects probably do not occur in the parameter range of interest to the induction linac. Runs were made using the best impedance functions we could construct applied to two full scale Fusion driver designs that had been developed for cost and systems studies. The result was catastrophic for the earlier of the designs, but the later one easily passed the test.

Longitudinal-Transverse Coupling

There are several three dimensional effects which must be explored. The beam is visualized as occupying a large fraction of the available aperture; as a result there will be a significant variation with radius of longitudinal electric field, which must drop to zero at the conducting walls. At the ends of the bunch, the self-field pattern is complicated and it is not clear that the trimming voltages mentioned earlier are sufficient to control beam behavior at the ends. Finally, the matching lenses at the entrance of the accelerator would be adjusted to accommodate space charge repulsion in the body of the bunch, leaving the lower density ends mis-matched. Loss of the leading and trailing ions could be tolerated but a continuous erosion of the bunch from the ends inward could not.

Questions such as these present a formidable analytic problem. The tactic we have adopted is to develop simulation codes, first in r and z only and eventually, we hope, fully three dimensional. Hofman has an r-z code in operation and Haber expects to be in the same position in the near future.

There is another aspect of three-dimensional behavior which is amenable to an analytic treatment. Since the bunch is long compared to its diameter, the problem of stability resembles more closely the problem of stability of a coating beam in a high energy storage ring, which has been studied exhaustively over the years, than it resembles the problem of stability of an r.f. linac bunch. However, because of the strong tune depression, both transverse and longitudinal modes are of the order of the plasma frequency and the assumption used in storage ring theory that longitudinal and transverse effects can be treated separately is suspect.

In order to investigate the interaction of longitudinal and transverse modes, we have considered a beam infinite and uniform longitudinally, subject to a constant linear transverse focusing force and with a longitudinal velocity spread. There are two choices of distribution function in transverse phase space amenable to analytic treatment — circular counter-rotating orbits or a K-V distribution.

The circular orbit model is even less realistic than the K-V distribution but has the mathematical advantage of leading to a simple differential equation and a dispersion equation in closed form for fully three-dimensional modes. The principal result of this work was to show that for an arbitrary wall impedance the longitudinal unstable modes are suppressed more easily by a velocity spread than in a purely longitudinal treatment while transverse modes are little affected.

Analysis of the K-V case was restricted to axially symmetric perturbations but even then the mathematical treatment is exceedingly complicated, leading to a dispersion relation in the form of an infinite determinant. An approximate solution leads to the result that the familiar longitudinal mode, as treated in one dimension, is not significantly affected by the coupling nor are Gluckstern's transverse modes, with one perhaps significant exception; at a tune depression of about a factor of three one of his low order modes couples with a low order longitudinal mode, the coupled system being unstable for all greater tune depressions. The effects of wall impedance and velocity spread are currently being investigated.

The tentative conclusion of this work is that, at least for a beam of infinite length, it is still a good approximation to regard transverse and longitudinal effects as independent.
Experiments

The Heavy Ion Fusion program has chronically suffered from meager financial support and consequently we have no experimental information regarding beam dynamics. Although much work has been done with electron beams in the parameter range of interest, beam quality is of minor interest at best in the development of klystron tubes and other electronic devices and is scarcely mentioned in the available literature. This situation is due to change in the near future. An electron beam transport system using solenoids has been set up at the University of Maryland to investigate transverse phenomena and an electrostatic quadrupole array forty periods long to propagate a 20KV cesium beam is being set up at Lawrence Berkeley Laboratory for the same purpose. Both experiments are designed to cover a wide range of parameters, including extreme tune depressions and should provide valuable information not only for theory but, equally important, for the practical problem of maintaining a nearly Brillouin flow pattern for a long distance, a feat which has never been demonstrated.

References


18. A. Sternlieb, "The Resistive Wall Instability in a Uniform Beam; Simulations and Analytical Results", Lawrence Berkeley Laboratory, LBL-12878 (HIFAN-167), July 1981.

19. I. Haber, private communication.


21. I. Haber, private communication.
The transport line experiment will be located in the space where the Berkeley ERA induction linac was.

The pictures I showed are for K-V distributions. A number of other distributions have been tried; they are less sensitive than the K-V, but much the same results apply.

An oversimplified way to explain where the resistive impedance that can cause longitudinal instabilities comes from is to say that when the beam comes to a gap in the module, energy can primarily flow out. There isn't much time for it to flow back in before the beam is past, and therefore it looks like a resistance to the beam.
COMPUTER SIMULATION OF LONGITUDINAL-TRANSVERSE SPACE CHARGE EFFECTS IN BUNCHED BEAMS*

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Summary

A newly developed 2 1/2 D particle-in-cell code with r-z geometry has been applied to derive criteria for longitudinal-transverse emittance transfer in ellipsoidal bunched beam with strong space charge. The main result is that emittance transfer occurs only if \( \sigma_x/\sigma_y \) is near or above 1.5, in which case equilibrium is approached due to coherent instability. It is also shown that final bunch compression by an induction linac for Heavy Ion Fusion is as effective with a realistic distribution function leading to flat-top pulses at target as it is by simple envelope calculation.

I. Introduction

Early computer simulation of high current linac bunches has indicated the existence of longitudinal-transverse coupling and emittance transfer \(^{1,2}\). In recent analytic work space charge driven coherent instabilities have been made responsible for this coupling and thresholds have been presented for x-y geometry \(^3\). In view of the practical consequences of emittance transfer and "equipartitioning" emphasized in recent linac beam dynamics studies \(^4,5,6\), we have used a newly developed code to check the applicability of these thresholds to r-z geometry (section II). Since this code has been developed primarily to study beam dynamics of long intense bunches for Heavy Ion Fusion Drivers we are also reporting here about first results of simulation of final bunch compression by an induction linear accelerator (section III).

The simulation program advances particles in x, y, z and utilizes a fast Poisson solver (by Schumann and Sweet \(^7\)) on a mesh in r, z assuming a conducting radial cylindrical boundary with periodic boundary conditions in z. Periodic focusing forces have been replaced by equivalent constant forces. After each time-step charges are distributed on the four nearest grid points and Poisson's equation is solved. A 24 x 120 mesh and 8000 particles have been found sufficient for simulation of short ellipsoidal bunches which require about 150 msec CPU per time-step (~ 25% of this time for the Poisson solver) on a Cray I. Simulation of long intense pulses require higher resolution and a larger number of particles, unless the very different scales for longitudinal and transverse motion in a real beam are brought closer together in the simulation. For a case with 130,000 simulation particles on a 32 x 80 mesh we have required ~ 1.4 sec CPU per time-step (3% for Poisson solver).

II. Coherent Instabilities and Emittance Transfer in Linac Bunches

I. Theoretical Model of the Instability

In recent theoretical work eigenfrequencies of "third-order" and "fourth-order" coherent modes have been calculated using the Vlasov equation for an initial Kapchinskij-Vladimirskij distribution with arbitrary emittance ratio \( \epsilon_x/\epsilon_y \), tune ratio \( \sigma_x/\sigma_y \) and intensity. For given \( \epsilon_x/\epsilon_y \), thresholds for the onset of instability have been found to depend on \( \sigma_x/\sigma_y \) and the tune depressions \( \sigma_x/\sigma_y \), as is shown in Fig.1. We note that the \( \sigma_x/\sigma_y \) are tuned in an equivalent continuous focusing; but subsequent simulation has shown, however, that in periodic focusing with the same tune ratios the same thresholds hold, provided that structure resonances are avoided (for instance by choosing \( \sigma_x < 600 \)).

It is interesting to compare these coherent instabilities with the nonlinear resonances of a single particle in the potential of the "third-order" mode, for instance. Assuming harmonic unperturbed equations of motion, the space charge potential of the "third-order even" mode \( V^1 \sim x^3 + Axy^2 \), yields for the y-motion a coupling term

\[
y'' + \sigma_y^2 y = \delta \cdot y \cos(\sigma_x s)
\]

whereas the "third-order odd" mode \( V^1 \sim y^3 + Byx^2 \) yields

\[
y'' + \sigma_x^2 y = \delta \cdot \cos(2\sigma_y s)
\]

Equ.(1), which describes a "gradient error" indicates the existence of a half-integer or parametric resonance, if

\[
\frac{\sigma_x}{\sigma_y} = 2
\]

The resonance condition for the "inhomogeneous" or integer resonance in Equ.(2) is

\[
\frac{\sigma_x}{\sigma_y} = 1/2
\]

The actual bandwidth of these resonances depends on the strength of the coupling term (here denoted by \( \delta \)), which is however determined by the collective behaviour of all other particles. At this point the single-particle description of the resonances breaks down and one needs a collective description in terms of resonance between coherent eigenmodes (as was done to obtain the thresholds in Fig.1). Nonetheless it is instructive to recognize that the resonances of Equ.(3, 4) coincide with the peaks in the threshold plot of Fig.1. Hence we conclude the following:

(i) At low intensity \( \sigma_x/\sigma_y = 1 \) the coherent instability occurs only if \( \sigma_x/\sigma_y \) is very close to the single-particle resonance values 1/2 or 2. Inside the unstable area an arbitrarily small deviation from uniform density (hence small nonlinear coupling term) is predicted to grow exponentially.

(ii) With increasing intensity the unstable bands become broader and extend towards large values of \( \sigma_x/\sigma_y \), hence the collective behavior dominates entirely over the single-particle behavior.

A similar analysis can be made for the "fourth-order" mode, which has a peak at \( \sigma_x/\sigma_y = 1 \) (for "even" symmetry). In order to connect the limits in \( \sigma_x/\sigma_y \) to the energy anisotropy in a frame moving with the bunch, we use the relationship

\[
\frac{E_x}{E_y} = \frac{\sigma_x}{\sigma_y} \cdot \frac{\epsilon_x}{\epsilon_y}
\]

and predict that anisotropy limited by

\[
\frac{E_x}{E_y} < \frac{\epsilon_x}{\epsilon_y} < \frac{2}{\epsilon_y}
\]

for \( \epsilon_x >> \epsilon_y \) does not lead to emittance transfer. The question of how for \( \sigma_x/\sigma_y \) can be above the limit 1/2 without getting significant instability and emittance transfer is beyond the linearized theory and requires computer simulation.
2. Simulation of a Bunch in r-z Geometry

The purpose of this simulation has been to check whether the predictions on instability from x-y geometry also hold for the equivalent quantities in r-z geometry with longitudinal-transverse coupling (quantities in parenthesis in Fig.1). Hence, we assume $e_y > e_t$ and consider ellipsoidal bunches, which are matched to equivalent continuous focusing forces by means of the r.m.s. envelope equations. The initial charge distribution is chosen uniform with the phase space distribution located on a hyper-ellipsoidal surface. External force constants $\sigma_y^2$, $\sigma_y^2$, $\sigma_y^2$, and $\sigma_{r,t}$ are chosen in such a way that the desired tune depressions $\sigma_0$ are achieved in longitudinal and transverse directions.

Results obtained for $\sigma_y/e_t = 4$ are shown in Table 1. The locations of the different cases are indicated in Fig. 1; a contour plot for case D is shown in Fig. 2.

Table 1. The emittance change and energy anisotropy of r-z simulation of bunches with 8000 particles ($e$ is defined as r.m.s. emittance, $E$ as r.m.s. velocity squared in moving frame).

<table>
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<th>Case</th>
<th>A</th>
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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<td>1.9</td>
<td>1.6</td>
<td>12</td>
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</table>

References

12. L. Smith, ERDA Summer Study of Heavy Ions for Inerteal Fusion, LBL-5543, p.77 (1976)

*Work supported by the Bundesminsterium für Forschung und Technologie
Fig. 1 Thresholds for lowest order x-y coupling modes (only non-oscillatory) with $c_{x}/c_{y} = 4$. A given mode is linearly unstable, if both tune depressions (in x, y or l, t) are within shaded area; circles indicate location of r-z simulations.

Fig. 2 Equi-potential lines (total potential) for unstable case D. Dashed lines are density contours at 1/3 and 2/3 of maximum density. Initial energy anisotropy is evolving rapidly into almost equidistribution with a strongly nonlinear intermediate potential distribution (time scale: $c_{ot} = 1 \text{ sec}^{-1}$).

Fig. 3 Long bunch compression scheme showing half-length ($zm$), momentum spread ($\pm \Delta p/p$), applied force ($\pm E_f$) and space charge force ($\pm E_s$) as function of distance.

Fig. 4 Line density of realistic bunch (initially r.m.s. equivalent to ideal case in Fig. 3), compressed with linear applied force as in Fig. 3. Flat-top profile is conserved at focus, only bunch ends are leaking out.

Fig. 5 Projections of 6D phase space into z-x and z-$v_z$ planes near focus, showing 8000 out of 32000 simulation particles. Aberration "wings" due to unbalanced excessive self-force near bunch ends, where line density gradient is large. Frames apply to 60 m, 30.0 m and 0 m away from focus.
Discussion

It was asked if we saw transverse emittance growth when compressing a long pulse in the compression studies. We did not have enough betatron oscillation periods in this study to observe what happens in the transverse plane. The time scales of betatron to synchrotron or longitudinal oscillation is very different, and to save computer time, we did not run out to several betatron wavelengths.

With the bunched beams and an initial rms emittance ratio of four, we did observe growth of the smaller rms emittance by a factor of 2 to 3 (90% emittance growth grew even more), and the initially larger rms emittance decreased a little.

To the questions of whether the bunched beam modes are a classic Weuball instability: the Weubull is electromagnetic. What we have here can be illustrated in terms of a plasma in a magnetic field--if the temperature perpendicular to the magnetic field is different from the longitudinal temperature, the situation is unstable. When the medium is infinite, a minor temperature difference or anisotropy will set up long-wavelength modes and isotropization will occur. In a bunch, however, the finite geometry means you can't have wavelengths longer than the bunch, and so there must be a threshold on the amount of anisotropy required before instability occurs.
Conditions for minimum transverse emittance growth in rf linacs are discussed. Properties of coherent resonances are estimated analytically. The results are checked by multiparticle simulations for realistic rf linac designs. Most important are the phase dependence of the rf defocusing and the envelope resonance.

**Minimum Transverse Emittance Growth**

There exist both lower and upper limits for the transverse tune $\sigma$ if one aims for a high current rf linac design with minimum transverse emittance growth. The lower limit is determined by the phase dependence of the rf defocusing at injection, where the bunch phase width is largest. To avoid transverse emittance growth not only the transverse motion on the average but also that of the bunch head (index h below) must be stable. This condition can be formulated in smooth approximation from the envelope equation:

$$k^2 h^2 + k^2 (1 - \sin \phi / \sin \phi_h) + k^2 sh (1 - k/k_h) \quad (1)$$

$$k = \varepsilon/a, \quad \varepsilon = \text{unnormalized transverse emittance}/\pi$$
$$a = \text{average bunch radius}$$
$$\sigma = \text{kNBA, N = 2 for FD focusing in an Alvarez}$$

$$k^2 h = -q\sigma E T \sin \phi_h (mc^2 \beta y^3) = \text{rf defocusing}$$

$$k^2 sh = 90q\pi \Lambda M \sigma (mc^2 \beta y^3 a^2 b) = \text{space charge effect}$$

It follows that the average tune $\sigma$ is larger than that at the bunch head $\sigma_h$, which is in turn fixed by the condition that the average bunch radius $a_h$ fits well within the aperture. In case the defocusing due to the finite emittance and due to space charge can be neglected compared to the rf defocusing the condition for the minimum average tune results to

$$\sigma_{min}^2 \geq -2q\pi ET \Lambda (\sin \phi - \sin \phi_h)/(mc^2 \beta y^3)$$

(2)

Taking into account also a finite emittance would lead to a larger $\sigma_{min}$. A high space charge diminishes the influence of the rf phase dependence, allowing a lower tune than required from Eq. 2.

An upper limit for the transverse tune can be derived from the well established requirement to avoid the envelope resonance (3), which is assured if the zero current tune $\sigma_z$ is below 90°. As $\sigma_z$ is obtained by subtracting the space charge effect from $\sigma$ one obtains for the space charge tune shift in smooth approximation

$$\sigma_{max}^0 \leq \sigma^2 - \sigma N180\pi \Lambda M \pi (mc^2 \beta y^2 \varepsilon_n \Delta \phi)$$

(3)

with $\varepsilon_n = \text{normalized transverse emittance}/\pi$, $\Delta \phi = \text{half phase width of the bunch}.$

The range of transverse tunes at which a linac can be operated with minimum transverse emittance growth gets the smaller the larger $\lambda/\beta$ (Eq. 2) and the larger $\lambda/(\delta \beta)$ (Eq. 3) is.

Once one has decided on a tune $\sigma$ (e.g. according to Eq. 2) the requirement to avoid the envelope resonance transforms into a lower limit for the transverse emittance:

$$\varepsilon_{n, min} \geq \frac{N180\pi \Lambda M \pi (mc^2 \beta y^2 \varepsilon_n \Delta \phi)}{(\pi/2 - \sigma^2)} \quad (4)$$

**Conclusions from Multiparticle Simulations**

The results presented above are based on simplifying assumptions, such as modeling the bunch by a uniformly charged ellipsoid and smooth approximation. They were checked by multiparticle simulations based on the Alvarez linac design for the SNQ project. The major linac parameters are protons, frequency 108 MHz, injection energy 450 keV, average electric field on axis $E=2MV/m$, transit time factor $T=0.7$ near injection, synchronous phase $-35°$, bunch phase width at injection about $+30°$, FD quadrupole focusing. The matching parameters at injection and the quadrupole gradients corresponding to a specified tune $\sigma$ were obtained by an improved version of the CERN ADAPT code. The multiparticle simulations traced 2500 particles fully three dimensional, assuming no symmetries, using an improved version of the CERN MAPRO code. The phase space filling was ellipsoidal, uniform in the four transverse, and independently uniform in the two longitudinal coordinates.

Emittance growth was studied as a function of the transverse emittance. Fig. 1 shows the transverse

![Fig. 1 Transverse emittance growth for zero current](image)
emittance at 14.5 MeV for zero beam current, Fig. 2 for 100 mA, and Fig. 3 for 200 mA. The minimum tune required according to Eq. 2 is 43°, which agrees reasonably well with the results in Fig. 1. This suggests that the large emittance growth observed at lower tunes is indeed caused by the phase dependence of the rf defocusing, also for zero current there is no other cause plausible. With increasing beam current this kind of emittance growth diminishes as can be verified by comparing Fig. 1, 2 and 3. This is in accordance with the fact that the defocusing forces tend to get relatively more dominated by the space charge defocusing which does not depend on the phase for the uniformly charge ellipsoid model. For more realistic phase space density distributions this is no longer the case, then the tune depression due to space charge is largest where the charge density is largest, that is probably near the bunch center.

Analyzing the above figures further most striking is the occurrence of a resonance structure in the emittance growth once space charge forces come into play. The proof that indeed this is caused by the envelope resonance is given in Fig. 4. Here the upper row of bars is the range over which the zero current tune \( \alpha_0 \) varies in half a betatron oscillation for the tune \( \sigma \) at resonance, analyzed for the cases of Fig. 2, 3. Zero current tunes expected from Eq. 12 for \( n=2 \) are also shown. Likewise the lower row of bars is the \( \alpha_0 \) range corresponding to the \( \sigma \) at minimum emittance growth, that is when with increasing \( \sigma \) the emittance growth due to the onset of the resonance starts to balance the decreasing emittance growth due to the rf defocusing. The average \( \alpha_0 \) for this case is about 90° as predicted for the onset of the envelope resonance.

Of further interest is the scaling suggested by Eq.3: the onset of the resonance should scale like \( I_M/V_C \), which is verified in Fig. 2 and 3. Increasing the current by a factor of two can transversely be coped with if the transverse emittance is increased by a factor of two as well. Also the growth rates are rather similar in the corresponding cases. Minor differences in this scaling can be contributed to the smaller transverse form factor \( M_x \) at the larger emittance, shifting the resonance slightly higher tunes. The conclusion is that the ratio current/transverse emittance plays a more important role in transverse emittance increase then the closely related brightness. Further, the prediction that at a given tune \( \sigma \) the transverse emittance should not be smaller than indicated by Eq. 4 is verified in Fig. 2 and 3. On the other hand, in the high current cases for a given transverse input emittance a transverse tune can be found at which the transverse emittance growth is minimized. The smaller the input emittance the smaller this optimum tune is, and the more the emittance is blown up due to the phase dependence of the rf defocusing.

Some results for the corresponding longitudinal emittance growth are given in Fig. 5 also as function of the transverse tune. The analysis is complicated by the fact that the matched longitudinal input emittance for non zero current depends both on the current and on the transverse tune. The bunch phase
width at injection was chosen to be about ±30° for all cases, anticipating the rapid growth in longitudinal acceptance due to the acceleration after injection. Thus the corresponding matched energy spread decreases with increasing current and transverse tune. For the zero current case most obvious is the emittance transfer from the longitudinal to the transfer plane at small tunes caused by the phase dependence of the rf defocusing. This effect is hidden at 200 mA current, but is still noticeable at 100 mA, as the final emittance is smaller than the input one at σ = 15°. At 200 mA and tunes above about 40° the longitudinal motion is strongly unstable and the longitudinal emittance growth is large. No resonance structure is detectable in the longitudinal emittance growth.

In Figs. 6 a, b the beam motion is followed along the first tank of the SNQ linac for 100 mA current, a 0.2 mm mrad normalized transverse rms emittance at injection, and for a constant 20° transverse tune design, which yields according to Fig. 2 a minimum transverse emittance growth for the input emittance chosen. The average tunes at the bunch center are evaluated from the MAPRO results in smooth approximation. The transverse tunes at the bunch head and tail are computed starting from this average tune, taking the tune difference for head and tail from ADAPT. Remarkable is the strong correlation between the transverse tune qₙ at the bunch head and the transverse emittance growth: the growth rate is large as long as qₙ is imaginary, thereafter the emittance still grows but at a much smaller rate. This again supports the view that most of the rapid initial growth is caused by the phase dependence of rf defocusing. Due to this growth the transverse tune gets larger than designed, as for a larger bunch radius the space charge defocusing is reduced. The growth happens nearly evenly in the two transverse coordinates, and the beam matches itself gently to the new conditions. After about 3 MeV energy only very small mismatches remain. The linac design can be further improved by incorporating the theoretically well-understood emittance growth due to
Following form:

\[ \frac{\partial}{\partial t} \phi + A_n \cos \phi + \ldots = 0 \] (6)

For \( a_0 = a_1 = 0 \) this equation describes the unperturbed motion of the azimuthal Fourier components in the \( n - \phi \) phase plane. \( \phi \) is the incoherent single particle tune of the unperturbed motion. It is the tune obtained from the zero current \( n \) of the magnet structure and rf defocusing together with the downward shift due to incoherent space charge. Compared to this the coherent space charge has a coherent tune of on the average \( n \phi \), arising from the density modulation (Eq. 7). \( \sigma_n \) lies between 0 and \( \sigma_0 \) and is represented by the \( a_n \) term. The modulation by the lattice gives \( a_1 \cos \phi \) and higher terms. Eq. 6 can be rewritten with

\[ b_1 = a_1/(1 + a_0) \] (7)
and

\[ a_n^2 = \sigma_0^2 (1 + a_0) \]
as

\[ x'' + (n \sigma_n/2\pi)^2 (1 + b_1 \cos \phi + \ldots) X = 0 \] (8)

Now the modes width and excitation rate are estimated by substituting into Eq. 8 trial solutions

\[ X = A \exp (i \phi' / 2) + \text{complex conjugate} \]

neglecting fast terms proportional to \( \exp (\pm i \phi) \).

The range of \( \sigma_n \) over which the \( b_1 \) term is sufficient to lock the mode onto the lattice is estimated by taking the two special solutions with purely real and imaginary \( A \), and assuming \( A \) to be independent of \( \phi \). The result is

\[ \sigma_n = \pi / (n \sqrt{1 + b_1^2}) \] (10)

To estimate the excitation rate one chooses the tune \( n \phi = \pi \) exactly on resonance further allows \( A \) to depend on \( \phi \), neglects \( A^n \) compared to \( A \), and considers only the particular solution with \( A^e = -i A \). One finds

\[ A = (1 + i) A_0 \exp (b_1 \phi / 8) \] (11)

with a real \( A_0 \) and the growth rate \( b_1/8 \).

The accurate determination of \( b_1 \) requires the solution of the radial eigenvalue problem for some specified equilibrium distribution. In the following only a rough estimate is made. Consider first \( a_0 \). The coherent force constant for the \( n \)-th order mode is obtained by adding to the incoherent force constant at full current a certain fraction \( F \) of the incoherent space charge force constant:

\[ \sigma_n^2 = \sigma_0^2 + F (\sigma_0^2 - \sigma_n^2); \quad a_0 = \sigma_n^2/\sigma_0^2 - 1 \] (12)

For the dipole mode (e.g. bunch center off axis, \( n = 1 \), \( F = 1 \)) the coherent force constant equals the zero current one. With increasing mode order it is reduced towards that of the incoherent motion at full current. For the symmetrical quadrupole mode it is known that \( F = 0.5 \), for the independent quadrupole mode corresponding to the envelope resonance discussed above one has \( n = 2 \), \( F = 0.4 \), and it seems reasonable to estimate that for an independent third order mode \( n = 3 \) and \( F = 0.2 \).

Next consider \( a_1 \). The transverse space charge force in \( x \)-direction varies like \( M_x a_{xy} \) in a transverse...
focusing period in \(x-x'\)-coordinates. In the \(n-\phi\) -representation used here this transforms into \(s = \frac{M_{\phi\phi}}{\phi^2}\), since in this plane the effect of a given small extra force constant varies like \(\phi^2\). Requiring that the tune modulation \(1 + \frac{a_1}{a_0} \cos \phi\) equals that of the space charge force constant modulation yields

\[\frac{a_1}{a_0} = \frac{(S - 1)}{(S + 1)}, \quad S = \frac{s_{\text{max}}}{s_{\text{min}}} \quad (13)\]

The properties of the coherent resonances depend on the actual beam parameters. They are evaluated for a few cases in Table 1.

<table>
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<th>(\varepsilon_n)</th>
<th>tunes/deg.</th>
<th>unstable region</th>
<th>growth rate (b_{1/8})</th>
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<td>(\sigma)</td>
<td>(\sigma_2)</td>
<td>(\sigma_3)</td>
</tr>
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<td>65 120 91</td>
<td>96+12</td>
<td>90+13</td>
</tr>
<tr>
<td>0.6</td>
<td>45 91 67 57</td>
<td>-8.4</td>
<td>50+6.5</td>
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<tr>
<td>at injection</td>
<td>0.2 20 97 64 48</td>
<td>90+13</td>
<td>60+4.4</td>
</tr>
<tr>
<td>after 20 cells</td>
<td>0.2 39 81 59 50</td>
<td>-8.5</td>
<td>60+5.3</td>
</tr>
</tbody>
</table>

Table 1: Properties of coherent resonances. Current = 100 mA. \(\varepsilon_n\) = normalized rms emittance at injection in \(\pi \text{ mm mrad}\); \(\sigma\) = incoherent tune; \(\sigma_0\) = zero current tune; \(\sigma_2, \sigma_3\) = coherent tunes

For \(\varepsilon_n = 0.6\) the evaluation was done at the \(n = 2\) resonance, and at minimum emittance growth (Fig. 2). The predicted bandwidth for the \(n = 2\) resonance agrees qualitatively with the results of Fig. 2. At minimum emittance growth the \(n = 2\) resonance cannot be excited, and \(\sigma_3\) is just at the edge of the corresponding unstable region. However, no resonances are observed in the tune range \(\sigma\) from 45° to 55° (Fig. 2), so the excitation of the \(n = 3\) resonance must be weak in the simulations.

For \(\varepsilon_n = 0.2\) both coherent tunes are outside their unstable regions, so that the observed emittance growth (Fig. 2, 6) must have other causes, as discussed above.

**Conclusions**

1. To avoid transverse emittance growth due to the phase dependence of the rf defocusing the motion at the bunch head must be stable. The minimum transverse tune required scales as \(\lambda/\beta\) (Eq. 1, 2). For smaller tunes the transverse emittance grows in a predictable and controllable manner.

2. To safely avoid the envelope resonance (\(n = 2\)) the zero current transverse tune must be below 90°, hence there exists a lower limit for the transverse emittance scaling as \(I_0 \alpha / \beta_0 \phi ((\pi/2)^2 - \sigma^2)\) (Eq. 4).

3. In the linac designs presented above temperature exchange between phase planes and the excitation of 3rd order coherent particle oscillations have not been noticeable.

4. The width of the 2nd and 3rd order coherent resonances are roughly about 90° ± 10° and 60° ± 50°, their amplitude grows roughly by a factor \(e\) in 3, respectively 4 transverse focusing periods.

**References**

SUMMARY

Emittance growth has long been a concern in linear accelerators, as has the idea that some kind of energy balance, or equipartitioning, between the degrees of freedom, would ameliorate the growth. M. Prome observed that the average transverse and longitudinal velocity spreads tend to equalize as current in the channel is increased, while the sum of the energy in the system stays nearly constant. However, only recently have we shown that an equi-partitioning requirement on a bunched injected beam can indeed produce remarkably small emittance growth. The simple set of equations leading to this condition are outlined below. At the same time, Hofmann, using powerful analytical and computational methods, has investigated collective instabilities in transported beams and has identified thresholds and regions in parameter space where instabilities occur. This is an important generalization. Work that he will present at this conference shows that the results are essentially the same in r-z coordinates for transport systems, and I will present evidence below that shows transport system boundaries to be quite accurate in computer simulations of accelerating systems also. Discussed are preliminary results of efforts to design accelerators that avoid parameter regions where emittance is affected by the instabilities identified by Hofmann. These efforts suggest that other mechanisms are present. The complicated behavior of the RFQ linac in this framework also is shown.

CONDITIONS FOR EQUIPARTITIONING

A simple derivation for energy balance in a weakly coupled harmonic oscillator system requires equality of the average kinetic and potential energies in each degree of freedom: \( \langle 1/2 \frac{mv^2}{N} \rangle = \langle 1/2 k\phi^2 \rangle \), where \( k \) is the appropriate force constant. If we characterize the motion in terms of the oscillation's phase advance over an accelerator system period, we can write the mean-square velocity as \( \langle v^2 \rangle = \frac{\phi^2}{N} \). At a location where the correlation \( \langle xv \rangle \) is zero, rms emittance is defined as \( \epsilon = \langle x^2 \rangle^{1/2} \langle v^2 \rangle^{1/2} \), and the two envelope equations, useful in accelerator motion, follow directly.

\[
\epsilon_t = \frac{\sigma^2}{N} \quad \text{and} \quad \epsilon_x = \frac{a^2}{b^2} \frac{\sigma^2}{N},
\]

in terms of longitudinal and transverse planes, where \( a \) is the average transverse rms beam radius, and \( 2b \) is the physical rms bunch length. The emittances are unnormalized, and we define both phase advances over the same focusing period. It can be shown rigorously that Eq. (1) describes the matched envelope equations \( \epsilon_t = \epsilon_x = 0 \), for the rms envelope behavior of particle distributions in linearized periodic systems.

If we require equal average energy in each of the coupled degrees of freedom, by equating \( \langle v^2 \rangle = \langle v^2 \rangle \) and \( \sigma^2 \), we find

\[
\frac{\sigma^2}{\epsilon_t} = \frac{a^2}{b^2} \frac{\epsilon_x}{\epsilon_t}.
\]

Systems satisfying Eqs. (1) and (2) simultaneously will be both matched and equipartitioned. Both are important to minimum emittance growth.

Using the notation of Mittag, we complete the design equations for drift-tube linacs with focusing.

\[
\sigma^2 = \cos^{-1} \left( \frac{\cos \phi^2 + \frac{3(3b-a)}{\pi^2 b^2}}{\epsilon_x^2} \right),
\]

and

\[
\epsilon_x = \frac{2 \cos^{-1} \left( \frac{\cos \phi^2 + \frac{15(3b-a)}{\pi^2 b^2}}{\epsilon_x^2} \right)}{\epsilon_x^2},
\]

where \( N \) above = 2 for a drift-tube linac, \( \phi^2 \) and \( \phi^2 \) are zero-current phase advances (\( \phi^2 \) is over one cell), \( I \) is average current over one rf cycle and \( W_0 \) is rest energy.

\[
\sigma_t = \cos^{-1} \left( 1 - \frac{\frac{4 \pi^2 E^0 T}{W_0}}{W_0^2} \right),
\]

and

\[
\sigma_x = \frac{\pi^2 E^0 T}{W_0},
\]

\( \Delta \) is the quad-filling factor, \( E^0 \) the average accelerating gradient, \( T \) = transit-time factor, \( \lambda \) = wavelength, \( \theta_s \) = synchronous phase angle, and

\[
\frac{\epsilon^2}{\epsilon_x} = \frac{B^2}{B_0^2}
\]

for the case at hand, with \( B \) the quad gradient and \( B_0 \) the magnetic rigidity. We define the relation between space charge and external forces

\[
\mu_t = 1 - \left( \frac{\sigma_t}{\epsilon_t^2} \right) \quad \text{and} \quad \mu_x = 1 - \left( \frac{\sigma_x}{\epsilon_x^2} \right).
\]

Similar equations for other focusing systems, and auxiliary formulas for ellipse parameters and other quantities are derived in the literature.

The equations may be solved in various ways, depending on what is chosen a priori. For example, if we chose \( \mu_t = 0.9 \), \( \sigma_t = 49^\circ \), \( \sigma_x = 24.7^\circ \) using...

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*Work supported by the US Department of Energy.
the injection point of the FMIT drift-tube deuteron linac, taking $e_t = 0.006 \text{ cm}^2 \text{ rad}$, and requiring both matching and equipartitioning, we solve for $I = 0.120 \text{ A}$ and $b = 0.642 \text{ cm}$ (or phase spread $= 17.5^\circ$), requiring $e_t/e_f = 0.96$. As shown in Fig. 4, Ref. 3, the rms emittance growths are only about 20% over 70 cells. In contrast, in a design using a conventional buncher in which narrow phase spreads are difficult to achieve, we might start with a phase spread nearly equal to $\delta_5$. Using only Eq. (1) to match the beam, we would find that the injected beam was not equipartitioned. Figure 3, Ref. 3 is such an example, where the initial transverse and longitudinal velocity spreads are quite unequal, and the equipartitioning process during acceleration caused transverse emittance growth of magnitude (~x2) typical of that seen in operating machines run in this way. We will now relate this result to the instabilities identified by Hofmann.

**Coupling Instabilities**

Expressing the channel in terms of tune depression, $\sigma / \sigma_0$, in each plane and the tune ratio, Hofmann derived the eigenoscillation frequencies of anisotropic KV distributed beams in transport channels, and gives stability limits for various modes for a given emittance ratio. Figure 1 is such a chart, showing thresholds for three modes at emittance ratios of four. If $\sigma / \sigma_0$ is below one of the thresholds, a perturbation in the particle distribution will grow. Because emittance is a projected and averaged quantity, it is very difficult to quantify the emittance growth resulting from the change in distribution, but the effective emittance does grow. In a linac, the changing parameters with acceleration result in a trajectory on this chart; indicated in the figure is a typical smoothed trajectory of a linac with a large initial anisotropy between longitudinal and transverse. Because the emittance ratio is shifting, it is presently tedious to check the stability; Fig. 2 shows the unstable regions versus the rms emittance growth for a linac with a given magnetic focusing law giving constant $\sigma_0^t = 50^\circ$, constant $E_0$ and $\delta_s$, under three conditions: (1) full nonlinear and coupled accelerating-gap transformation, (2) nonlinear gap but longitudinal-transverse

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**Fig. 1.** Mode chart showing trajectory for initially anisotropic beam in constant $\sigma_0^t = 50^\circ$, constant $E_0$ linac. Moves into clear area as energies balance.

**Fig. 2.** Emittance growth and cells where unstable modes are excited for initially anisotropic beam in constant $\sigma_0^t = 50^\circ$, constant $E_0$ linac. (1) full nonlinear and coupled rf gaps. (2) nonlinear gap, longitudinal-to-transverse coupling off. (3) linearized gap, longitudinal-to-transverse coupling off. In each case, modes are top-third, odd; middle-third, even; bottom-fourth, even.

---

*The detailed trajectories show complicated loops as various effects oscillate and beat. The phase advances are presently computed directly from the beam properties by assuming a local match and using Eq. (1).*
coupling turned off, and (3) linearized gap with \( \varepsilon - t \) coupling off. In Case 3, the effect of passing through unstable regions is quite evident as the beam initially moves toward equipartition and later receives small emittance increases. In Case 2, the third-odd mode has the major effect. The longitudinal emittance continues to grow from some other cause—probably the emittance has grown enough to be filaments by the nonlinear forces. In Case 1, the rf \( \varepsilon - t \) coupling appears to have a large effect, adding an initial peak \( \varepsilon \), and, after the strong initial push toward equipartition from the unstable modes, continuing in some manner to push the transverse emittance up, while keeping the longitudinal growth smaller. By Cell 17, the trajectory on Fig. 1 has moved into the clear zone where \( \sigma / \sigma^t \) < 0.5 and the energies are well balanced. The longitudinal emittance has apparently remained small enough so filamentation has less effect. The growth rates when the instabilities are excited also are complicated functions; they are characterized by the plasma frequencies, which fall between the full- and zero-current frequencies. If an unstable region is entered, the energy-equalizing process drives the tunes toward a stable region, reaching it within about one plasma period in the slower of the two planes. Less free energy is then available for the next possible excursion into an unstable region to cause growth.

What would then happen if the input distribution were isotropic? This is the equipartitioned case described above; the trajectories, shown in Fig. 3, are mostly in a region free of instability. Near the end (Cells 60-72) of this system, the third-even mode is excited in the longitudinal plane, but the effect on longitudinal emittance is small because little free energy is available.

If the main eigenmode instabilities are avoided, one might expect that the simple formulas Eqs. (1) and (2) might be used to generate a linac with constant \( \sigma / \sigma^t \). By letting the physical beam length vary as \( \sigma^{1/3} \) to \( \sigma^{1/2} \), this generation was done in various ways for \( \sigma / \sigma^t \sim 0.9 \) and \( \varepsilon / \varepsilon^t \sim 1 \). However, full simulations through the resulting designs did not exhibit constant \( \sigma / \sigma^t \), although several gave quite low emittance growth. This is further evidence that other factors are at work.

When \( \varepsilon / \varepsilon^t \sim 4 \), Hofmann's charts show a clear region where \( 0.25 < \sigma / \sigma^t < 0.5 \). Eqs. (1) and (2) were used again, with \( \varepsilon \) varying as \( \varepsilon^{1/4} \), to generate three linacs, with constant emittances: \( \varepsilon / \varepsilon^t = 4 \), \( \sigma / \sigma^t = 0.375 \); and \( \sigma^t = 90^\circ, 50^\circ, \) or \( 40^\circ \). The depressed tunes were initialized by setting \( \sigma / \sigma^t = 0.2 \) and moved upward by varying \( \varepsilon^t \) and the quads. This time, the prescription worked well enough that \( \sigma / \sigma^t \), stayed within the desired band, and \( \varepsilon / \varepsilon^t \) stayed near four. But the rms emittances did not stay constant—both grew almost linearly over the 75 cells tested. The \( \sigma^t \) growths for \( \sigma^t = 40^\circ \) and \( 50^\circ \) were both about a factor of 2, and \( \sigma^t \) to 4 for \( \sigma^t = 90^\circ \). The differences could be the influence of the \( 60^\circ \) envelope mode. In all three cases, the \( \sigma^t \) was almost linearly over the 75 cells tested. The \( \sigma^t \) growths for \( \sigma^t = 40^\circ \) and \( 50^\circ \) were both about a factor of 2, and \( \sigma^t \) to 4 for \( \sigma^t = 90^\circ \). The differences could be the influence of the \( 60^\circ \) envelope mode. In all three cases, the \( \sigma^t \) was almost linearly over the 75 cells tested.

Behavior in the RFQ

The present Los Alamos RFQs use a design strategy that involves transverse matching a dc beam at injection; a shaper section, where the longitudinal rf potential well is developed and kept filled to a constant fraction of its depth; a gentle-buncher section, where the beam's physical length is kept constant, while the accelerating gradient and synchronous phase are brought to their final values; and an accelerator section, where \( \varepsilon^t \) and \( \phi^t \) are usually held fixed. The energy increase between injection and the end of the gentle buncher is about a factor of 10, and the current-limit bottleneck occurs at the end of the gentle buncher rather than at injection. This type of RFQ design has high capture efficiency and transverse emittance growth in the area of \( x^2 \) at the designated operating current, usually about half the current that could be transmitted at full saturation (with loss of about half the input current). At the operating current, we have found that the space charge to focusing force ratios \( \mu_t \) and \( \mu_L \) are remarkably high—in the range 0.84 - 0.9. The adiabatic beam handling is clearly allowing very efficient use of the channel.

The trajectories of the Hofmann charts are intricate, with the \( \varepsilon / \varepsilon^t \) ratio passing through 1, as indicated in Fig. 4. The unstable regions are noted on the emittance-growth plot in Fig. 5; again, growth does seem to be correlated with the
Conclusions

The important work by Hofmann, identifying the collective modes of beam-transport systems driven by anisotropies, appears to be directly useful in accelerating channels as well. The mode charts provide a much improved cartography for estimating current limits under various conditions, and for contemplating trajectories for an accelerating system. Because equipartitioning of initial anisotropy is a self-limiting process if the unstable regions are entered, higher current limits can be expected if some of the initial emittance can be sacrificed. Initially isotropic distributions offer very good performance. The RFQ, which carefully molds a bunched distribution, can probably be made to present an optimum distribution to a following drift-tube linac. Other effects, such as external nonlinearities and couplings, still affect emittance growth in relatively less-defined ways and require further work. The behavior of total effective emittance of all the particles, important to beam losses, is still a virtually wide-open subject.

Acknowledgments

The author is indebted to R. S. Mills for computing assistance, and to I. Hofmann, R. Gluckstern, W. Lysenko, M. Reiser, and M. Pabst for many helpful discussions.
References


5. P. Channell, private communication.


Discussion

The simulation results are from full PARMILA simulations, including space charge, so the particle trajectories are as realistic as we know how to make them, and do not come from simple envelope equations. I do use the computed rms emittances and beam sizes at each cell from PARMILA in the envelope equations to get the phase advances. I tried to start with the full, very complicated rf linac, and through a series of computer experiments, to sort out some of the major effects. It is very satisfying to find that the full linac behaves in many respects nearly like the simpler transport lines that have been studied very carefully by Hofmann, Reiser, the LBL team, and others; for example, it appears that Hofmann's stability charts are also useful guides for accelerating channels.

Do the ideas we have been discussing apply to electron machines, where the acceleration is so rapid that any resonances are passed through so rapidly they would be insignificant? That is a good point; even in ion linacs there is seldom a steady-state, and this can be used to advantage for some applications. In the electron case, the ideas would apply, but I don't know how the circuit required to produce the proper fields would be made. I think there will be a growing interest in this, because there seem to be interesting requirements for high-quality, high-intensity electron beams, but most discussions start by assuming an injector.
BEAM PARAMETER MEASUREMENTS FOR THE SLAC LINEAR COLLIDER*

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ABSTRACT

A stable, closely-controlled, high-intensity, single-bunch beam will be required for the SLAC Linear Collider. The characteristics of short-pulse, low-intensity beams in the SLAC linac have been studied. A new, high-intensity thermionic gun, subharmonic buncher and S-band buncher/accelerator section were installed recently at SLAC. With these components, up to \(10^{11}\) electrons in a single S-band bunch are available for injection into the linac. The first 100-m accelerator sector has been modified to allow control of short-pulse beams by a model-driven computer program. Additional instrumentation, including a computerized energy analyzer and emittance monitor have been added at the end of the 100-m sector. The beam intensity, energy spectrum, emittance, charge distribution and the effect of wake fields in the first accelerator sector have been measured. The new source and beam control system will be described and the most recent results of the beam parameter measurements will be discussed.

I. INTRODUCTION

The Stanford Linear Collider (SLC) is a major project at the Stanford Linear Accelerator Center (SLAC) to reach an energy of 100 GeV in the center-of-mass within a few years. The existing 3-km linac is being upgraded to produce a high-quality, high-intensity, single-bunch beam with an energy of slightly more than 50 GeV for injection into a pair of collider arcs having an average radius of 300 m. The linac beam will consist of both a positron and an electron bunch accelerated within the same RF pulse of the linac. A dc magnet at the end of the linac will separate the two bunches into the two collider arcs. At the interaction region, where after half a turn the two arcs come together again, the beams will be focused to micron dimensions to improve luminosity. However, as the beams pass through each other they will undergo a high degree of disruption so that recovery of the beams after the collision will not be possible.

Linear colliders are a new class of accelerators that have been receiving increasing attention recently. In a true collider, which consists of two linacs aimed at each other, the loss of RF power through synchrotron radiation is eliminated. Thus at some energy colliders, for which the cost scales linearly with the center-of-mass energy, \(E_{cm}\), acquire a decided economic advantage over storage rings, whose cost scales as \(E_{cm}^2\). To learn more about colliders, the SLC, in which a single linac is used, has been proposed. The SLC design-energy, which is somewhat greater than the predicted mass of the neutral vector boson, \(Z^0\), will permit an efficient investigation of the interaction of the electromagnetic and weak forces. Although the 3-km electron accelerator at SLAC is the basis of the SLC, the requirements for the SLC beam are quite different from the properties of the present linac beams. The SLC-beam requirements are compared in Table I with the typical characteristics of the electron beam used to fill PEP. In addition to a 50% increase in the energy, it is seen that the beam must be confined to a single, very intense bunch with the conflicting requirement that the beam emittance be improved. Experience gained with linac operations in the past suggests that with charge densities of the magnitude proposed for the SLC, beam breakup can be avoided only by careful control of the beam while it is still at low energy.

With these problems in mind, the design and construction of a new injector was undertaken to produce the high-intensity single-bunch beams required for the SLC. In addition, the first 100 m of the linac (Sector 1) was modified to allow close control and monitoring of short-pulse beams in a manner similar to that which will be introduced eventually to all 30 linac sectors required for the SLC. This system and the beam tests which have been made using this system will be described.

II. INJECTOR

As shown in Table I, the SLC requires an injector capable of producing \(5 \times 10^{10}\) electrons in a single S-band bunch with a transverse emittance area on the order of 0.03 \(\pi m^2\).
A bunch length of $\sigma_z \approx 1$ mm is desirable, and the energy spread while not critical should be no more than one percent at the end of Sector 1.

Single-bunch beams have been available at SLAC for several years, but the intensity was limited to $\sim 10^9$ electrons per bunch. Since the single bunches were selected by passing the regular linac gun beams through a travelling-wave RF-chopper, the transverse emittance was quite poor. During the past year a new injector (CID) matching the characteristics desirable for the SLC has been installed at SLAC. As shown in Fig. 1, CID utilizes two resonant-cavity bunchers placed in series and operated at the 16th subharmonic of the linac accelerating frequency (2856 MHz) to compress the gun pulse sufficiently that the beam may then enter an S-band buncher and accelerator section. The CID accelerator section and the identical section in the main linac injector are similar to the approximately 950 standard 3-m disk loaded waveguide (DLWG) sections which make up the linac. The two injector sections as well as the first three sections in Sector 1, which are driven by separate klystrons, each contribute $\sim 40$ MeV to the beam energy. The remainder of Sector 1 consists of repeated 4-section modules. Each module, powered by a single klystron, contributes $\sim 80$ MeV (without SLED).

The CID gun must produce a very high-intensity, very narrow beam pulse. In addition, the gun must be capable of being pulsed twice during the period of the accelerating RF pulse. The second bunch will be directed to the positron target located near the high-energy end of the linac.

Two separate guns have been developed for CID -- a photoemission gun and a thermionic gun. The latter operates on the principle of photoemission from a GaAs cathode activated by a Q-switched laser. Polarized electron beams, which may prove important at high energy for the study of polarization-dependent effects, may be produced by using circularly polarized laser light of the correct frequency. Installation of the laser gun has been delayed pending improvements in the CID vacuum system.

The gun which has actually been used in CID is a new thermionic gun having a large diameter (1.5 cm) dispenser-cathode planar-grid assembly made by Eimac. The extremely small separation of the grid and cathode permits narrow gun pulses. The present avalanche-type pulser produces one 3-ns gun pulse during a single accelerating RF pulse. (A second generation pulser is under development to produce 1-ns gun pulses with full recovery on the order of 20 ns.) The new thermionic gun, which has been operated with CID for $\sim 10^3$ h with no significant difficulties, will produce peak currents of up to $\sim 7$ A at repetition rates of up to 180 pps.

III. SECTOR 1

Earlier studies at SLAC with relatively low-intensity single-bunch beams made it clear that the transmission of high-intensity beams through the linac structure would be impossible unless the control system were vastly improved. The beam is affected by the fields generated by charged particles passing through the accelerating structure. These wake fields remain for a finite time after the passage of a particle so that an electron at a given axial position in the linac is affected by the resultant force due to the wake fields remaining from all electrons which previously passed the same position. The longitudinal forces, which increase the energy spread of the bunch, are generated by wake fields which simply...
decrease with time, so that as a bunch is lengthened, electrons in the tail of the bunch are less affected by the longitudinal fields generated by electrons in the head. There is a similar beneficial effect when the separation of two bunches is increased.

The transverse forces are somewhat more complex. The strength of the transverse wake field depends on the displacement of the generating particle from the axis of the accelerating structure as well as the elapsed time since the passage of the generating particle. For a short time, on the order of 20 ps, the transverse wake fields, unlike the longitudinal fields, increase. Thus for the SLC beam in which $\sigma_z \sim 3$ ps, the transverse forces at the tail of the bunch are expected to be severe unless the beam can be kept on axis.

The present linac control system, in which the operator controls individual linac components with the aid of a mini-computer is inadequate for the SLC in several respects: the characteristics of the beam control devices are not well known; the beam must be tuned by a time-consuming trial-and-error method; and the beam monitoring is not precise enough or is totally insensitive to single-bunch beams. To overcome these problems the new computer control system will be model-driven, that is, the characteristics of each beam control device will be represented mathematically in the control program. A model for each control function — focusing, orbit correction, emittance measurement, etc. — will be an integral part of the control program. The control program will calculate on-line the needed values for the appropriate linac devices according to the control operation selected by the operator and display the predicted effect on the beam. Upon command the control program will set the calculated values in the appropriate linac devices. All critical beam parameters, such as transverse beam-position, will be continuously monitored.

To implement this system in Sector 1, the quadrupoles, which are located at the short drift sections between 12-m girders, were calibrated and a standardization procedure established. Inside each quadrupole, integral with the drift tube connecting the two accelerator sections, new stripline position monitors were installed. Steering dipoles were also added at each quadrupole. The control computations as well as storage of data was accomplished in a central computer (VAX 11) connected to local CAMAC crates via a wide band cable system.

The magnet lattice was a FODO structure adjusted to minimize $\sigma_{\text{max}}$ in the following manner: knowing the emittance at the beginning of Sector 1, and temporarily neglecting the effects of acceleration, the strength of the quadrupoles in the first half of Sector 1 required to match the beam into a 90°/cell configuration in the second half were computed on-line by the SLC control program. The resulting quadrupole strengths were then scaled by the correct energy. Such a solution is shown in Fig. 2(a) and (b). Once the quadrupole lattice was set, the beam orbit could be measured and the strengths of the dipole magnets required to center the beam computed and set.

Travelling-wave stripline beam position monitors were developed which fit inside a Sector 1 quadrupole as shown in Fig. 3. The four monitor strips are each $l = 12.5$ cm long, grounded at their downstream end. The beam induced pulse read out at the upstream end of a strip is a doublet in which a leading negative pulse (for electrons) is followed $\frac{2v}{c}$ later by a positive pulse. The pulses are stretched, combined into a single pulse with a dc restorer, and digitized.

![Fig. 2. A typical quadrupole configuration.](image)

Fig. 2. A typical quadrupole configuration. The calculated beam radius, $\sigma_y$, in Sector 1 is shown in (a) for the magnetic strength (integrated gradient) in (b) which has been calculated to match a beam with a measured emittance area of $0.06 \, \text{m}\cdot\text{c}^2\cdot\text{cm}$ into a 90°/cell FODO lattice. With the quadrupoles in Sector 0 empirically adjusted as shown in (b), the calculated radius is given in (c).
signal from each strip is read into the SLC program database. The transverse position of the beam is computed for each plane from the difference signal for two opposite strips, while the sum signal computed from all four strips is proportional to the beam intensity. The computed transverse position is designed to be accurate to within 0.1 mm.

An energy analyzer was installed at \( z = 10 \) m during the original construction of the linac. This analyzer consists of a 30° bending magnet and 12 SEM foils each with a resolution of 0.3%. Analog signals only are available from these foils. More recently a new energy analyzer was installed at the end of Sector 1 having a 12° and 23, 0.3% foils plus one 0.1% foil. These foils are read out by a scanning ADC controlled by the SLC control program. The magnet supply was also under the control of the SLC program so that once enabled by the operator, the SLC program had complete control of energy analysis.

To compute an accurate transverse emittance, the control program must have access to a quantitative measure of the beam radius. For this purpose two new profile monitors were installed at \( z = 10 \) m and at \( z = 100 \) m respectively. These monitors had a standard SLAC CSI screen which could be inserted remotely. Each screen was viewed with a Reticon camera, an image digitizer which utilized a 32x32 array of photodiodes. The image was displayed both locally on a TV screen and remotely in either video or graphic form via the SLC control program.

### IV. BEAM PARAMETER MEASUREMENTS

The parameters of the new high-intensity single-bunch beam that have been measured include the beam emittance, intensity, transmission, and the effects of transverse deflecting fields.

The transverse emittance of the beam was found by measuring the beam radius at a Reticon profile monitor for several orientations of the beam phase space ellipse. The ellipse was rotated by the control program by changing the strength \( k \) (integrated gradient/beam rigidity) of one of the upstream quadrupoles. If the behavior of the beam at the profile monitor is represented by the beam sigma matrix, \( \sigma(k) \), then \( \sigma_0(k) \), the square of the beam radius, describes a parabola,

\[
\sigma_0(k) - \sigma_0(k_0) = M_2 C (k-k_0)^2,
\]

in which \( k_0 \) is the quadrupole strength for the minimum spot size at the monitor, \( M_2 \) is an element of the matrix for the transport of the beam between the quadrupole and the monitor, and \( C \) is a constant. Since \( \sigma_0(k_0) \) and \( C \) can be found from a parabolic fit to the data, the transverse emittance, \( \varepsilon_x \), can be computed by the control program from the expression

\[
\varepsilon_x = \sqrt{\sigma_{22}^2 - \sigma_{21}^2} = \frac{\sigma_{11}(k_0) C}{M_{12}^2},
\]

where \( M_{12} \) is known theoretically. In these expressions the \( x \) and \( y \) motions are assumed to be decoupled and \( \varepsilon_y \) can be found by substituting the \( y \) subscripts 3,4 for 1,2. An example of a set of curve fits for a relatively low intensity beam (\( \approx 5 \times 10^9 \) electrons/bunch) is shown in Fig. 4. The emittance area calculated from these curves is \( \varepsilon_{xT} = 0.02 \pi m_0 c \text{cm} \) and \( \varepsilon_{yT} = 0.009 \pi m_0 c \text{cm} \).

The emittance at higher beam intensities was not
measured although under the existing control conditions it was clearly larger.

The energy and energy spread was measured at the end of Sector 1 with the new 12° energy analyzer. The energy spread, shown in Fig. 5, was typically about 2 foils wide or $\Delta E/E \sim 0.6\%$ at 770 MeV.

A single foil from this same analyzer was used to determine the longitudinal charge distribution. The analyzed current, $dq/dy$, was measured as a function of the phase, $\phi$, of the klystron immediately upstream. Two spectra were observed 180° apart from which the charge distribution could be deduced according to the following expression: 

$$dq = \frac{(dq_a/dy)(dq_b/dy) \gamma \sin \frac{1}{2} (\phi_b - \phi_a)}{|dq_a/dy| + |dq_b/dy|},$$

where $\phi$ is the beam phase and $\gamma$ is the peak energy contribution of the analyzing klystron. The charge distribution shown in Fig. 6 was calculated by assuming the peaks of the two measured spectra correspond to the same $\phi$, and that points at the same percentage of the peak value represent nearly the same $\phi$. For the SLC beam at low intensities, $\sigma$ is on the order of 1 mm, a factor of 2 greater than typical SLAC linear beams.

Fig. 5. Typical scan of the 24 SEM foils at the energy analyzer at $z=100$ m. Each bin represents a foil for which $\Delta E/E = 0.3\%$. The magnet current corresponded to a beam energy of 770 MeV at the center foil.

Fig. 6. Longitudinal charge distribution measured for the beam profile shown in Fig. 9.

100 ps rise time and connected to the gap monitor via a high-quality air-dielectric coaxial cable is shown in Fig. 7. The unfortunate tendency of these monitors to ring at S-band frequencies somewhat complicates the measurement, but by varying the timing of the gun pulse relative to the subharmonic buncher RF to create first a pre-bunch and then a post-bunch, it was possible to determine that the beam pulse did indeed contain but a single S-band bunch. The gain of the gap monitors was calibrated in the laboratory and so provided an independent measure of the beam intensity.

A third type of intensity monitor, which solved the problem of proper location, was the stripline beam position monitor described earlier. These monitors provided an accurate although not absolute measurement of intensity at each quadrupole location for the SLC control program.

The beam intensity was measured in several ways. At the beginning and end of Sector 1 are located toroids with which the charge in a linac beam pulse can be measured with an accuracy of ±10%. Since the SLC pulse contains about the same charge as a standard 1.6 μs linac beam pulse, these toroids are excellent standards although their locations are limited and in addition they cannot distinguish between single- and multiple-bunch beams.

This latter problem is solved by monitoring the beam induced pulse at a ceramic gap in the beam pipe. By reducing the resistance across a short gap to < 10 Ω the rise time of the induced pulse was kept below 100 ps. Ceramic gaps were installed at the $z = -16, -10, +10,$ and +100 m locations. A typical signal observed at the $z = -10$ m location using a sampling scope with a
known operating conditions.

was experienced in the vicinity of both the first effectiveness of the SLC control program is illus,

is at a radius > o" aperture, it appears that a great deal of scraping Fig. 8 (curve a) to be ~50% is consistent with the through the injector region which is indicated in and third triplets. Since about half the charge located at z ~ 0. To get the beam through this Sector 1 lattice. Post-experiment analysis has calculated from the emittance measured at the beginning of Sector 1 was

adjusted through the SLC control program, but the transport of the beam to Sector 1 was not modeled. Instead the strength of each focusing element was adjusted to give a betatron phase shift of 90° per period by maximizing the transmission through the succeeding element.

The modeling for Sector 1 began at z = 11 m where the third quadrupole triplet shown in Fig. 1 was located. This triplet was generally operated as a doublet to improve the match into the Sector 1 lattice. Post-experiment analysis has shown that a match was never in fact achieved Fig. 2(b) and (c) shows a typical result where the quadrupole configuration for Sector 1 was identical with that for Fig. 2(a).

The matching was unlikely to succeed since the emittance at the beginning of Sector 1 was calculated from the emittance measured at z = 100 m. The task of efficiently transporting the beam to Sector 1 was also difficult because of a limiting orifice of r = 4.9 mm (a collimator) located at z ~ 0. To get the beam through this aperture, it appears that a great deal of scraping was experienced in the vicinity of both the first and third triplets. Since about half the charge is at a radius > r, the observed transmission through the injector region which is indicated in Fig. 8 (curve a) to be ~50% is consistent with the known operating conditions.

Even with the poor match in Sector 1, the effectiveness of the SLC control program is illus

trated by the high transmission shown for this region in curve b of Fig. 8. However, when the current in Sector 1 increased above about 1.5x10^10 electrons/bunch, wake field effects became a limiting factor. As the current increased unstable "arms" were extended from the main beam profile observed at the end of the Sector. At the highest intensities the entire profile appeared to be unstable.

To study the transverse wake fields under more controlled conditions, the intensity was reduced to ~10^9 electrons/bunch, a level for which the beam was fairly stable through Sector 1. The beam was then allowed to drift for the last 50 m — equivalent to approximately 180° of betatron phase advance — of the Sector. Using the dipole corrector magnets located in this region, the drifting beam was given known offsets between ±2 mm (confirmed with the position monitors), and then recentered at the end of the Sector. The wake fields generated by the off-centered beam displaced the tail of the bunch relative to the head. The displacement was observed as a shift in portions of the beam profile at the end of the Sector. A comparison of the profile in the horizontal plane (summed over the vertical plane) for horizontal displacements of 0 and of ±2 mm are shown in Fig. 9(a), (b) and (c).

The beam profile at the end of Sector 1 for a zero emittance beam can be computed for any assumed wake function using a model of the linac and a given longitudinal charge distribution. The results of such a computation by R. Stiening, using the measured charge distribution (Fig. 6) corresponding to the data of Fig. 9, and with the undeflected beam profile of Fig. 9(a) folded in, is shown in Fig. 9 for three assumed values of the wake function. The wake function was calculated by P. B. Wilson and K. Bane from a modal analysis of the SLAC accelerating structure with analytic extension. In Fig. 9(d), (e) and (f), a weight of 0.5, 1.0 and 2.0 was assigned to the calculated wake function. Clearly the computed profile of Fig. 9(e) is most like the measured profiles of Fig. 9(b) and (c). This result suggests the computed transverse wake function is correct within a factor of 2.

V. CONCLUSIONS

As the beam intensity was increased, it was evident that the emittance increased beyond the desired level. Since the effects of wake fields measured at low intensities agreed with the computed effects, it seems that the conditions for beam injection were not optimized. The most likely source of the problem would be an unstable power supply for one of the injector dipole orbit correctors — indeed a post-experiment check of all CID power supplies revealed a likely candidate. The inclusion of the CID corrector power supplies in the SLC control program will help eliminate this problem.

To achieve the maximum possible transmission, a model must be developed for the transport of the beam from CID to Sector 1. Control of the beam would also be improved by the addition of a new quadrupole triplet at the exit of the CID DLWG-section.

![Fig. 8. Beam transmission as a function of current at output of CID (see Ref. 12). Curve a is for Sector 0 only, curve b is for Sector 1 only.](image-url)
Fig. 9. Beam profiles in the horizontal plane (32 bins/cm): measured profiles with beam offset of (a) 0 mm, (b) +2 mm, and (c) -2 mm; computed profiles for an offset of -2 mm using a computed wake function with a weight of (d) 0.5, (e) 1.0, and (f) 2.0. All profiles are integrated over the vertical plane and have normalized areas. Note the reversed abscissa in (b).

The SLC beam tests in Sector 1 will continue during the present linac operating cycle. With the improvements just described it should be possible to increase in a controlled manner the beam intensity transmitted through Sector 1.

Discussion

We don't think it will be necessary to add any new quadrupoles to optimize the matching section, certainly not in Sector 1. The one triplet we are adding at the 40-MeV point of the injector output will give us more control over the phase ellipse orientation coming out of the injector solenoid. Our calculations indicate that the phase ellipse at that point can be entered into the transport model and a good match into Sector 1 results.

We made longitudinal charge distribution measurements, but we did not make measurements of the long, Wake-field effects.

REFERENCES

6. Anode currents of 20 A have been produced with a different pulsar. See P. F. Koontz, "CID Thermionic Gun System," this conference.
12. The current measured at the Faraday cup at z = -9 m and at the gap monitor at z = -10 m was used as the basis for the source current since this location was far enough away from the buncher to be unaffected by the unbunched electrons. However the computed transmission from CID may be unduly low since it is based on the intensity measured by a beam position monitor located near CID at z = -13 m.
14. Up to 40 nC in a single bunch has been produced with the L-band linac at ANL using a new double-cavity buncher operated at the 12th subharmonic, although the useful charge is generally limited to 25 nC.
15. G. Mavrogenes, ANL, private communication.
16. Although the accelerator drift sections have a radius of ~12 mm, the limiting aperture within each 3-m DLWG section has a radius of ~6.7 mm.
17. The analysis made use of the computer program TRANS for finding the modes in the structure as described in B. Zotter and K. Bane, PEP-NOTE-308 (1979).

We think the gun should be kept outside any magnetic field as possible to keep the emittance small. However, it may be a valid point that our emittance problems may occur before we are relativistic while still within the solenoid, so there may be an argument that the cathode should be inside the solenoid.
CAVITY LOADING ASSOCIATED WITH HIGH-CURRENT RF LINACS

by
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ABSTRACT
The limitations on high-current rf linacs due to cavity loading are studied. A linear analysis as well as self-consistent particle simulations of a multipulsed 10 kA beam indicate that only a negligible small fraction of energy is radiated into nonfundamental cavity modes.

Cavity loading due to beam driven radiation is a well-known problem in radiofrequency linear accelerators. In fact, one of the major criticisms of the high-current rf linac concept was that beam driven radiation into unwanted modes would be catastrophic since the radiation energy source scales as $E \cdot J$, or as the charge of a micropulse squared. In particular, enhanced spectral content in unwanted modes not only serves as a sink for beam energy but it can seriously magnify transverse beam emittance. Even worse, the coupling to the non-axisymmetric $\ell = 1$ mode would deflect the beam into the drift tube wall. This last issue of the beam breakup mode\(^1\) is addressed in another report. In the present section we have undertaken a quantitative study of high-current driven cavity radiation to indicate both the magnitude and scaling of the axisymmetric beam loading.

A simple right circular, cylindrical cavity is employed to represent the essential physics, if not the details of more complicated, realistic cavity shapes. A major advantage of this is that the eigenmodes for such a system are readily calculable. Even though the ideal structure is perturbed by drift tube apertures of radius $r_\text{d}$, this is a relatively small effect so long as the cavity radius $R$ satisfies $R \gg r_\text{d}$. As a further simplification, we will consider only single cavities, driven at the fundamental TM frequency. While coupling of cavities is often done to enhance synchronism, we feel that this more complex configuration can best be illuminated initially by treating the single cavity loading exhaustively.

The study is limited to intense electron beams, which are at least modestly relativistic upon injection into the cavity. In fact, when treating the beam dynamics with simulation, the electrons are constrained to be neither relativistic nor to follow one-dimensional trajectories. Transport of multikilopondre beams into rf cavities, however, does require that they be relativistic enough to avoid space-charge limitations. For 10 kA micropulses this corresponds to about 3 MV.\(^2\) In the simulations, the transport itself was aided by assumption of a straight solenoidal magnetic guide field. Inclusion of more realistic focusing fields can be treated but there is no reason for doing so at this juncture.

The model we use to calculate the response of the cavity modes to the beam is well known.\(^3\) It is not a self-consistent calculation in that the modification of the beam distribution by the cavity fields is not taken into account. However, we find the results to be in good agreement with self-consistent electromagnetic, relativistic, two-dimensional, particle-in-cell simulation results.

In terms of the vector potential $\mathbf{A}$ and the scalar potential $\phi$, Ampere's law becomes
\[ \nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = -\mu_0 \hat{j} - \frac{1}{c^2} \frac{\partial}{\partial t} \nabla \phi \]  

We have chosen the Coulomb gauge: \( \nabla \cdot \phi = 0 \). The vector potential can be expressed in terms of the cavity eigenmodes \( \hat{a}_\lambda \),

\[ \phi = \sum_\lambda a_\lambda \hat{a}_\lambda \]  

which satisfy \( \nabla^2 \hat{a}_\lambda + (w_\lambda^2/c^2) \hat{a}_\lambda = 0 \). Because \( \phi = 0 \) on the cavity surface and \( \nabla \cdot \hat{a}_\lambda = 0 \) in the cavity volume, this term vanishes, and the time evolution of a cavity mode is given by

\[ \frac{\partial^2 a_\lambda}{\partial t^2} + \frac{w_\lambda^2}{c^2} a_\lambda = \frac{j_\lambda}{\varepsilon_0} \]  

where

\[ j_\lambda = \int_\Omega \hat{a}_\lambda \cdot \mathbf{j} \, d^3x \]  

As a starting point, we consider the cavity radiation driven by a point charge which enters the cavity at \( t = 0 \) and moves rigidly along the z-axis at velocity \( c \). For such a charge the current density is

\[ j_z(z,t) = pc \delta(z - ct) \delta(r)/2\pi \]  

Suppose we have a train of point charges separated by a time \( 2\pi/\omega_x \), the current density is then

\[ j_z(z,t) = pc \sum_{n=1}^N \delta[z - ct + 2\pi(n - 1) \varepsilon/\omega_x] \times \delta(r)/2\pi \]  

If we let \( \omega_x \to \infty \) and \( N \to \infty \) while keeping \( T = N \cdot 2\pi/\omega_x \) constant, we get the result for a constant current pulse of width \( T \). Thus, for a train of micropulses of finite pulse width the energy in an initially undriven mode after \( N \) pulses is then

\[ E_{n\omega_0} = \frac{2N^2 \mu_0^2}{\varepsilon_0 \pi R^2 d} \frac{1}{\chi_{10}^2(x_{01})} \left[ \frac{\sin(N\omega_0/\omega_{10})}{N \sin(N\omega_0/\omega_{10})} \right]^2 \times \left[ \frac{\sin(\omega_0 T/2)}{(\omega_0 T/2)} \right]^2 [1 - (-1)^p \cos(\omega_0 d/c)] \]  

Finally, the energy radiated into the fundamental mode is

\[ U_{010} = \frac{1}{2} \frac{\varepsilon_0 \varepsilon_{2010} R^2 d j_z^2(x_{01})}{\chi_{01}^2} - \frac{2N^2 \mu_0^2}{\pi \varepsilon_0 d} \frac{\sin^2(\omega_0 d/2c)}{\chi_{01}^2(x_{01})} \]  

Our first concern was to check the analytical results against particle-in-cell simulations. In Fig. 1 the amount of energy radiated into an initially empty cavity is plotted as a function of the number of micropulses passing through the cavity. The parameters are \( \rho = 1.74 \times 10^5 \text{ Coulomb/micropulse} \), \( R = 2.3 \text{ m} \), and \( d = 2.5625 \text{ m} \). The comparison between the analytic result and the "slug" beam is very good. Where a fully self-consistent beam is injected into the cavity, a combination of space-charge and induced fields reflects the beam after about 7 pulses, i.e., the energy in the cavity modes becomes about equal to the kinetic energy of the micropulse. The details of this simulation will be discussed in more detail later, but we feel that the analytic results will yield essentially the correct beam loading for an actual beam.

With some confidence in our result, the energy in unwanted modes was calculated for a 10 kA beam for various micropulse widths after 100 pulses. Again, the cavity dimensions are \( R = 2.3 \text{ m} \) and \( d = 2.5625 \text{ m} \). Basically, we find that the energy going into unwanted modes is negligible compared to the energy going into the fundamental. This will be true even for \( \omega \neq 0 \) modes as long as the cavity is "detuned", i.e., \( \omega_\lambda/\omega_{10} \neq \text{odd integer} \). A summary is given in Table I.

The simple model derived in the previous section is very useful for calculating the beam loading on the cavity. But it neglected space charge, finite transverse dimensions of the beam, and beam distortion by the cavity fields, however. In short, it did not attempt to evaluate the effect of cavity fields on the beam. To study the self-consistent dynamics, we have employed the two-dimensional particle-in-cell
Fig. 1. Energy radiated into cavity modes $\Sigma \lambda U_\lambda$ as a function of pulse number $N$. The open boxes represent the self-consistent simulation results, the closed circles the "slug" simulation results, and the x's the analytic theory.

code, CCUBE. This fully electromagnetic, relativistic simulation code has been used previously in a wide variety of intense non-neutral beam and accelerator studies. The present calculations were performed in cylindrical $(r,z)$ coordinates, with azimuthal symmetry (that is, $\phi = 0$).

A pill-box, right-circular cavity was used for these simulations. The cavity, when driven, was operated on the $TM_{010}$ mode. In fact, this cavity fundamental was the dominant mode excited in undriven cavities when a series of beam pulses was injected. The cavity length, $d$, was taken to be slightly larger than its radius, $R$, with $d/R$ ranging from 1.07 to 1.16. Since the calculations were scaled to the $TM_{010}$ mode, no absolute dimensions are attached to them. In fact, however, we are quite interested in PHERMEX, which operates at 50 MHz, or similar high-current linacs. For a PHERMEX-like cavity, $R = 2.3$ m and $d = 2.6$ m.

Because of the complicated dynamics of the full self-consistent loading, a series of calculations was performed to explicitly isolate various aspects of the problem. In the first, a sequence of fixed current profiles was propagated through the single cavity. These current "slugs" radiated electromagnetic fields into the cavity but were not in turn acted upon by the fields. These simulations were closest to the assumptions of the loading model derived above. The cavities were not driven so there was no confusion between the radiated field distributions and a pre-loaded field. The second type of simulation also contained no cavity pre-excitation but simulation macro-particles were used to construct the injected pulses. Because these pulses were free to respond to the self-excited cavity, space-charge effects and kinetic energy depletion due to $J \cdot E$ were self-consistently calculated. To facilitate pulse propagation across the cavity, a uniform solenoidal field $B_z$, such that $Q = i_\omega$, $Q = \frac{|e|B_z}{mc}$, was included. Although imposition of a non-fringing field of this magnitude around a 2.3 m radius cavity is possible, it is admittedly not practical. For these calculations, it was unnecessary to complicate the beam dynamics with focusing effects, however. Finally, the realistic accelerator problem was treated. We limited the studies to early cavity loading, because cavity loading is most severe before the beam has become too "stiff" ($\gamma > 1$). The cavity was driven in the $TM_{010}$ mode to between 9.0 MV/m at 50 MHz. Maximum peak currents injected were 18.5 kA and minimum, 0.6 kA. The former corresponded to an average current of almost 1.4 kA.

The base line calculations were slug simulations that can most easily be compared with the analytic model. There were several salient features of the model amenable to simple tests. The model, for instance, predicted that the total energy radiated into the cavity should vary as the square of the total charge per pulse. This was repeatedly verified for pulses of various radius and longitudinal extent. The spectral distribution of cavity energy moreover was identical for pulses of the same physical shape but different density. For pulses injected at the same frequency as the cavity fundamental, the model moreover predicted that the fraction of the total cavity energy outside the fundamental would decrease as the number of pulses increased. For a 9.2 kA peak current injection, Fig. 2 shows the fraction of the energy not in $TM_{010}$ as a function of pulse number in the simulation compared with the theory. As a complement to this, Fig. 1 shows the total radiated energy for this case as a function of pulse number. From these, it is evident that the pulses are very effectively driving the cavity $TM_{010}$ mode.

The magnitude of this field is increasing linearly with the number of pulses, so that after 10 pulses, the peak $TM_{010}$ field has attained a
magnitude of 2.8 MV/m. While this field is in the decelerating phase, it is a significant fraction of the accelerating gradient. This suggests the fascinating prospect of building an rf autoaccelerator. The purpose of such a configuration would be to overcome power limitations of existing radiofrequency sources. Creating an initial beam by pulse power certainly has limits, but these appear to be in the range of 10's of gigawatts for conventional power supplies. Thus, if a multi-terawatt electron beam can be induced to radiate its energy into a given cavity mode, it seems quite feasible to operate rf linacs in as high a gradient as the cavities can withstand (either Kilpatrick or field emission).

As mentioned above, we have verified that the total energy in the cavity increases as the square of the number of pulses but that the relative fraction outside the fundamental decreases. The excitation of higher order modes, therefore, becomes less important as the number of pulses increases. Even if the magnitude of fields in these unwanted modes were to remain high, we are confident that loading of the cavities with a frequency dependent absorber could reduce the levels to acceptable values. A more fundamental limitation is depletion of the pulse energy after the gradient reaches sufficient magnitude.

If the kinetic mean energy of an injected pulse is \((\gamma - 1)mc^2\), this pulse will lose all its energy once the loaded field has reached a magnitude \(E_z\), such that

\[
\int_0^d E_z \cos wt \, dz \geq (\gamma - 1)mc^2 \tag{9}
\]

where \(t = (z - z_0)/v_0\). This places an upper bound on \(E_z\) if \(E_z = w(\gamma - 1)mc^2/(ec \sin wd/2c)\).

Once this gradient is attained, we find that a moving virtual cathode forms on the pulse. By this we mean that a fraction of the beam is reflected, while the rest propagates through the cavity. In a low-current beam for which \(\Delta y/\gamma \ll 1\), it is plausible to treat single particle trajectories in which all particles are either transmitted or reflected. For these high-current pulses, however, the collective behavior of a virtual cathode is observed whenever the pulse kinetic energy drops below a finite, non-zero value. The reflected portion of the pulse is moving in the opposite direction, and so is in an acceleration phase. Since it extracts energy from the cavity, the net energy radiated is reduced from the nonreflecting case. Fig. 3 shows growth of rms \(E_z\) field at the cavity midpoint for a slug simulation compared with a fully interacting particle one. The field has reached pulse reflecting levels by pulse number seven. Interestingly, even after partial pulse reflection, the TM\(_{010}\) field continues to grow.

The net efficiency of field generation is clearly reduced, but as Fig. 4 shows, the relative magnitude of the TM\(_{010}\) mode increases vis-a-vis any of the non-fundamental and presumably deleterious modes. Actual operation in this fashion may prove undesirable because of breakdown problems associated with residual charge left in the cavity, but it is not ruled out on the basis of the spatial field distribution.

The spectral distribution of radiated energy is of considerable interest. Unfortunately, exact details of the spectra depend sensitively on details of the cavity structure. As an example, a series of calculations were performed in which the pulse structure and current were identical, with only the width of the cavity varied. Although the ratio of width to radius of

Fig. 2. Relative fraction of field energy in cavity fundamental \(w_{010}\) as a function of pulse number \(N\) for slug simulation \((\gamma = \infty)\); \(I_{\text{max}} = 9.2\) kA, \(I_{\text{ave}} = 0.6\) kA, \(T = 14.1\) \(\omega_p\).

Fig. 3. Comparison of rms magnitude of \(E_z\) in slug \((\gamma_0 = \infty\); closed circles) and particle \((\gamma_0 = 10.0\); open circles) simulations as a function of pulse number \(N\); \(I_{\text{max}} = 9.2\) kA, \(I_{\text{ave}} = 0.6\) kA, \(Q_0 = 1.0\) \(\omega_p\). Because of partial pulse injection initially on particle calculations, pulse number is shifted by one relative to actual time for plotting.
Finally, self-excitation of the cavities by intense injected pulses does not appear to have fundamental problems. A practical limitation may prove to be virtual cathode formation when too much energy is extracted from the pulse, but even this condition did not degrade the relative energy flow significantly. The efficiency of field accretion was reduced, however. Further work on this concept is apparently needed to assess its ultimate utility.

ACKNOWLEDGMENT

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REFERENCES


Discussion

One could increase the amount of stored energy available by using higher order modes.

A second comment is that the rate at which power goes into the cavity does not depend on the Q, but on the rf power source.

In point of fact, the only thing demonstrated about the relative decrease in the nonfundamental mode energy was that it was just a consequence of pulse length. Clearly, if pulses are injected at the fundamental frequency, the Fourier transform indicates that this mode will dominate. What wasn't obvious was that this result wouldn't change when finite beam injection gave very nonlinear effects in the beam dynamics, with virtual cathode formation, violent fluctuations in the beam, and so on.
The phenomenon of beam phase volume growth in acceleration process causes considerable difficulties in designing and operating high average beam current linacs. The emittance growth in linac-injectors of proton synchrotrons deteriorates the injection conditions.

This problem has been discussed in a number of papers [1-10], but however a unified theory embracing every aspect of this effect is not yet created. The existing experimental data are obviously insufficient and in many cases they are contradictory. This discrepancy is to some extent accounted for by the fact that the initial distribution is often measured at the linac input, while the emittance change in the matching channel remains uncontrolled. Besides, the final result is to a considerable extent influenced by different methods of data processing.

In our opinion it is very important to proceed with accumulating experimental data about the beam phase volume blow-up.

The linac I-2 belongs to one of the most intensive injectors with an output pulse current more than 200 mA. That is why the investigation of the beam phase volume blow-up with the help of this linac is of both practical and theoretical interest.

The measurements were carried out by means of two slits. The first measuring instrument was placed at the output of the preinjector in front of the buncher, behind which two quadrupole doublets of the matching channel could be found. Corresponding braking fields were created in the measuring instrument for reducing the influence of the secondary electron current. The input of the buncher and the input of the drift tube contained the beam current transformers. They were supplied with the variable aperture Faraday cups with the diameter equal to 38 and 20 mm correspondingly which were equal to the aperture of the subsequent part of the channel. The combination of the beam-current transformer with the variable aperture Faraday cup allows to measure the beam current incoming to the decreased aperture. The emittance of the beam at the linac input was estimated according to the data about the reduction of the beam current in the buncher and the first drift tube (DT-101). This evaluation is given below. The second measuring instrument after the linac also contained no lenses.

Fig.1a and 2a show the distribution of the equal phase-space density lines obtained respectively with the help of the first and second measuring instruments.

Absolute emittances \( \mathcal{E} = \int \sigma d\lambda \) were calculated in accordance with the figures limited by the equal phase-space density lines.

In order to make the comparison of input and output data more convenient absolute emittances were evaluated by the respective normalized value \( \mathcal{V}_o = \frac{\mathcal{E}}{\mathcal{E}} \).

The curves connecting the phase density values of the current \( \mathcal{I}/\mathcal{I}_{tot} \) with the values of the normalized emittances limited by the lines with the given density levels are dotted on Fig.1b and 2b. Let us call these curves subsidiary. The area of the figure limited by the axes coordinate and the subsidiary curve must be equal to the total current of the beam

\[
\mathcal{I}_{tot} = \int_0^\infty \mathcal{V}_o d\mathcal{V}_o \tag{1}
\]

The dependance of the relative quota of the current which is contained in the given part of the normalized emittance on the value of the emittance (continuous curves Fig.1b and 2b) \( \mathcal{I}/\mathcal{I}_{tot} \) are determined by means of subsequent summarizing of separate parts of this figure

\[
\mathcal{I} = \int_0^{\mathcal{V}_o} \mathcal{V}_o d\mathcal{V}_o \tag{2}
\]

The curves

\[
\frac{\mathcal{I}}{\mathcal{I}_{tot}} = \mathcal{V}_o \tag{3}
\]

give the distribution of the beam current versus emittance value.

It is necessary to point out the fact that the most important criterion of the precision of the carried out measurements is the coincidence of the total beam current values achieved by integration of the subsidiary curve and the total beam current obtained with the help of the direct measurements of the beam current intensity.

In order to evaluate the influence of the beam current intensity on the effect of the phase volume growth more than two tens of the current distribution at the linac input and output were divided into three groups depending on the beam current value in the first drift tube (I(10)) - Fig.3a and in the second viewing chamber (I(10)') - Fig.3b. The average distributions were made for each group. If one has a look at Fig.3 one will see that with the help of solid lines we depict the beam current average curves obtained in the first measuring instrument. For each curve we give the limits of the beam current change at the linac input (I(10)) on Fig.3b you can see the average curves obtained in the second measuring instrument after the linac.

The most considerable deflection of separately taken curves from the average distribution for each group did not exceed 3% for the beams with maximum intensity.
and reached 10% for the beams with the lower intensity. Taking into consideration this fact we shall use average curves of the beam current distribution for our further analysis.

The dotted lines (Fig. 3a) give the evaluation of the beam current distribution just at the linac input. The dotted lines were obtained by means of evaluation of respective solid curves (Fig. 3a). For this purpose it was necessary to determine the average ratio of the current incoming to the linac to the current measured at the viewing chamber corresponding to each distribution group at the output. The average ratio are given on Fig. 3 with the help of the dotted horizontal lines and are marked by the same index as the average distribution curves. The aperture of the buncher limits the beam mainly in coordinates and the aperture of the drift tube (TD 101) limits it also in transversal velocities. Between the buncher and the linac input the matching quadrupole lenses - two doublets are placed.

The presence of optics to some extent causes the mixing of the particles. The optics transforms the outline of the emittance and approximates it to the matching form. That was why it was assumed that the particles in the external sphere of the emittance were cut off between the viewing chamber and the linac input. The total beam current just at the linac input is taken for 100% and the part of the current distribution in the emittance lying below the level of the cut-off was proportionally stretched. This resulted in the respective dotted curves.

While comparing the current distribution at the linac input and output (Fig. 3a and 3b) one can easily see that in the process of acceleration a considerable increase of the beam phase volume takes place. The dependence of the beam emittance at the linac output on its intensity in the range of estimation of the pulse current varying from 60 to 200 mA is not practically observed. However in case of a comparatively low intensity (curvet on Fig. 3b) one can see quite distinctly the expansion of the peripheral field of the beam in comparison with the beam kernel.

Table I contains the average value of the current in the emittance 2 mm.mrad at the linac output and respective value of the average phase density for each group for evaluation of the growth of the beam kernel phase volume. It is possible to compare the estimated groups at the linac input and output. Judging by Table I one can note that the phase density in the beam kernel at the linac input is lower than the average phase density of the beam just at the linac input and is equal to 1/4 that differs a little from the 1/3 that is a capture coefficient value.

Thus the phase density in the beam kernel goes down insignificantly, while the growth of the phase volume in 3-5 times is mainly due to the peripheral component of the beam. As the emittance of the beam at the linac input goes down with the reduction of the beam current (Fig. 3b), the increase of the normalized emittance turns out to be greater for the lower intensity beam.

Fig. 3c shows the evaluated current distribution curves in the emittance borrowed from paper 4. Curve I corresponds to the even distribution of the phase density on the surface and is close to the experimental current distribution at the linac input, curve 5. Curve 2 was obtained by means of projecting to the phase plane of the four-dimensional hyperellipsoid with the even distribution of phase density in the hyperellipsoid volume. Curve 3 corresponds to the projection of the six-dimensional hyperellipsoid with the even distribution of density in the six-dimensional space. Curve 4 corresponds to (according to the terms used by the authors of paper 4) Gaussian distribution of phase density on the plane that is it is an exponent. Finally dotted curve 5 corresponds to the average distributions at the linac output (Fig. 3b). Experimental curves 5 and 6 were given to scale of the evaluated curves 1-4 by means of equalizing of the initial slope.

The comparison of the experimental current distribution (dotted curve 6) with the evaluated curves (Fig. 3c) shows that the average distributions for the high pulsed intensity beams at the linac output are most close to the curve corresponding to the even distribution of the density in the six-dimensional hyperellipsoid volume.

The authors express their sincere gratitude to I.M.Kapchinskij who initiated this work and helped to process the obtained experimental data. They want to thank V.A.Batalin for his participation in the discussions of the results of the experiments and are much obliged to V.S.Stolbunov for his assistance in preparing the measuring equipment.

References
Fig. 1  a) Plots of the equal phase-space density lines for the beam at the preinjector exit.
b) A phase-space density and percentage of the preinjector current distributions versus emittance value.

Fig. 2  a) Plots of the equal phase-space density lines for the output linac beam.
b) A phase-space density and percentage of the output linac current distributions versus emittance value.

Table I

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<tr>
<th>LINAC INPUT</th>
<th>LINAC OUTPUT</th>
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<td><strong>Full Current</strong></td>
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Fig. 3  a) Average distributions of the input linac current versus emittance value.  
b) Average distributions of the output linac current versus emittance value.  
c) A comparison of the various beam current distributions versus emittance value of calculated date (solid lines) and measured date (dotted lines). The interpretation of the curves there is in the text.
Summary

An accelerator for spallation breeding of fissile fuel must have low beam loss and high acceleration efficiency. An extensive investigation using the PARMTEQ and PARMILA computer beam dynamics codes has been undertaken to obtain a reference design for a 100% duty cycle 300 mA 10 MeV proton linac called ZEBRA (Zero Energy Breeder Accelerator) that could serve as the first stage of an accelerator-breeder. This paper discusses results of this investigation, showing how current carrying capacity and accelerating efficiency in both RFQ's and DTL's is affected by accelerator and injector parameters.

Introduction

The Zero Energy Breeder Accelerator (ZEBRA) is being designed as a demonstration injector for an accelerator breeder. A 300 mA cw proton beam at 10 MeV is required that is of sufficiently high quality to be further accelerated to 1 GeV with very low beam loss. In ZEBRA, beam spill on copper surfaces above 2.2 MeV (the neutron activation threshold for protons on copper) must be minimized. Below this energy, appreciable loss can be tolerated in the radiofrequency quadrupole structure (RFQ), medium energy beam transport line (MEBT) and drift tube linac structure (DTL) with limits being determined by sputtering and energy deposition. The ZEBRA reference design is summarized in Table 1.

<table>
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<td>Injector</td>
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The constraint associated with frequency doubling between the RFQ and DTL tanks puts stringent limits on beam phase and energy spread at the RFQ output. The computer codes RFQUIK, PARMEQ and PARMILA were used to search for a reference design that would meet the constraints described by Chidley et al. Briefly summarized, accelerator constraints used in the investigation of beam characteristics for different designs were as follows: frequencies of the RFQ and DTL were fixed at 108 and 216 MHz respectively and the RFQ output energy was fixed at 2 MeV. A current capability of 400 mA was used to provide a safety factor for the required 300 mA operating value. Peak surface electric fields in the RFQ and DTL structures were required to be less than 1.75 and 1.25 times the Kilpatrick breakdown limit, respectively. Other parameters such as the beam bore hole radii in the two tanks, and transition energies between the regions in the RFQ (shaper, gentle buncher, etc.) were freely varied to find a design that maximized RFQ transmission and efficiency while minimizing dc injection voltage and beam spill in the DTL.

RFQ Beam Dynamics

In designing the RFQ for ZEBRA, the additional constraints proposed by Crandall, Stokes and Wangler were imposed. They are discussed in a companion paper by Chidley et al. These constraints may not give the optimum RFQ design for high current and low injection energy, but they represent a conservative choice because the structure can be built and the required field pattern can be achieved. For the selected design, a 2000 particle PARMTEQ run with 460 mA of injected current gives a 375 mA, nominal 2 MeV beam with output characteristics shown in Fig. 1.
Sensitivity to Source Emittance

The matched input beam for the RFQ, as given by the code IMS, is identical in both planes and is: 
\[ \gamma = 0.62, \alpha = 7.5, \beta = 92.5, \varepsilon = 0.0475, \]
where 
\[ \gamma x^2 + 2\alpha xx' + \beta x'^2 = \varepsilon/\pi \]
is the equation of transverse phase space occupied by the input beam with \( \varepsilon \) having dimensions of cm-radians. Transmission of the RFQ as a function of input beam emittance \( \varepsilon \) for a 460 mA input beam is shown in Fig. 2.

Fig. 2 RFQ transmission versus input beam emittance.

\[ \gamma x^2 + 2\alpha xx' + \beta x'^2 = \varepsilon/\pi \]
\[ \alpha = 7.5 \]
\[ \beta = 92.5 \text{ cm/rod} \]
\[ \gamma = 0.62 \text{ rad/cm} \]

At the optimum \( \varepsilon \) value of 0.0475 \( \pi \) cm-rad, 81.5% or 375 mA is accelerated to > 1.9 MeV with an additional 23 mA of lower energy beam being transmitted. Most of the lower energy beam is < 0.6 MeV and does not get through the quadrupoles in the MEBT. Notice in Fig. 2 that the percentage of low energy beam does not change over the range of \( \varepsilon \) studied. Figures 3 and 4 show how the total transmission of the RFQ depends on the input beam transverse emittance shape parameters "\( \alpha \)" and "\( \beta \)". Further studies on variable current effects are necessary to understand accelerator operation and matching conditions.

Fig. 3 RFQ transmission versus input beam "\( \alpha \)".

Variable Current Operation

RFQ output current and transmission (for particles > 1.9 MeV) are shown as a function of input current in Fig. 5. These PARMTEQ runs indicate a current limit for this RFQ design of \( \approx \) 430 mA. To check that the ZEBRA design is suitable for an injector for a high energy linac, PARMILA runs with the DTL were taken to 100 MeV. These runs predict that > 98% of the beam exiting the RFQ at > 1.9 MeV can be captured and accelerated to 100 MeV. We should achieve the design 300 mA with \( \approx \) 360 mA into the RFQ.

Fig. 5 RFQ output versus input current (\( N_{\text{out}} > 1.9 \text{ MeV} \)).
A further requirement for ZEBRA is that the output (10 MeV) current should be variable from 300 mA down to 0 mA. A difficulty in achieving this current range is that a single stage injector has limited current variability at fixed voltage. The reference design calls for a two stage injector to provide variable current at constant injection energy but it may be preferable to use a single stage injector. At design current (360 mA input), 40 mA of low energy beam will be spilled on the RFQ vanes and it is assumed that the RFQ will be constructed to tolerate this. Therefore at lower input currents, a higher percentage spill should be tolerable provided that the total spill remains less than 40 mA and spill in the DTL is not increased. Beam spill in the RFQ as a function of input beam energy (injector voltage) is shown in Fig. 6.

Figure 6 shows that it should be possible to operate with an injector voltage of 60 kV when the input current is 110 mA and still have tolerable beam spill. Under these conditions, PARMTEQ predicts 40% transmission of output energy $> 1.9$ MeV (i.e. $> 45$ mA out). As with the design current case, there is little output beam in the energy range from 0.6 to 1.9 MeV so spill in the DTL should not be markedly different. By further reducing the injector voltage, the high energy output beam transmission continues to decrease, reaching zero at $> 53$ kV. Therefore, if by reducing the injector voltage to 60 kV the current can be decreased to $< 50$ mA (Shubaly discusses how this can be achieved), further small reductions in injector voltage should permit any desired remaining fraction of the beam to be dumped in the RFQ. By this means it should be possible to vary the current that will be accelerated by the DTL from the design operating value to zero with a single stage injector. More tests and detailed beam dynamics calculations are required to confirm or reject this proposal.

**DTL Beam Dynamics**

**Transverse Acceptance**

The calculated normalized acceptance of the DTL (3 π cm-mrad) is approximately 4 times the 90% normalized emittance of the RFQ output beam. Detailed matching between the RFQ and DTL will be done, but a simple MEBT comprising 6 drift tube quadrupoles at $\Delta$ spacing and a 216 MHz buncher is sufficient to provide 100% capture by the DTL in the transverse planes. Increasing the transverse emittance of the RFQ output beam by a factor of 2 reduces the capture to 96% according to PARMILA calculations with a 400 mA input beam to the DTL. Transverse matching and acceptance does not therefore appear to be a restriction for the ZEBRA DTL and MEBT assuming misalignment errors do not significantly degrade the acceptance. The misalignment errors that seem to present the most potential problems are longitudinal rotation errors in the quadrupoles. Calculations with quadrupole rotations show that if the uncertainties are less than $\pm 1^\circ$ there should be no problems. However if the uncertainties are $\pm 5^\circ$, emittance growth by an additional factor of 2 and beam loss up to 30% is possible.

**Longitudinal Acceptance**

Total phase spread for the output beam from the RFQ is approximately $85^\circ$ at the 108 MHz RFQ frequency. Thus at the 216 MHz DTL frequency, the phase width is $170^\circ$ - too broad to be completely captured by the DTL. The capture percentage in the DTL was improved by operating the first ten cells at a higher gradient and larger synchronous phase than the remaining 20 cells where the gradient and phase are closer to the optimum for accelerator efficiency. Calculations demonstrated that capture was still inadequate and a buncher was included in the MEBT. PARMILA calculations with this configuration predict that $> 99\%$ of the beam from the RFQ with energy $> 1.9$ MeV can be captured with most of the lower energy particles being spilled into the MEBT beam line.
Phase-energy profiles and emittance plots for the ZEBRA reference design are shown in Fig. 7. Of particular concern is the tail on the PHI-W plot (lower right) at the output of the ZEBRA tank. These are particles that have not been captured longitudinally and would be lost in a longer DTL at energies sufficient to cause activation problems. It appears therefore that better discrimination and longitudinal matching in the MEBT will be necessary.

Conclusions

Beam dynamics calculations show that the ZEBRA reference design meets most of the requirements for an accelerator breeder injector. Improvement is required, in the longitudinal phase space capture of the RFQ output beam by the DTL operating at twice the RFQ frequency, to reduce high energy beam spill in the DTL. Possible means of improving the capture, including modifying the RFQ design recipe, alternate bunching schemes such as incorporating a drift plus kick into a lengthened RFQ, and different fields and field gradients in the DTL, will be investigated.

References

2. B.G. Chidley et al., "Design and Constraints for the ZEBRA Injector, RFQ and DTL", ibid.
STATISTICAL TREATMENT OF MISALIGNMENTS IN LINEAR ACCELERATORS

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Summary

Geometrical misaligned elements cause displacement of the beam center from the ideal accelerator axis and an increase of the beam radius, which are discussed in some detail in the literature. For any quasiperiodic accelerating structure and independent statistical distributed displacement errors of the single elements, a formalism is presented by which both effects can be calculated. The obtained rms radius increase is almost independent of the beam current. The optimal position for steering magnets can easily be determined. As an example, the radius increase is plotted as a function of the beam energy for the SNQ 324 MHz disk-and-washer proton linac.

The main effect here is the transverse displacement of a single quadrupole in a doublet. Rotations of quadrupoles about the beam axis and field errors are negligible. With 5 pairs of steering magnets, the shift of the beam center away from the ideal axis is less than 5 mm everywhere.

Description of the Formalism

a) Transverse Displacements of an Element

If the transverse and longitudinal motions are not coupled and space-charge effects are neglected, then the motion of the particles inside of an aligned element is described by a linear (2 x 2) transfer matrix. The motion of the particles inside of an aligned element is described by a linear (2 x 2) transfer matrix. The position of the beam center is shifted away from the ideal axis by the fixed amount Ax,

\[ x_j = x_j^{\text{normal}} + \Delta x_j \]  

Here \( x_j^{\text{normal}} \) is the unperturbed particle position and \( \Delta x_j \) is a correction term

\[ \Delta x_j = \sum_{n=1}^{j} (\alpha_n e_n^i + \gamma_n e_n^f) \]  

The parameters \( e_n^i, e_n^f \) are the initial (final) displacements of the n-th element from the ideal axis, the dynamical coefficients \( \alpha \) and \( \gamma \) are linear in the undisturbed matrix-elements.

If the individual displacements are known, then the beam center is shifted away from the ideal axis by the fixed amount \( \Delta x_j \). For random distributed errors however, this shift varies within a certain range, and we must use statistical arguments to calculate this interval.

Due to the central limit theorem, the beam looks like a Gaussian with mean value \( \mu \) and width \( \sigma \). For every error distribution, \( \mu \) and \( \sigma \) are the first and second moments of the single particle displacements x:

\[ \mu = \int x f(T_i) \, dT_1 \ldots dT_n \]  
\[ \sigma^2 = \int (x(T_i) - \mu)^2 f(T_i) \, dT_1 \ldots dT_n \]  

Here \( f(T_i) \) is the normalized distribution function of all statistical distributed parameters \( T_i \), which are the initial conditions of the beam and the errors of the elements. The parameter \( \mu \) is the position of the beam center, whereas \( \sigma^2 \) is the rms beam radius.

For pure transverse displacements of the elements, \( \sigma^2 \) is independent of the initial beam conditions and \( \sigma^2 \) is the maximal displacement of the beam center from the ideal accelerator axis.

For independent and symmetrical distributed errors \( c \) around the ideal accelerator axis, the position \( \mu \) of the beam center and the rms radius \( \sigma^2 \) are given by

\[ \mu = \mu_0 \]  
\[ \sigma^2 = \sigma_0^2 + \sigma_x^2 \]  

with

\[ \sigma_x^2 = \frac{1}{2} \left( \sum_{n=1}^{j} \left( \alpha_n^2 c_n^i + \gamma_n^2 c_n^f \right) \right) \]  

Here \( \mu_0, (\sigma_0^2) \) is the position (rms radius) of the unperturbed beam, \( \sigma_x^2 \) is the by displaced elements caused increase of the rms radius, \( c_n \) are the second moments (variances) of the single errors \( e_n \). For errors distributed uniformly in an interval between \( \pm \Delta_n \), one has
\[ \sigma_n^2 = \Delta_n^3/3 \] (7).

Eq (6) is correct only for independent distributed errors. For a focusing doublet, in which the individual quadrupoles are positioned relative to the common support, the independent quantities are linear combinations of the displacements of the two quadrupoles. 4

Up to now we have completely ignored space-charge effects. For an uniform distributed beam and a perfect aligned accelerator, the beam center stays on the \( z \)-axis all the time. For transverse displaced elements however, the position \( x_C(z) \) of the beam center is identical to the correction term \( \Delta x \), defined in Eq (4), where all the matrix-elements are not affected by the beam current. The other particles in the bunch are oscillating around the curve \( x_C(z) \) with the space-charge reduced frequency, their position relative to this line is not affected by misalignment errors. The particle displacement \( x_j \) from the ideal axis is then approximately given by:

\[ x_j = x_j^{\text{normal}} + x_C(j) = x_j^{\text{normal}} + \Delta x_j \] (8).

Here \( x_j^{\text{normal}} \) is the unperturbed, but space-charge effected particle distance relative to the position \( x_C \) of the beam center. The transverse misaligned elements will therefore cause a radius increase which is nearly independent of the beam current.

b) Rotation about the Longitudinal Axis

Rotation of a quadrupole about the beam axis couples the \( x \) and \( y \) motion. Carrying out the transformation to first order, we obtain for small rotation angle \( \alpha \), neglecting space-charge effects 1,4

\[
\begin{pmatrix}
  x \\
  x' \\
  y \\
  y'
\end{pmatrix} =
\begin{pmatrix}
  M & \alpha (M-N) \\
  x' \\
  y' \\
  y'
\end{pmatrix}
\begin{pmatrix}
  x \\
  x' \\
  y \\
  y'
\end{pmatrix}
\] (9)

Here \( x, y, x', y' \) are determined by

\[
\begin{align*}
M & = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \\
N & = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
\end{align*}
\]

At the end of the \( j \)-th rotated quadrupole, the additive correction term \( \Delta x_j \) to the unperturbed particle position is given by

\[
\Delta x_j = \frac{1}{2} \sum_{n=1}^{N} \sigma_n \left( A_n y_0 + B_n y_0' \right) \] (10)

Here \((y_0, y_0')\) are the individual particle coordinates in the \( y \)-plane at the beginning, the dynamical coefficients \( A \) and \( B \) are linear in the undisturbed matrix elements.

For statistical independent distributed angles \( \alpha_n \), we get a rms radius increase \( \sqrt{\sigma_{\Delta x}^2} \)

\[ \sigma_{\Delta x}^2 = \sum_{n=1}^{N} \sigma_n^2 \left( A_n^2 y_0^2 + 2 A_n B_n y_0' y_0' + B_n^2 y_0'^2 \right) f(y_0, y_0') dy_0 dy_0' \] (11)

\[ f(y_0, y_0') = \text{beam distribution in the } y \text{-plane, } \sigma_n^2 \text{ are the second moments of the angles } \alpha_n. \]

Contrary to the situation for a transverse displaced element, the correction term \( \sigma_{\Delta x}^2 \) depends on the initial beam parameters in the \((y, y')\)-plane. For an elliptical distributed beam, an upper limit for \( \sigma_{\Delta x}^2 \) is given by

\[ \sigma_{\Delta x}^2 \leq \sigma_{\Delta y}^2 \sum_{n=1}^{N} \sigma_n^2 \] (12)

\[ r_y \] is the total initial beam radius in the \( y \)-direction, the dynamical coefficients \( \sigma_n \) are determined by the orientation of the ellipse.4

For a round beam, space-charge effects almost cancel in the correction term \((M-N)\), and therefore the increase of the beam radius in only weakly effected by the current.

c) Field and Length Errors

Field errors change the normal \((2 \times 2)\) transfer matrix \( M \rightarrow M + (\delta k) M_1 \), length errors can be handled like field errors.1,4 \( \delta k = (\delta R/k) \) is the relative error of the quadrupole strength \( k \). The resulted additive correction term \( \Delta k \) to the unperturbed particle position depends on the initial beam parameters in the \((x, x')\)-plane. An upper limit for the increase \( \sqrt{\sigma_{\Delta k}^2} \) of the rms beam radius is given by

\[ \sigma_{\Delta k}^2 \leq r_x^2 \sum_{n=1}^{N} \sigma_n^2 n^2 \] (13)

\[ n=1 \]

Here \( r_x \) is the total initial beam radius in the \( x \)-direction, \( \sigma_n^2 \) are the variances of the relative errors \( \delta k/k \), the dynamical coefficients \( \sigma_n \) are determined by the orientation of the ellipse. For a non zero beam current, Eq (13) remains the same, but now the term \( \sigma_{\Delta k}^2 \) has to be calculated by using current dependent matrix-elements, which are known for a linear approximation of the space-charge forces.

d) Summary of all Geometrical Errors

For arbitrary misaligned accelerator elements, including field errors, but neglecting space-charge effects, the rms beam radius \( \sqrt{\sigma_{\Delta k}^2} \) is given by

\[ \sqrt{\sigma_{\Delta k}^2} = \sqrt{\sigma_{\Delta x}^2 + \sigma_{\Delta y}^2} \leq \sqrt{\sigma_{\Delta x}^2 + \sigma_{\Delta y}^2} \] (14)

Here \( \sqrt{\sigma_{\Delta x}^2} \) is the unperturbed rms beam radius, the error dependent terms \( \sigma_{\Delta x}^2, \sigma_{\Delta y}^2, \sigma_{\Delta k}^2 \) are defined in Eq (6, 12, 13). The correction term \( \sigma_{\Delta k}^2 \) is only weakly effected by the beam current, as shown before. If we add steering magnets to the beam line, we get an aligned beam, but we still have a slight increase of the radius due to the nonvanishing \( \sigma_{\Delta x}^2 \) and \( \sigma_{\Delta k}^2 \) terms. The optimal position of these magnets can be found by setting an upper limit for the maximal shift of the beam center.
Application to a DAW-Structure

The disk-and-washer (daw) accelerator of the proposed German Spallation Neutron Source SNQ will accelerate a 100 mA proton beam from 100 MeV to 1.1 GeV. In the linear approach, the disk-and-washer consists of about 65 quasiperiodic focusing periods. Each period has a rather long rf-tank and a short focusing doublet, separated by drift-space elements. For the following maximum error intervals:
- quadrupole deviation from the doublet axis ≤ ± 0.3 mm
- doublet deviation from the ideal beam axis ≤ ± 0.5 mm
- rf tank deviation from the ideal beam axis ≤ ± 1.0 mm

the increase of the rms beam radius √S is plotted as a function of the beam energy (or cell number) in Fig. 1. Rotations about the beam axis and field errors are neglected. They give a rms beam radius increase of less than 0.7 mm due to their initial radius dependence. Therefore ± √S is the maximal displacement of the beam center from the ideal accelerator axis.

For the first 23 periods, a smooth curve is obtained rising proportional to N, as expected. At a beam energy of 300 MeV (N=23), the periodicity of the disk-and-washer is changed from one focusing doublet for each rf-tank to one doublet for two accelerating tanks. In the used design of the linac, the transition between these two periods was not matched as yet.

In Fig. 2, the effect of optimal positioned steering magnets is shown, counteracting the same errors as were assumed for Fig. 1. Five pairs of steering magnets are needed to keep the maximal displacement of the beam center below 5 mm. The mismatch effects seen in Fig. 1 are canceled because there is no influence of former elements anymore.

Fig. 1  rms radius increase as a function of the beam energy; no steering magnets in the beam line

Fig. 2  Radius increase as a function of the energy; steering magnets are added to the beam line

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References

2. R.L. Gluckstern, Non Linear Effects, in Linear Accelerators, op. cit., p 797
5. J.E. Vetter (Editor), The Basic Concept of the SNQ Linear Accelerator, Karlsruhe KfK-Report 3180 B (1981)
The features of the newly developed multiparticle simulation code MOTION are outlined. It solves the general three dimensional equations of charged particle motion in arbitrary external fields, taking into account also the internal space charge forces. The transition from an unbunched to a bunched beam can be handled. Results are presented for focusing by a solenoid yielding a hollow beam profile. Further, the acceleration of a bunched beam by rf gaps is calculated and compared to the results of the MAPRO code.

Program Description

Initial Distributions

The program handles particles of any mass or charge. The initial particle distribution in the six-dimensional phase space can either be generated according to specified distribution functions and Courant-Snyder parameters, or it can be taken from an input file. In case the distribution is given at a fixed axial position, e.g. z=0, the code drifts the particles back such that their coordinates are then known at a fixed time and all z-coordinates are negative. Then, using time as the independent variable, the particles are traced forward again. External and internal fields are switched on individually for each particle when it crosses the measuring plane z=0. In case that bunching is to occur at a frequency f=c/\lambda, the axial extension of the initially unbunched beam is taken to be \beta \lambda. In case of no bunching elements also particle distributions with zero longitudinal extend can be traced.

External Fields

A major purpose of MOTION was to trace charged particles in external fields which cannot be described sufficiently well by analytical formula. Especially this is the case if higher order correction terms have to be taken into account, as might be necessary for high intensity, high duty cycle, high energy linacs. Examples are: bunching or accelerating by a rf gap in case the energy gain across the gap is not small compared to the particle energy; focusing by a solenoid in case that aberrations come into play. The fields in such elements can be calculated by means of computer codes like POISSON, SUPERFISH or CLAS, yielding the fields at a mesh which in turn are used as input data to MOTION. The field value at the actual particle position is obtained by interpolation. Alternatively, the external field can be described by an analytic formula, e.g. a series expansion.

Space Charge Fields

The space charge forces are calculated at pre-specified time intervals. By this means the program user can choose the accuracy for computing the space charge force independent of that for solving the equations of motion. At present, the space charge forces are calculated by summing up the mutual Coulomb forces among the simulated macro particles. To avoid artificial close collision effects the macro particles are assumed to be uniformly charged spheres occupying the total bunch volume, and having altogether the total bunch charge and mass. The particle onto which the space charge forces are just calculated is assumed to be a point charge. Then the force onto this test particle by a neighboring macro particle simply drops linearly with distance once the test particle penetrates into the volume of the macro particle. The total number N of macro particles is chosen such that the results of MOTION do not depend any more on the choice of the macro diameter.

If the transition from an unbunched to a bunched beam is to be treated, the effect of the two neighbor bunches is taken into account. The neighbor bunch trailing in time is obtained from data stored when the bunch was a period back in time. The other neighbor bunch being ahead in time is estimated by assuming the space charge forces on it to be the same as those experienced by the bunch on the average during the last period, corresponding to a smooth approximation for the space charge force. The external fields for the neighbor bunches are taken properly into account.

Equations of Motion Solver

The equations of motion are solved numerically using cartesian space coordinates. Time is the independent variable, since then there are no special transformations necessary to obtain the space charge forces. The equations are solved in the following form:

\[ \gamma_2 \dot{v}_2 = \gamma_1 \dot{v}_1 + \frac{q}{m} \int_1^2 (E + v \times B) \, dt \]

\[ \gamma_2 = \gamma_1 + \frac{q}{m c^2} \int_1^2 v \cdot E \, dt; \quad x_2 = x_1 + \int_1^2 v \, dt \]

Measuring Planes, Output, Restart

For data evaluation the particle coordinates are wanted as a function of the axial position. Such measuring planes can be specified as input data. The particle coordinates at these planes as well as at the specified time intervals can be stored in a mass storage system. Thus a restart of MOTION at the end of a previous run is possible to continue the calculation of a long beam line. At last, the information at all measuring planes is available e.g. for plots as a function of z.

Computing Time and Storage Requirements

MOTION was developed to be able to make accurate checks of beam line designs of linear accelerators. The method chosen requires large computing times and large storage systems. As an example, to trace 2500 macro particles fully three-dimensional through an Alvarez linac MOTION needs at present about 40 minutes per linac cell on an IBM 3033, which is about a factor of 25 more than the MAPRO code (for 15 space charge calculations per linac cell compared to 2 in MAPRO, and for a relative error of less than 5 \times 10^{-5} in each time integration step).

First Applications of MOTION

Focusing by a Solenoid

By using MOTION to calculate the particle trajectories in a solenoid all aberrations can be included together with space charge effects. As an example the transport of a 20 keV proton beam through a solenoid has been calculated without space charge. At first, the magnetic field of the solenoid was calculated by POISSON, which yields the field values on
a triangular mesh. From this the fields on a square mesh are generated which are input values to MOTION. As a check for the accuracy, the particle motion was calculated for several cases: the mesh size of the original mesh of the POISSON run was varied by a factor of two, the same was done for the secondary mesh; further the accuracy for solving the differential equations in MOTION was varied by a factor of 10. For all possible combinations of these parameters the change in the particle trajectories transported through the solenoid was negligible. The particle energy changed by less than 2 x 10^{-5} which is another check for the accuracy of the program, as in a magnetic field the particle energy must be a constant of the motion.

To demonstrate the accuracy of MOTION by physically meaningful quantities, two aberration constants for the solenoid were evaluated from a set of particle trajectories. Again this was done for several cases: for a beam initially parallel to the solenoid axis, for an initially divergent beam originating from a point source on the solenoid axis, and for three different solenoid focusing strengths. The particle trajectories for the strongest focusing strength used are shown in Fig. 1.

![Fig. 1: Focusing by a solenoid](image)

The effect of aberrations is obvious near the focuses, the constants related to them are plotted in Fig. 2 as a function of the particle radius at the solenoid center. Theoretically this must yield a constant value for particles moving close to the solenoid axis. This is confirmed by the evaluation for radii between about 1.5 cm and 3.5 cm. For smaller radii the error in evaluating the constants get large (subtraction of two small numbers of nearly equal size, error in extrapolating the focus for the on-axis beam). For particles moving more than about 1/3 of the solenoid aperture away from the beam axis terms of fifth order start to come into play.

![Fig. 2: Aberration constants of a solenoid for 20 keV protons.](image)

The focal lengths $f_2$ (distance between focus and principal plane) for the three field values are given in Table 1, together with the thin lens focal lengths. The smallest field can be described by the thin lens approximation extremely well, whereas for the largest field the deviations are about 12%.

The effect of aberrations can yield a hollow beam density profile close to the beam focus. To show this, the beam density was evaluated as a function of beam radius, 2.4 cm before the beam focus for an incoming parallel beam and for $B_z(r=0) = 0.166$ T. The density of the initial beam was uniform in space, the beam density was limited to 2.75 cm in front of the solenoid (= 27.5% of the solenoid aperture). The density was evaluated by assuming it to be proportional to the inverse of the distance between neighboring particles, the result is shown in Fig. 3. This profile changes rapidly when approaching the beam focus, as then the particle trajectories cross.

### Table 1: Thin and thick lens focal lengths $f_0$, $f_2$ for different magnet strengths.

<table>
<thead>
<tr>
<th>$B_z(r=0)$ [T]</th>
<th>Ampere turns [A]</th>
<th>$f_0$ [m]</th>
<th>$f_2$ [m]</th>
<th>p [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0415</td>
<td>9375</td>
<td>5.009</td>
<td>5.046</td>
<td>+1</td>
</tr>
<tr>
<td>0.083</td>
<td>18750</td>
<td>1.252</td>
<td>1.293</td>
<td>-2</td>
</tr>
<tr>
<td>0.166</td>
<td>37500</td>
<td>0.313</td>
<td>0.357</td>
<td>-9</td>
</tr>
</tbody>
</table>

### Acceleration by an Alvarez Linear Accelerator

The theory of Lapostolle-Schnizer on the acceleration by a rf gap 1 takes into account terms up to the order of (energy gain / 2 kinetic energy), which amounts to 0.11 at the first gap of the proposed proton linear accelerator SNG 2. A bunched beam (protons, 450 keV injection energy, 100 mA beam current, 108 MHz Alvarez) was traced through the first 10 gaps of this linac by MOTION and the results obtained were compared with those of the MAPRO 3 code. The fields in the beam aperture region were calculated from the potentials given by CLAS 3. One of
various checks of MOTION was to compare for zero current and zero rf, that is quadrupole fields alone. The agreement was better than 10^{-3}. Also the difference between MOTION runs with 10 compared to 15 space charge calculations per linac cell was about 10^{-3} in rms quantities. The differences between MAPRO and MOTION results at the end of the first rf gap, zero current, is given in Table 2. It is of the order of 10^{-3}. The differences in bunch envelopes and rms emittances are shown in Fig. 4, 5, 6. The conclusion is that MAPRO certainly is accurate enough for traditional rf linac designs. In future designs in which particle loss problems play an important role the MOTION code will be a useful tool.

<table>
<thead>
<tr>
<th>plane</th>
<th>Δε</th>
<th>Δβ</th>
<th>Δγ</th>
<th>δα</th>
<th>ΔR</th>
</tr>
</thead>
<tbody>
<tr>
<td>xx</td>
<td>-0.28</td>
<td>5.4</td>
<td>-4.2</td>
<td>-16</td>
<td>8.5</td>
</tr>
<tr>
<td>yy</td>
<td>0.44</td>
<td>12</td>
<td>-16</td>
<td>-19</td>
<td>13</td>
</tr>
<tr>
<td>φW</td>
<td>-0.12</td>
<td>9.9</td>
<td>10</td>
<td>-9.5</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 2: Relative (Δ) and absolute (δ) deviations between MAPRO and MOTION for the first rf gap of the SNQ Alvarez linac, zero beam current. ε = rms emittance, β, γ, α = Courant-Snyder parameter, ΔR = mismatch factor = relative residual rms envelope oscillation in a phase space coordinate system in which the rms ellipse of the MOTION results is a circle 4. ΔR is invariant against transformations having unity determinant.

Fig. 3: Hollow beam density profile before the solenoid focus

Fig. 4: Transverse bunch envelopes along the SNQ linac

Fig. 5: Phase width along the SNQ linac

Fig. 6: Emittance growth along the SNQ linac

References

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NONINTERCEPTIVE TRANSVERSE BEAM MEASUREMENTS*

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Summary

Totally noninterceptive techniques for accurate measurement of transverse beam distributions are required for high-current continuous wave (cw) linacs, such as the Fusion Materials Irradiation Test (FMIT) accelerator.† Sensors responding to visible radiation from beam interactions with residual gas and computer algorithms reconstructing spatial and phase space distributions have been implemented. This paper reports on early measurements of the beam from the injector of the prototype FMIT facility at Los Alamos. The first section indicates hardware setup and performance whereas the second section describes the data-processing software. The third section outlines the resultant measurements and further developments are discussed in the fourth section.

Hardware/Setup

The basic data-acquisition system has been reported previously.2,3 Silicon intensified target (SIT) television cameras are provided with four transverse beam profiles by a compact set of mirrors. These profiles correspond to transverse projections of the beam light intensity at the horizontal, vertical, and two nonopposing 45° angles. The cameras were specially set up with externally adjustable gain settings. Cameras from three longitudinal stations are multiplexed into a video digitizer with a present resolution of 0.57 mm per digitized point. Camera gain and bias level of the digitizer are adjusted for maximum peak to background ratio, presently about 245 (for an 8-bit ADC) to 70 (camera signal-to-noise ratio of 37 dB). Stability of camera, mirror, and electronics has been excellent, leading to better than anticipated reproducibility of emittance parameters. Data are quite high quality, owing at least partially to premium SIT tubes in the cameras and to light-tight enclosures. Some effort has gone into getting all the cameras onto a common ac circuit for identical phasing and into eliminating ground loops. Mirrors are front surface and were prepared with a quarter-wavelength antireflective coating. All surfaces were black anodized to reduce reflections. With these preparations, set-up, adjustment, and stability of the mirror mounts have been easy and straightforward.

Software/Acquisition

After the initial gain adjustment, the remainder of a measurement sequence is automatic.

A single command sequences the multiplexer through the cameras with synch-registered TV frames passed onto the computer's magnetic disk. The TV line and column windows select the region of interest; backgrounds are well fit by a linear subtraction with the resultant line-averaged profiles being presented to the computational algorithm. The maximum entropy criterion used to compute a density distribution (either spatial or phase space) has been reported previously.4–6 The maximum entropy (MENT) technique agrees well with traditional measurement techniques.4,6 The version reported here differs only in having been modified to run interactively in a minicomputer (DEC PDP-11/60) and has been verified to produce results identical to those from the original main-frame (CDC 7600) version. The computed density distribution is put into a 51 by 51 array for further calculation or output plots specific to an application.

Various checks of the automatic process are available. The raw frames may be plotted either as intensity contours or in an isometric projection. Individual lines or columns from these frames may be plotted. Matrices connecting the associated profiles may be checked and adjusted. These are rotation matrices for an x-y spatial reconstruction at one station, or transport matrices for a given axis for an emittance reconstruction from several stations. Other parameters are adjustable, although no detailed exploration of the available options has yet been carried out. Backgrounds may be fit by higher order polynomials, although this has not been necessary with the present quality of the data. Outputs may be plots of either equal intensity contours, projections, or isometric views. Numerical information concerning total contained intensity, area covered, or rms parameters describing the distribution may be readily calculated. Projections from the solution distribution may be compared with the input data profiles.

Measurements

The system described above has been used for a preliminary characterization of the beams emerging from the injector of the FMIT prototype. Capable of up to 75 kV and greater than 100 mA cw operation, the injector is being optimized for FMIT requirements. Data sets may be taken with less than 1-min separation with 1% repeatability. Figure 1 shows a typical beam profile as a single line of composite video. The first step in that characterization is to establish the level of space-charge neutralization of the beam. An rms emittance is calculated for the beam, assuming drift-only transport. This emittance value encloses about 47% of the very nearly bi-Gaussian distribution. Courant-Snyder shape parameters are extracted corresponding to 87% of the beam. Using
Fig. 1. A single line of composite video after digitizing to 512 points by an 8-bit ADC. The projection of beam light intensity is clearly defined with minimal noise contribution.

Fig. 2. Emittance distribution equal intensity contours as reconstructed by the MENT algorithm from projections of beam light intensity. The contours shown enclose approximately 99%, 87%, and 47% of the total intensity.

Future Improvements

The TV scheme has proven to be an accurate, repeatable measurement system for transverse distributions and emittances of the beam in a totally noninterceptive fashion. Long-term reliability and stability are expected but not yet confirmed. Ease of use is comparable to traditional methods.

There are several possible techniques for improving the spatial resolution from the present 0.57 mm to 0.1 or 0.2 mm per point. We hope soon to have automatic gain-setting capability for the cameras and to have permanently installed fiducial markings in the view box. The MENT algorithm soon will run in a local LSI-11/23 with an attendant reduction in data-transfer times. A 4D version of MENT will be reworked to operate in the minicomputer environment as a means of following x-y correlations through a solenoidal magnet focusing system. The fit to space-charge neutralization level will be initiated by a linear algorithm that will be much faster and that may be used as a fast feedback readout for real-time operator tuning.

References

POWER REDUCTION BY CHANGING THE DESIGN PARTICLE PHASE*

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The side-coupled linac at the Clinton P. Anderson Meson Physics Facility (LAMPF) at the Los Alamos National Laboratory operates at a design phase of -30 degrees, except for the first few modules, which have design phases tapering from -36 to -30 degrees in order to increase the acceptance. (Design phase for this stepped-beta structure is equivalent to synchronous phase. The rf amplitude is proportional to the secant of the design phase, and thus a module operated at -36 degrees has a higher amplitude than one operated at -30 degrees.) Calculations with the GROPE and SIMALAC codes indicate that the longitudinal and transverse beam characteristics would be little affected if the design phase of the downstream end of the linac was gradually ramped to -20 or -15 degrees, thus lowering the rf amplitude for this part of the linac. Experimental tests of this mode of operation are described, and the expected power savings are discussed.

Introduction

The LAMPF 805-MHz linac is used to accelerate H+ and H- beams from 100 to 800 MeV. It is a side-coupled structure consisting of 104 tanks coupled in fours or twos to form 44 modules. (The modules are numbered from 5 to 48.) It is a stepped-beta structure in that within each tank, the cell length is constant. The original design specified a design phase of -30 degrees, meaning that the accelerated particles cross the cell centers 30 degrees before the peak of the rf field on the average. When the 805-MHz linac was operated this way, it was difficult to capture all of the beam exiting from the drift-tube linac upstream, and it was decided to increase the acceptance of the 805-MHz linac. This was done by increasing the design phase of the first module to -36 degrees and letting the design phase decrease in 0.5 degree steps until -30 was reached, continuing with -30 degrees through the rest of the linac as before. This did improve the performance of the machine.

Currently two major thrusts of investigation are in progress with the aim of further improving the capability and performance of the 805-MHz linac. One is to see if power can be saved by reducing the acceptance of the downstream end of the linac. The other aims to better measure and control the transverse behavior of the beam while maintaining satisfactory longitudinal performance so that high intensity beams of both H+ and H- can be accelerated. (Currently only the H+ has high intensity, up to 600 microamperes average current.) This paper will discuss only the investigation of whether power can be saved and related matters.

Figure 1 shows that the phase spread along the linac remains about constant or shrinks slightly approaching the downstream end. At the same time, as one approaches the downstream end of the linac, the acceptance of the remaining portion of the linac increases. This suggests that the acceptance of the downstream end of the machine is

<table>
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<tr>
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<th>NS</th>
<th>WAVG</th>
<th>PHASE PROFILE (80 DEG)</th>
</tr>
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<td>799.70</td>
<td>X0000000000</td>
</tr>
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Fig. 1. Phase spread relative to design particle phase along the 805-MHz linac. NG is the number of particles, and WAVG is their average energy (MeV).

*Work supported by the U. S. Department of Energy.
not as critical as at the front end, and that it may be possible to decrease the rf field amplitude in the downstream end of the machine.

**Expected Benefits**

Figure 2 shows the present design phase and two proposed design phase configurations. Calculations show that the design phases of curves B and C would result in power savings of 5% and 8% respectively.

If one assumes that the power going into the 805-MHz linac may be reduced by 5% by such means, and if one assumes that the efficiency of the klystrons and their power supplies is approximately independent of power level, the power consumption of the 805-MHz linac facility will also be reduced 5%. If one assumes that typical operation requires 7 megawatts for the facility and that it is operated for 8 months of the year, the annual consumption of electricity by this part of LAMPF is reduced by 2000 megawatt hours. For electricity costing 30 mils per kilowatt-hour, this would mean an annual saving of $60 000.

**Beam Dynamics Calculations**

The analysis of a proposed design phase configuration is done in two steps. In the first step, a code named GROPE is used to optimize the longitudinal dynamics for a single particle. In the second step, the module-to-module rf phases found in step one are used in a code named SIMALAC to analyze the longitudinal or longitudinal and transverse behavior of a bunch containing up to 500 particles.

The GROPE code was written by K. R. Crandall. It analyzes progressively larger sections of the linac, finding the optimum beam phase and energy at the entrance and exit, first considering individual tanks, then individual modules, and finally the whole linac. Input to the code includes design phases for each module and lengths and spacings for each tank. Output includes module-to-module phases and various parameters needed to set the amplitudes and phases of the modules of the accelerator (where amplitude and phase cannot be measured directly to the required precision).

The SIMALAC code was developed by K. R. Crandall and G. R. Swain to trace particle trajectories through the 805-MHz linac. When one is simulating both longitudinal and transverse motion, the effects of misalignments, earth's field, and certain quadrupole magnet imperfections may be included.

Calculations for the cases shown in Fig. 2 indicate that the longitudinal and transverse behavior is not greatly affected by tapering the design phase to -20 or -15 degrees at the downstream end of the machine.

**Experimental Results**

Configuration C of Fig. 2 was tried on LAMPF on the accelerator development period of 24 August 1981. A series of time-of-flight measurements called the delta-t procedure is used to set the rf amplitude and phase of the linac modules. With only a few minor adjustments after the delta-t procedure was completed, a beam of 6 milliamperes peak, 230 microamperes average current was achieved. Some beam spill was seen along the linac, but it was thought that the spill could have been reduced with further intuitive minor adjustments.

On 30 August 1981 this configuration was tried again during the tuneup for the following production cycle. This time, there was spill for a broad spectrum of energies along the machine, and no simple intuitive adjustment could be found which would reduce the spill. The operators returned to configuration A for production.

**Future Investigations**

The experimental tests on reducing the rf amplitude at the downstream end of the 805-MHz linac indicate that configuration C of Fig. 2 is just beyond the limit of what is practical for this linac. It is planned to test a configuration such as B which is intermediate between the present production configuration (A) and that tested in August (C).

Further beam dynamics calculations with SIMALAC have failed to indicate specifically why configuration C is not satisfactory, but a new area for investigation was suggested: longitudinal matching. Profiles showing the energy spread of the beam relative to the design energy, as shown in Fig. 3, did not change in overall character as one changed from one of the design phase configurations to another. However, it may be observed that there is an abrupt increase in energy spread near module 13. Calculations indicated that in theory, one can reduce this jump in the energy spread by adjusting the design phases in this region of the linac. An example of
exhibits any such sudden jumps, and if so, seeing the energy spread in the LAMPF 805-MHz linac too large, the klystrons will be unable to supply admittance will be inadequate, and if it is made too small, the results is shown in Fig. 4. Of course one is limited in the amount one can adjust the design phase since if it is made too large, the klystrons will be unable to supply sufficient power. Possible areas for future investigation in this new area include seeing if the energy spread in the LAMPF 805-MHz linac exhibits any such sudden jumps, and if so, seeing if adjustments to the design phase in the vicinity can reduce them.

Fig. 3. Calculated energy spread before longitudinal matching.

Fig. 4. Calculated energy spread after longitudinal matching.

References

MICROWAVE MEASUREMENTS OF ENERGY LOST TO LONGITUDINAL MODES BY SINGLE ELECTRON BUNCHES TRAVERSING PERIODIC STRUCTURES

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SUMMARY

In the design of future linear colliders, it will be important to minimize the loss of beam energy due to the excitation of higher-order modes in the accelerator structure by single bunches of electrons or positrons. This loss is not only detrimental in itself but also gives rise to energy spectrum widening and transverse emittance growth. This paper describes microwave measurements made on disk-loaded and alternating-spoke structures to determine the loss to the longitudinal modes. In these measurements the Gaussian bunch is simulated by a current pulse of the same shape transmitted through the structure on an axial center conductor. Results to date are presented for the total longitudinal loss parameter per period K in volts per picocoulomb.

INTRODUCTION

Future linear colliders, to become technically and economically feasible at energies of several hundred GeV, will require accelerating structures with a new set of properties. These properties together with the RF systems needed to power these structures have been described elsewhere.1,2 The requirements are summarized below:

a) High accelerating field gradient E_a to minimize machine length. This implies structures with a low ratio of peak-to-accelerating electric field E_p/E_a to minimize the risk of electrical breakdown.

b) High ratio E_a/w where w is the energy stored in the structure per unit length. This ratio, which is equal to w/4Q for the fundamental mode of the structure, is a measure of the efficiency with which the available microwave energy is used.

c) High group velocity v_g to reduce the filling time t_f, where t_f = w/v_g for each section of length l.

d) Low content of transverse and higher-order longitudinal modes that can be excited by single bunches traversing the structure. The longitudinal modes cause beam loading and energy spectrum widening while the transverse modes cause emittance growth.

Except for electrical breakdown, these properties can be calculated for simple structures with cylindrical symmetry such as the disk-loaded waveguide. Properties (a), (b) and (c) traditionally are also measured by microwave bench tests. The longitudinal and transverse wake fields under (d) can be measured with an electron beam,3,4 but these measurements require that a long length of accelerating structure already be available. Thus to test and select new structures, it is desirable to have a bench test in which the turn-around time is short and the cost is low. The work described in this paper used such a test to measure the longitudinal higher-order mode content of structures which may also be desirable with respect to the other listed properties. A conceptual method to measure the transverse modes has also been proposed5 but has not yet been tried experimentally at SLAC.

Experimental Method

When a single + or - bunch of charge q traverses a structure on its axis, it deposits in the structure an energy per unit length u = qk2. The total loss parameter k is summed over all the synchronous longitudinal modes and depends on the axial charge distribution in the bunch. If we assume a Gaussian bunch with standard deviation σ_z,

\[
k = \sum_{n=0}^{\infty} k_n e^{-\left(\frac{w_n \sigma_z}{c}\right)^2}
\]

where k_n is given by \(\left[\frac{\omega_n}{4}(r/Q)\right]_n\) for each mode of frequency \(\omega_n\). The figure of merit of the structure is then designated by \(B(\sigma_z) = k/k_0\), where a low value of B indicates a low content of higher-order modes which do not participate in the acceleration process and are thus parasitic.

The method used in this paper is that originally proposed by M. Sands and J. Rees6 and which was used extensively for the optimization of PEP vacuum chamber components.7,8 The electron bunch is simulated by a current pulse of the same shape transmitted on an axial wire stretched through the structure. The measurement layout is illustrated in Fig. 1.

![Fig. 1. Measurement layout](image-url)
Conical tapers and extended cylinders are provided on each side of the test piece to connect it to 500 lines and to minimize the effect of internal reflections. The Gaussian pulse generator on the left consists of a tunnel diode step generator, a tee-junction with a shorted stub (available in several lengths) by means of which a short pulse of desired duration is produced. A low-pass filter is used to make the pulse Gaussian. On the right a sampling head and oscilloscope is connected to an X-Y recorder which plots the transmitted pulses. In order to minimize jitters and drifts, all active components are thermally stabilized by means of water cooling.

The measurement is made in two steps. In the first step, the test piece is simply a hollow pipe of inner diameter proportional to that of the accelerator structure (commonly called 2b, see Fig. 2). The current pulse transmitted through the system to the recorder is i(t).

\[ i(t) = \text{Gaussian pulse} \]

\[ i(t) = \text{Gaussian pulse} \]

In the second step, the internal periodic elements of the structure are added one by one (the total length is kept constant), and the transmitted pulses \( i_m(t) \), modified by the addition of each successive obstacle, are recorded. As shown in Refs. 6-8, the experimental value of \( k \) is obtained for each \( i_m(t) \) from:

\[ k = \frac{2Z_0}{q} \int [i_0(t) - i_m(t)] \frac{i_0(\tau) + i_m(\tau)}{2} d\tau \tag{2} \]

where

\[ q = \frac{1}{2} \int [i_0(t) + i_m(t)] d\tau \]

and \( Z_0 \) is the characteristic impedance of the pipe without periodic elements. The curves obtained from the X-Y recorder are digitized by means of a graphic-to-digital converter and the integration is performed by computer. For all structures measured here, it was found that the results converged in a satisfactory manner after 3 or 4 periods and an average \( k \) was obtained.

One of the most important features of these tests has to do with the \( \sigma_z \) of interest in future colliders. If one assumes an S-band structure like at SLAC (2856 MHz), then \( \sigma_z = 1 \) mm or 3.33 ps. Unfortunately, the best available step generator has a rise time with a lower limit of 20 ps, leading to a Gaussian pulse with a \( \sigma_z \) of at least 28 ps. For this reason, it was necessary to scale all the dimensions of the test piece from S-band by an enlargement factor \( S \) between 8 and 11. This resulted in a test cell with an I.D. of 70.8 cm and a periodic length of about 30 cm.

Measurements and Results

Measurements were performed for two types of structures. The first was the disk-loaded waveguide (2π/3 mode) used at SLAC. This measurement was made for two (scaled) values of the dimension \( 2a \) (see Fig. 2a) corresponding to the 45th (average) cavity of the constant-gradient structure \( (2a = 2.325 \text{ cm}) \) and the largest cavity \( (2a = 2.622 \text{ cm}) \). Changes in the corresponding \( 2b \) (8.265 cm to 8.346 cm or about 1%) was neglected. The measurement for each structure was made for four different values of \( \sigma \) as shown in Table I.

Table I. Results of Measurements for Disk-Loaded Structures

<table>
<thead>
<tr>
<th>( \sigma_z ) (mm)</th>
<th>Measured</th>
<th>Scaled to 2856 MHz</th>
<th>( K(V/pC) )</th>
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<td>( \sigma_z )</td>
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<td>( 2a = 2.622 \text{ cm} )</td>
<td>( (K-V/pC) )</td>
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<td>1.84</td>
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In each case, five data points were obtained for 1, 2, 3, 4, and 5 disks cumulatively added in succession, and an average \( K \) was recorded. The results are given in Table I and plotted in Fig. 3. It is interesting to note that the microwave measurement for the "average" (45th cavity) iris agrees very well with the single bunch measurement described in Ref. 3 when normalized to a Gaussian distribution with a \( \sigma_z = 1 \) mm. Both measurements give values of \( K \) that are \( \sim 35% \) higher than the theoretically calculated curve, also shown in Fig. 3. This discrepancy is identical.
The preliminary measurements presented here indicate that a microwave bench test on a scaled structure can predict, at least comparatively from structure to structure, the total energy lost per period to all the longitudinal modes by a Gaussian bunch of total charge \( q \). Since the method requires only inexpensive models, it can be used to quickly check the design and help in the experimental selection of periodic structures for future linear colliders.

ACKNOWLEDGMENT

The authors wish to thank J. Styles and D. F. Wang who were extremely helpful in the measurements.

REFERENCES

4. J. E. Clendenin, Beam Parameter Measurements for the SLAC Linear Collider; paper presented at this Conference.
Summary

The funneling of heavy ion beams can be achieved by first bending the beams by septum magnets towards the common axis, and then deflecting them onto the axis by rf-deflector elements with time varying electric field strength. The main properties of these deflection elements are discussed. Formulas are given for calculating the maximal allowed length of any transition section, if the longitudinal phase width should stay below an upper limit. These limits are important for a heavy ion beam funneling section. As an example, beam envelopes are shown for funneling two 100 mA, 1.7 MeV Bi²⁺ beams into one 108 MHz Alvarez accelerator.

Description of a Funneling Line

The idea of funneling two or more beams together is an important point for most heavy ion fusion scenarios. Particle beams, coming from identical low frequency accelerators, are funnelled into a single higher frequency accelerator in such a way that every bucket of the high frequency accelerating field is filled.

A funneling line must therefore fulfill the following conditions: the beam centers must be brought to one common axis and stay there; the transverse and longitudinal emittances at the end of the line must be smaller than the acceptances of the following linac. For a heavy ion beam with high stiffness and relatively large beam separation initially, long bending and deflection sections are required. Their length, however, is limited by the increase of the longitudinal phase width. For a linear rebunching field, the phase width should stay below an upper limit of about ± 30°. If there is a frequency jump, this length limitation is quite severe. Therefore, in such a funneling line, there will be mainly bending and deflecting elements, almost no focusing quadrupoles. But then it has to be demonstrated that the resulting transverse radii are smaller than the apertures of the following elements.

A schematic drawing of a possible funneling line is given in Fig. 1. The lines starts with two beams, symmetrically distributed about the longitudinal axis of the following accelerator, produced by arbitrary, but identical linacs. These beams are transferred by bending magnets, quadrupoles and rebuncher cavities to the end of the last low frequency rebuncher, the beginning of the actual funneling line. From this point on both beams are transported through the same elements. First they are bent to the common axis by septum magnets. These magnets have two beam lines with equal, but opposite fields. The following beam deflection is done by rf-deflector elements with time varying electric field strength, the most important elements of the whole line. The time varying field cause transverse...
and longitudinal emittance growth\(^3,4\). After the last deflector, where the two beam centers are brought together and stay on the common axis, the beam is longitudinally and transversely focused into the following linac.

To be more specific, we will discuss some general properties of the rf-deflection elements and of longitudinal length limitation.

Finally first results are presented for funneling two 100 mA beams into one 108 MHz Alvarez accelerator. This line is made for the HIBALL-scenario, a heavy ion fusion parameter study\(^5\).

**a) Deflection of the Beam**

We discuss separately the deflection of the beam center, and the movement of the other particles inside an rf-deflector, the main element of our funneling line.

The deflector is a plate condenser of length \(L_{RF}\), symmetrically placed about the z-axis (= the longitudinal axis of the following accelerator) with time-varying electric field. The beam center is moving along the line \(x_c(z)\) in the \((x,z)\)-plane.

If the electric field inside the deflector has only a \(x\)-component
\[
E_x(t) = A \sin \omega t
\]  
(1)

and if contributions of the magnetic field to the Lorentz-force are neglected (low velocity of heavy ions), then the displacement \(x\) and the angle \(x'\) of the beam center are approximately given by

\[
x_c(L) = x_c(0) + L x_c'(0) + e(L)
\]
\[
x'_c(L) = x'_c(0) + f(L)
\]  
(2)

with

\[
e(L) = -\frac{q}{m v_c^2} [\sin(\frac{\omega}{v_c} + \phi) - \frac{\omega}{v_c} \cos \phi \sin \rho]
\]
\[
f(L) = -\frac{q}{m v_c^2} \left[\cos\left(\frac{\omega}{v_c} + \phi\right) - \cos \phi\right]
\]  
(3)

\(0 < L < L_{RF}\).

\(A \sin \rho\) is the electric field strength of the rf-deflector, when the beam center enters; \(v_c\) is the beam velocity.

In order to deflect both bunches, separated in time, the electric field of the deflector must change its sign. The frequency \(\omega\) is given by

\[
\omega = 2\pi f_0 (2n + 1) \quad n = 0,1,2,...
\]  
(4)

where \(f_0\) is the frequency of the two previous linacs. Normally the deflector operates in fundamental mode.

In our funneling line (see Fig. 2) we have 9 rf-deflector elements. The beams are brought together in the last element. In the previous elements, the beam is mainly kicked to the axis. The maximal deflection angle is obtained by operating in the fundamental mode. The field strength must have its maximum, when the beam center is in the middle of the deflector and we use one half cycle of a sinusoidal oscillation. These conditions correspond to

\[
\rho = 0, \quad \frac{\omega L_{RF}}{v_c} = \pi, \quad \omega = 2\pi f_0
\]  
(5)

which yields

\[
|\Delta x'|_{MAX} = \frac{2q A}{m v_c} \frac{\omega}{\omega v_c}
\]  
(6)

and a zero electric field of the deflector, when the beam center enters or leaves the element.

For a 1.7 MeV/N Bi\(^{12}\) -beam and a peak electric field gradient of \(A = 5\) MV/m, we get a deflector length of \(L_{RF} = 16.8\) cm and a change of the angle by 1.5 mrad in one deflector.

\(\Delta x'\) is correct only for the displacement \(x_c\) of the beam center, because \(v_c\) is the velocity of the bunch and \(\rho\) is the phase of the electric field when the beam center enters the deflector. The displacement \(x_c\) of the other particles is described by a similar equation, if we replace \(v_c\) by the particle velocity \(v_p\) and \(\rho\) by a phase \(\rho_p\), and we neglect space-charge effects. The difference \(\rho - \rho_p\) is the phase deviation of a particle from the synchronous phase; head and tail of the bunch are seeing different fields in the deflector.

In order to calculate the beam radius, a Taylor expansion is made for the difference \(x - x_c\), the approximate distance of a particle from the beam center.

This expansion gives a movement, which is the same as in a drift-space element plus an additional term \(A\), which depends on the phase deviation \(\Delta\phi\) and the energy spread \(\Delta W/W\) of a particle\(^3,4\).

In first order and for the maximal deflection angle (see Eq 5), this correction term \(A\) is given by

\[
\Delta = \frac{q A}{m v_c^2} \left(\frac{2\lambda}{\Delta W} \Delta W + \frac{1}{2} \frac{L_{RF}}{\Delta W} \Delta W\right)
\]  
(7)

\(\Delta\phi\) is the phase deviation of particle from the synchronous phase and \(\Delta W/W\) is the energy spread.

The quadrupoles in the funneling line (see Fig. 2) will deflect a beam, whose center is not on the quadrupole axis, either away or towards the quadrupole axis. The transfer matrix for the beam center and for the other particles is the normal quadrupole matrix.

**b) Longitudinal Length Limitation**

In a rebuncher cavity, the phase width \(\Delta \phi_{MAX}\) of the beam should not exceed an upper limit in order to get a linear rebunching field. No such limitations, however, exist for the energy spread. Therefore we want to calculate the maximal allowed distance between two
rebuncher cavities for a given upper limit of the phase width \( \Delta \phi_{\text{max}} \). \( \Delta \phi_{\text{max}} \) is related to the longitudinal \( \beta \)-function, which has the unit \( m \) in the \( (\Delta \phi, d\Delta \phi/dz) \)-plane.

Let us assume a longitudinally focused beam at the end of one rebuncher cavity and, after some drift, a defocused beam at the beginning of a second cavity. The maximal phase widths at these points should be \( \Delta \phi_i \) and \( \Delta \phi_f \).

For two rebunchers, operating at the same frequency, and equal values \( \Delta \phi_i = \Delta \phi_f \), the maximal allowed distance between them is given by

\[
L_{\text{max}}(\Delta \phi_i - \Delta \phi_i) = \beta_i
\]

(8).

\( \beta_i \) is the longitudinal \( \beta \)-function in the \( (\Delta \phi, d\Delta \phi/dz) \)-plane, corresponding to a maximal phase width \( \Delta \phi_i \).

If the frequency of the second rebuncher is twice the frequency of the first one, then the maximal drift length for going from a phase width \( \Delta \phi_i \) to a width \( \Delta \phi_f = \Delta \phi_i/2 \) is given by

\[
L_{\text{max}}(\Delta \phi_i - \Delta \phi_i/2) = \beta_i/2
\]

(9).

With real rebuncher cavities, these maximal length values cannot be achieved due to limited rebunching field strength. It is, however, possible to obtain a 10% - 20% less value. 

\[\text{Table 1: Main parameters of the funneling line.}\]

<table>
<thead>
<tr>
<th>Element Parameters</th>
<th>100 mA, 1.7 MeV/N Bi^2(N=209)</th>
</tr>
</thead>
<tbody>
<tr>
<td>first two septum magnets</td>
<td>( B_0 = 1.5 ) T</td>
</tr>
<tr>
<td>last septum magnet</td>
<td>( B_0 = 0.5 ) T</td>
</tr>
<tr>
<td>peak deflecting field gradient</td>
<td>( A = 5 \frac{MV}{m} )</td>
</tr>
<tr>
<td>deflector frequency</td>
<td>54 MHz</td>
</tr>
<tr>
<td>rebunching field</td>
<td>( E_{0T} = 2.5 \frac{MV}{m} )</td>
</tr>
<tr>
<td>of the triplet</td>
<td>( B' = 40 ) T/m</td>
</tr>
</tbody>
</table>

All formulae are correct for a zero-current beam. For an assumed 3-dimensional bunch ellipsoid, similar formulae can be derived, including space-charge effects.
In our funneling line (Fig. 1), we have a longitudinal waist at the end of the previous 54 MHz Wideroe accelerator with a phase width of ±10° and an energy spread ΔW/W of ±1%. For an assumed upper limit of ±30° at the beginning or end of any rebuncher cavity, these values correspond to a maximal length of 16.5 m between two 54 MHz cavities, 8.3 m for the transition between a 54 MHz and a 108 MHz cavity (= funneling region), and 4.1 m between two 108 MHz cavities. In the design (see Fig. 2), the actual chosen distance is 20% smaller due to space-charge effects.

c) Calculation of Envelopes

As an example, first results are given for funneling two 100 mA, 1.7 MeV/N Bi²⁺-beams, produced by a 54 MHz Wideroe accelerator. The funneling line starts after the last 54 MHz rebuncher cavity (see Fig. 1). In Fig. 2 and Tab. 1, the beam parameters, the elements of the line, the 3 envelopes and the distance x_c of the beam center from the axis are given. The line ends in front of the following 108 MHz Alvarez accelerator with longitudinal and transverse decreasing envelopes.

At the beginning of the line, a phase width of ±32° (for 54 MHz) was chosen in order to transport the beam without rebunching over 7 m (see Eq 9). The longitudinal emittance E_z (see Tab. 1) corresponds to a phase width of Δφ = ±10° (for 54 MHz) and an energy spread of ΔW/W = ±1% at the end of the previous Wideroe accelerator. Transversely, the used radii and angles are somewhat arbitrary. All initial parameters can be obtained with a matching section, transverse and longitudinal, in front of the funneling line. The phase width stays below ±33° in the previous 54 MHz rebuncher. The radii in x- and y-direction are defined perpendicular to the motion of the beam center.

The septum magnets have a field index n = 0 and no edge focusing. Coupling of the longitudinal and transverse motion are neglected. Dispersion effects do only weakly influence the transverse envelopes due to a bending angle of 80 mrad and an energy spread of 1%. All quadrupoles are positioned exactly on the z-axis. We use units of 3 rf-deflectors, separated by 0.15 m drift-space elements. The deflection angle is maximal in these elements (see Eq6). The beam radius is effected only by an amount 10⁻⁴mm due to the phase width and the energy spread of the beam (see Eq 7). All 108 MHz rebuncher cavities are located after the last deflector element, where the beams are finally brought together. Helices or spiral resonators can be used as rebunchers. A rather strong focusing triplet with a field gradient of B' = 40 T/m focuses the beam radially. This gradient corresponds to a peak field of B₀ = 1.4 T at an aperture radius of 3.5 cm. All elements are separated by 0.15 m drift-space elements.

The maximal beam radius is 2.0 cm in the triplet, the phase stays below ±33° (for 108 MHz) in the rebuncher cavities.

The calculations were done with the linear transport program "Enveto", including space-charge forces of a 3-dimensional bunch ellipsoid. The design will be checked by a multiparticle code, where the neglected longitudinal-transverse couplings are taken into account. The needed accuracy of the bending and deflection fields will be discussed later.

Acknowledgements
We thank K. Mittag and M. Pabst for numerous stimulating discussions. Helpful comments for designing a funneling line from members of GSI Darmstadt are gratefully acknowledged.

References

8. This program was written by K. Mittag, Kernforschungszentrum Karlsruhe.
SUMMARY

Ultimately, the true measure of a control system lies in how well initial decisions allow for exigencies, as the overall machine evolves and requirements solidify. Recognizing that advances in electronic technology virtually guarantee that any system will be technologically out of date by the time it is operational, the criteria really do not involve the state of the technological advancement, but instead legitimately ask whether the control-system design can adjust to the inevitable machine-design changes, whether the operators can use it to control the machine in a reasonable manner, whether it was built within budget constraints, or—in short—whether it works. On these bases, our initial decisions on the racetrack microtron (RTM) control system have been increasingly vindicated as the system has evolved, and we feel that our experiences have shed some light on just which criteria are of real importance, and which are merely a part of the lore of popular misinformation. Unless the basic requirements are met, technical elegance is no virtue, and when they are met, design simplicity is no vice.

Control System Requirements

The RTM is a compact, multipass, cw electron accelerator. The multipass design requires many focusing and steering magnets and beam diagnostics, but the entire machine fits into a 15- by 15-m room. Because this machine is to be not only a research tool, but also a prototype for a much larger microtron, there is a strong compulsion to build it within the budget. We could not afford the luxury of a large development effort on the control system, nor esoteric maintenance problems later on. The control system has to be reconfigurable to accommodate extra diagnostic equipment and future additions expected with a prototype machine. Furthermore, because the machine is being built in Washington, DC and the control system at Los Alamos, NM, there is a necessity to construct it of independent pieces. The National Bureau of Standards had already decided to buy a larger number-crunching computer, which they want to link into the control system for more sophisticated applications codes, but which must operate independently of the local control system.

We feel that human response time on the control system is of very high priority, because frequent parameter changes will be necessary. To permit future expansion and application program accommodation, we put strong emphasis on wide-ranging software support.

Summarizing, the requirements constraining the design of the RTM control system are

a) cost,
b) reconfigurability,
c) two-location development,
d) separation of tasks between number cruncher and local control stations,
e) human response time, and
f) maximum software support.

As a final note on system constraints, there is an almost universal tendency to venerate maximum-system generality. We too would like to claim that our system can do anything for anyone; but as it evolved, we were sometimes forced to decisions that not only simplified our design, but more directly oriented it toward the RTM. As only a few of several examples, we limited the maximum data base of each secondary to 250 entries, and our choice of the star network to interconnect secondary and primary stations limits the number of secondary stations to some practical maximum—perhaps six to eight—which is noisome to some purists. For these and other decisions, we make no apology, for they have enabled us to meet the above criteria.

General Configuration

Figure 1 indicates the general system configuration. As shown, the PDP-11/44 host computer is linked to the primary control station through a standard RS-232 9600-baud serial line. Clearly, this limits the number cruncher to off-line or quasi on-line displays and calculations. The primary station provides service to the main control console and to the star link to each of the secondary stations. The primary, and each secondary station, consist of a Multibus crate with appropriate support boards, a keyboard, a standard video display, and a control console. In addition, the primary is fitted with a dual floppy-disk drive unit during system development, thus eliminating the need for an expensive additional software-development station. Each Multibus crate can be fitted with as many single-board computers (SBC) as its requirements dictate. Each secondary will have a minimum of two SBCs, and may have more, a

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*Work supported by the US Department of Energy.
potential that is an advantage of the design features; whenever additional tasks are added to a given system, additional equipment is easily added without the need for total system reconfiguration. This, of course, is only true up to some practical maximum, and currently we do not anticipate the need for parallel-bus-priority resolution. This decision limits us to four bus masters in a given crate with serial bus resolution, but for the RTM, this is adequate.

As Fig. 1 also shows, it is possible to add tertiary stations linked to the secondary, but now this is only contemplated in the case of the injector station, which requires a single-domed controller at high voltage, linked by fiber-optic cable to its secondary. The link between each of the secondaries and the primary is a parallel byte-wide transmission line of eighteen twisted-pair wires--a 1-cm-thick cable. Because the maximum cable length here is not over 100 m, this larger cable is a small price to pay for the increased speed of the transmission, and the enormous simplification of both software and hardware. Our transmission rate is currently 5 MHz, with error checking and hand-shaking, and can be increased greatly by using direct-memory data transfers. We anticipate no need for further increase in link speed; however, because here the driving consideration is operator response time.

Secondary Station

To date, most of our effort has gone into the design of the secondary station. Each such station consists of its Multibus crate with an Intel 80/24 SBC, secondary software in 32 K on-board EPROM, a binary/link board, control-panel interface board, 16 K core-memory board for the nonvolatile data base, a Zendex 80/05 SBC for data-base update, and stepping-motor driver and DAC/ADC boards as required. The station also has a keyboard, video display unit, and the operator's console. The latter consists of two infinite-turn knobs and eight interrupting function push buttons with a four-button status register.

The Intel 80/24 SBC handles all traffic between the primary station, or operator's console, the data base, as well as the keyboard data-base edit and interpreter functions. The additional SBC was added to the system to provide the actual interface between the measurement and control elements (motors, DACs, ADCs, binary, etc.) and the data base. This decision to add the second SBC at the outset of the secondary station development had the propitious consequence of splitting up the software tasks and greatly simplifying the executive tasking between the various system requirements.

The keyboard provides the editing features needed to update, delete, add to, and move blocks around the data base. This makes adding hardware to a secondary station a simple increment, in the data base, without the need to reconfigure the EPROM software.

The video display is a commercial unit capable of 30-line by 80-character data-base display, and is used to set up and read values from each data base entry using the control panel knobs and the keyboard.

The control panel consists of two infinite-turn knobs providing respectively, cursor control on the data-base display, and value adjustment on the various data-base parameters. Eight interrupting push buttons are used to select which aspect of the data base is to be displayed, or whether the interpreter is to be used. This eliminates the need for an arcane dialogue between the operator and the system through the keyboard. Four additional push buttons are used as a status register to select the units for values displayed. Figure 2, the secondary-station photograph, makes clear the various functions described.

The stepping-motor controller is a custom designed Multibus board consisting of four CY-500 stepping-motor-controller processors that operate independently of the SBC processors. The desired function for the motor is simply downloaded from the SBC through the Multibus; the CY-500 provides pulse control for the motor.

The binary-link board is another custom Multibus board that handles the parallel link to the primary station, as well as providing 24 lines of binary I/O: 8 bidirectional control lines and 16 status binary lines. The decision to design our own boards was always made after careful consideration of commercial offerings; but in these few cases where we have chosen to use our own designs, we did so because of the enormous simplification and more compact design. In a few cases, we actually custom designed to overcome commercial design flaws. Sometimes commercial equipment is cheaper and more reliable; but here again, one must avoid the cutting edge of an overworn dogma.

Software

We chose to use the Intel Multibus system not only because it is now an industry standard with a large repertoire of available ancillary boards, but also because of the enormous software library available for software development, as well as canned applications codes. For our code development, we used the CP/M floppy-based operating system, and utilities consisting of editors, assemblers, loaders, debuggers, and PROM burners. The software available for use with CP/M is truly astounding, and generally is inexpensive. We now have macroassemblers, video-text editors, disk maintenance utilities, symbolic debuggers, various BASIC interpreters and compilers, Fortran compiler, PASCAL compiler, PL/1 compiler, and C compiler. Currently, the latter is getting much attention from Industry, because it is versatile, portable, and offers structured programming--as well as producing code that is nearly as efficient as assembly code. This, of course, is in contrast to the enormous memory inefficiency of PASCAL or Fortran.

Figure 3 shows the software design for the secondary station, the only part of the software system generally complete. The secondary software itself consists of the interrupt handler and four main stations: the console-operator code, the database editor, the interpreter, and the I/O driver/data-base update code. The console-operator code provides the interface between the console and the data base, using the knobs and push buttons to change the data-base display on the video monitor for operator interaction. It also permits value
changes by the value control knob, setting new values into the data base accordingly. A multi-module hardware floating-point board is used in conjunction with the 80/24 SBC to provide data conversion in units requested by the operator.

The data-base editor provides the edit capabilities for the data base itself, permitting the operator to insert new lines, move blocks of data around, delete data lines, and change conversion and calibration values in the data base.

The interpreter provides the engineer with a powerful debugging tool during initial system testing. It implements simple loops and delays, together with binary and analog data read-and-write commands, to permit stand-alone control loops for scoping and problem-isolation testing. Data-base values can be assigned variable names and read at prescribed intervals. Periodic printing of these variables with the "type" statement yields a chronological record of parameter performance over periods of milliseconds, seconds, or minutes. The interpreter is patterned after BASIC, in its approach with line-numbered statements, and a "help" table to remind the occasional user of the command structure. We feel this interpreter may well prove to be one of the most valuable software tools in the initial phases of machine checkout.

Fig. 3. Secondary station software overview.

Conclusion

The RTM control system has evolved around a standard bus-structured (Multibus) distributed-intelligence design that is sufficiently versatile to permit additions to the machine, and sufficiently RTM-oriented to be relatively simple and within initial budget projections. The choice of a rather undistinguished eight-bit processor has made available a vast collection of inexpensive, well-debugged utility and library software. The dual-processor secondary station has greatly simplified the software by taking advantage of the Multibus master-slave serial bus arbitration protocol. Many commercial boards are available for use in this system, as needed; but religious adherence to a "commercial only" philosophy has been sacrificed where the system performance and simplicity could be thereby enhanced. The operator controls are interrupt-driven, providing best response time and system performance.

Acknowledgments

J. M. Potter has helped greatly with the CP/M software and disk-handler codes. Our hours of hair-tearing (at least on his part) together, trying to get commercial equipment to work, are remembered; we are grateful for the time he spent with us. D. A. Swenson is responsible for the idea of the interpreter on the secondary station, a contribution that likewise is appreciated.
H- BEAM EMITTANCE MEASUREMENTS FOR THE PENNING AND
THE ASYMMETRIC, GROOVED MAGNETRON SURFACE-PLASMA SOURCES

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Summary

Beam-intensity and emittance measurements show that the H- beam from our Penning surface-plasma source (SPS) has twice the intensity and ten times the brightness of the H- beam from an asymmetric, grooved magnetron SPS. We deduce H- ion temperatures of 5 eV for the Penning SPS and 22 eV for the asymmetric, grooved magnetron.

Experimental Apparatus

As part of an accelerator development program at Los Alamos, we measured the H- beam intensity and emittance for our Penning SPS1 and for the BNL Mark III magnetron2 (called the asymmetric, grooved magnetron, or AGM, in this paper). Figure 1 shows a schematic of our experimental arrangement. The H- beam is extracted from the source emission slit (10 by 0.5 mm?) with an extraction electrode at ~15 kV across an ~2-mm gap. The beam is transported through 90° by a dipole bending magnet having a field index n ≈ 0.85. After exiting the dipole magnet, the beam drifts 17 cm (19 cm for the Penning source) to the two (orthogonal) emittance scanners. Each emittance scanner has an acceptance of ±130 mrad in angle and ±8 cm in position. The mechanical angular resolution of the emittance scanners is ±1/4 mrad.

A Faraday cup (7 by 5 cm?) is mounted on one of the emittance scanners for beam-current measurement (FC2 in Fig. 1). Comparison of the FC2 current with the FC1 current (FC1 is inserted just after the extraction electrode) determines the beam-transport efficiency through the dipole magnet to the emittance scanners. After correcting for stripping losses of the H- beam in the background hydrogen gas (a 1 to 2% correction), the transport efficiency is typically 90% for the Penning source and 70% for the magnetron.

The Penning1,3 and AGM2 source dimensions are contained in Refs. 1 and 2 respectively, with the exception that the AGM emission slit was changed from 45 by 0.6 mm2 to 10 by 0.5 mm2. The source operating parameters used to obtain our measurements are given in Table I.

Emittance Measurements

Figure 2 shows the measured two-dimensional, normalized emittance ε as a function of the beam fraction F for the Penning and the AGM sources. The beam fraction F = It/I0, where It is the beam current included in the brightness contour set by the threshold t, and I0 is the total beam current measured at FC2. The normalized emittance is calculated from

\[ \varepsilon(F) = \beta \gamma A(F)/\pi, \]

where A is the phase-space area of the beam and β and γ are the usual relativistic parameters. The normalized brightness values B(F x F) are calculated from

\[ B(F x F) = 2I_0/[x^2 \varepsilon_x(F) \varepsilon_y(F)], \]

The total H- beam current and the emittance at F = 0.63 are given for both sources in Table I. The I0 values given in Table I are typical of the H- currents that routinely can be obtained in FC2. The maximum values for I0 are 60 mA and...
Fig. 2. Two-dimensional, normalized emittance \( e \) versus the beam fraction \( F \) for a 79-mA, 17-keV \( H^- \) beam from the Penning SPS (open points, solid curves) and for a 40-mA, 14-keV \( H^- \) beam from the asymmetric, grooved magnetron SPS (solid points, dashed curves) in the \( x \) (circles) and \( y \) (squares) planes. The curves are calculated from Eq. (3) as discussed in the text.

Discussion

Recently, Allison\(^5\) proposed a simple model of \( H^- \) ion beam emittance that allows calculation of the emittance as a function of the beam fraction. In this model, it is assumed that the \( H^- \) ions have a Maxwellian velocity distribution of temperature \( T \) and are emitted uniformly in space from the rectangular emission slit. The predicted functional dependence of beam fraction on emittance is

\[
F = \text{erf}\left(\pi \sqrt{\frac{2}{2R^2}} \sqrt{\frac{kT_m}{m c^2}}\right) \tag{3}
\]

where \( R \) is the slit half-width and \( m \) is the ion mass. The curves in Fig. 2 were calculated using Eq. (3), normalized to the values of \( e \) at \( F = 0.63 \). The resulting estimates of the \( H^- \) ion temperature are \( kT_x = 5\text{ eV} \) and \( kT_y = 840\text{ eV} \) for the Penning and \( kT_x = 22\text{ eV} \), \( kT_y = 5650\text{ eV} \) for the AGM sources.

Two second-order aberrations in the dipole magnetic field couple the \( x \)- and \( y \)-plane emittances,\(^6\) resulting in the larger emittance of the \( x \)-plane masking the initially (far) smaller emittance of the \( y \)-plane.\(^*\) This explains why the ratio of \( x \)- to \( y \)-plane emittances is 1.5:1 for the Penning SPS, instead of the 20:1 ratio of emission-slit length to width. The two second-order magnet aberrations cannot be simultaneously eliminated, their combined effect only can be minimized.\(^6\) This \( x \)-\( y \) coupling results in spuriously large \( kT_y \) values for both sources; we therefore use the \( x \)-plane emittance values to estimate the \( H^- \) ion temperature in the source emission region, 5 eV and 22 eV for the Penning and AGM SPS sources, respectively. We observed oscillations in the discharge voltage of \(<0.5\) V for the Penning SPS and \(>10\) V for the AGM SPS (1-MHz bandwidth on the oscilloscope amplifier used to measure the voltage fluctuations). These voltage fluctuations may indicate the presence of plasma instabilities that couple to the \( H^- \) ions in the discharge to increase their apparent temperature.

\(*\)Our pepper-pot measurements (unpublished) for a 100-mA, pulsed \( H^- \) beam from a Penning SPS, similar to that of Ref. 7, show an \( x \)- to \( y \)-plane emittance ratio of \( \sim 10:1 \) after the beam has traversed \( \sim 2 \text{ cm} \) in the dipole magnet.

---

### TABLE I

<table>
<thead>
<tr>
<th>Operating Parameters and Measured Beam Quality for the Penning and AGM SPS Sources.</th>
<th>Penning SPS</th>
<th>Asymmetric, Grooved Magnetron SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge current, A</td>
<td>100</td>
<td>49</td>
</tr>
<tr>
<td>Discharge voltage, V</td>
<td>48</td>
<td>200</td>
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<tr>
<td>Discharge-voltage fluctuations (peak-to-peak), V</td>
<td>&lt; 0.5</td>
<td>10</td>
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<tr>
<td>Magnetic field, T</td>
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<td>0.20</td>
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<tr>
<td>Pulse length, ms</td>
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<td>3.0</td>
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<tr>
<td>Duty factor, %</td>
<td>0.98</td>
<td>0.16</td>
</tr>
<tr>
<td>Beam energy, keV</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>( H^- ) current (I(_0), mA)</td>
<td>79</td>
<td>40</td>
</tr>
<tr>
<td>Emission-slit dimensions, mm(^2)</td>
<td>10 by 0.5</td>
<td>10 by 0.5</td>
</tr>
<tr>
<td>( c_x ) (0.63) x ( c_y ) (0.63), ( \mu \text{cm}^2\text{rad}^2 )</td>
<td>0.041 by 0.027</td>
<td>0.087 by 0.070</td>
</tr>
<tr>
<td>( B(0.63 \times 0.63), \text{A/cm}^2\text{rad}^2 )</td>
<td>14</td>
<td>1.3</td>
</tr>
<tr>
<td>( kT_x ), eV</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td>( kT_y ), eV</td>
<td>840</td>
<td>5650</td>
</tr>
</tbody>
</table>

\(^*\)Measured at the emittance-scanner Faraday cup (FC2 in Fig. 1) after magnetic analysis of the beam. Before magnetic analysis the \( H^- \) current (FC1 in Fig. 1) is 89 mA and 58 mA for the Penning and AGM sources, respectively.
Conclusions

We find that for a 10- by 0.5-mm$^2$ emission slit and beam transport through the same $n = 0.85$ dipole magnet, the H$^-$ beam from our Penning SPS has 2 times the intensity and 10 times the brightness of the H$^-$ beam from the AGM SPS. The H$^-$ ion temperature, deduced from a Maxwellian model and our emittance measurements, is 5 eV for the Penning SPS and 22 eV for the AGM SPS.

Acknowledgments

It is a pleasure to thank Th. Sluyters and J. G. Alessi for the loan of the Mark III magnetron source used in these measurements. The assistance of J. G. Alessi is gratefully acknowledged.

References


The rf system of the Photon Factory 2.5 GeV injector electron linac now under construction is described. The rf system is composed of four stages: a master oscillator, a main booster amplifier (cw, 476 MHz), sub-booster amplifiers (pulse, 2856 MHz) and forty two high power klystrons. The output rf power of the klystrons is 30 MW and the rf power of each klystron is split and fed into four accelerator guides composing one acceleration unit.

Almost all of the rf equipment and components have been installed in their positions and are in the final adjustment stage.

Outline of the rf system

The Photon Factory (PF) injector electron linac consists of 160 accelerator guides, and an electron beam of 50 mA is accelerated up to the energy of 2.5 GeV. The main parameters of the rf source are as follows:

- Number of klystrons: 42 (including 2 klystrons for the injector and de-buncher)
- Peak power per klystron: 30 MW max.
- RF pulse length (flat top): 2 μsec
- RF repetition rate: 50 pps max.
- Operating frequency: 2856 MHz

It is necessary to adjust the rf phase of the drive signal to each klystron to the correct acceleration angle with respect to the rf wave crest of the electron bunch to within ±2°. The system which transmits the coherent rf wave to each klystron is the "drive system". After various studies, the drive system was decided to be as shown in Fig. 1.

The frequency of the master oscillator was chosen to be 476 MHz, the sixth sub-harmonic of the accelerator frequency, this reduces transmission loss in the 400 m main drive line. A main booster amplifies the 476 MHz rf power to 2 kW (cw). The main drive line with five directional couplers corresponding to each of the five "sectors" transmits this rf power to frequency multipliers. The rf multiplied from 476 MHz to 2856 MHz by frequency multipliers is amplified to two 10 kW pulses by a sub-booster installed at the middle of each sector. A subdrive line with three or four directional couplers transmits the 2856 MHz, 10 kW rf power to each of the four or five high power klystrons in each half sector. The 2856 MHz rf power is amplified up to 30 MW by the high power klystrons and is transmitted to each of four accelerator waveguides by high-power wave-guides.

RF driver

Main booster The main booster consists of a 10 W driver amplifier and a cw klystron amplifier, which amplify a 476 MHz rf signal from a master oscillator to 2 kW cw. For the main booster klystron the Varian 3RM3000LA is used. This tube is a UHF TV klystron which has three external cavities, it is capable of 2.5 kW cw output power and 30 dB gain at 476 MHz. The collector high voltage power supply is very well-regulated by series regulating transistors, with an output of 9 kV at 620 mA. The stability of the rf output is kept to better than 0.1 %/hour.

Sub-booster The sub-booster amplifier is required to provide 20 kW in order to be to drive eight or nine main klystrons. The use of a pair of Thomson CSF TH2436 klystrons was decided upon, each of which drives the upstream or downstream four or five main klystrons. This tube has four integral tuneable cavities and uses a permanent focusing magnet. It is rated at 10 kW for our application. Stringent specifications for the sub-booster modulator are...
imposed on the rise and fall times and amplitude tolerance of the output pulse, because the pulse shape determines the rf output and any change in the amplitude causes phase shift in the rf output. The phase shift caused by variation in acceleration voltage applied to the klystron is 8 degrees/percent. Wave forms of the phase detector output and the rf output pulse are shown in Fig. 2. The modulator is of the hard tube type, it consists of two pulsers with a storage capacitor and switching tubes (Eimac 4 PR-60), a high voltage power supply, G1, G2 power supplies and a grid driver.

Drive line The main drive line transmits the output power of the main booster, installed at the injector head, to the end of the klystron gallery 400 m away. The power split by five directional couplers spaced about 80 m apart, is fed to the frequency multiplier in each sub-booster. For high phase stability in spite of environmental changes a 1/8 in. semirigid phase stabilized coaxial cable is used for the main drive line. The cable is filled with \( \text{H}_2 \) kept at a constant pressure. Its electrical length temperature coefficient and attenuation are \( 3 \times 10^{-6}/\degree \text{C} \) and 0.024 dB/m, respectively at 476 MHz.

The sub-drive line transmits the 10 kW output power from one sub-booster klystron equally divided to drive four or five main klystrons, each receiving the drive power in an IDA unit. The same cable as for the main drive line is also used here.

Isolator, phase shifter and attenuator unit (IDA)

The functions of this unit are: 1) to adjust the phase relation between the rf accelerating field and beam bunch, 2) to protect the klystron output window and waveguide window by only gradually increasing the klystron input power on start up, and 3) to adjust the rf input power level to the following klystron in the sub-booster or main modulator. Typical measurements give an isolation greater than 25 dB, insertion loss less than 3 dB and linearity between the electrical phase shift deviation versus mechanical rotation angle of within \( \pm 2 \) degrees.

Main Modulator and pulse transformer

The main modulator supplies pulse modulated power to the high power klystron. At full rating this modulator is required to generate pulses with 22.5 kV peak voltage and 3600 A peak current. To prevent phase modulation and amplitude variation from pulse-to-pulse, pulse top flatness and amplitude stability are important. Specifications of the main modulator are listed in Table 1, a simplified diagram is shown in Fig. 3. Regulation of the output pulse voltage is accomplished by the de-Q'ing circuit which controls the charging voltage to the PPN. The IVR controller unit automatically tracks the dc high voltage to keep the operating range of the de-Q'ing regulation with a constant ratio by rotating the induction voltage regulator. The RC series circuit inserted in output circuit is for lowering the spike noise produced at the pulse rise, it is effective and overall the noise is small.

Table I  Specifications of main modulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power output</td>
<td>84 MW</td>
</tr>
<tr>
<td>Average power output</td>
<td>15 kW</td>
</tr>
<tr>
<td>Output pulse voltage</td>
<td>22.5 kV</td>
</tr>
<tr>
<td>Output pulse current</td>
<td>3600 A</td>
</tr>
<tr>
<td>Output impedance</td>
<td>6 ( \Omega )</td>
</tr>
<tr>
<td>Pulse width (flat top)</td>
<td>2.0 ( \mu )s</td>
</tr>
<tr>
<td>Pulse rise time</td>
<td>0.5 ( \mu )s</td>
</tr>
<tr>
<td>Pulse fall time</td>
<td>0.8 ( \mu )s</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 pps</td>
</tr>
<tr>
<td>Pulse height deviation from flatness</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Pulse amplitude variation and drift</td>
<td></td>
</tr>
<tr>
<td>short term</td>
<td>0.2%/min</td>
</tr>
<tr>
<td>long term</td>
<td>0.5%/hour</td>
</tr>
</tbody>
</table>

Fig. 3  Block diagram of main modulator.
enough that standard TTL circuit signal level IC's can be used for low-level control.

The equipment implementing the modulator control system can be divided into 3 groups. 1) Sensors, signal conditioners and output effectors distributed throughout the modulator-klystron area. 2) A hardware logic controller (relay, diode, TTL) for personnel and machine protection which allows independent operation of each klystron. And 3) Microprocessor (MC 6800) based modules for remote control and data collection.

In particular, they interface to a 500 kbps serial loop network, sequence and recycle the modulator power supplies on and off, set the De-Q'ing trigger voltage and the klystron input rf phase.

The pulse transformer is to step the voltage up to the level necessary for the klystron and to match the impedance between the modulator output and klystron load. The core of the pulse transformer is wounded from a 0.05 mm thick, grain-oriented silicon steel. The step-up ratio is 1:12. Even at the full 270 kV secondary voltage, it is not necessary to apply any core reset bias current.

High power klystron and focusing magnet

The high power klystron used is a MELCO (Mitsubishi Electric Corporation) PV-3030A. The specifications for this klystron were based on the XK-5 developed at SLAC for a high energy electron linac rf source. The klystron has five cavities, its perveance is $2.1 \times 10^{-6}$ A/V$^3$, and the peak rf output power is 30 MW, with 40% efficiency and 51 dB gain. A permanent magnet focuses the klystron electron beam. Compared with an electromagnet, use of a permanent magnet gives the advantages of maintenance-freedom and minimum operating cost. Fig. 4 shows a cut-away view of the magnet and Fig. 5 shows its magnetic field distribution. The magnet is composed of numerous permanent magnet rods (28 mm in diameter and 47 mm in length) packed cylindrically in a stainless-steel enclosure. The magnetic material used is Alnico 9 which was made by the zone-melting method. This material has a columnar shaped magnetic anisotropy and a large maximum energy product ($BH_{max}$), making it possible to design a compact magnet. The bar magnets are to compensate for the reversal field of the main magnet and to make possible fine adjustments of the field near the gun, since the region near the cathode is very critical with regard to the magnetic field distribution. Almost all of the klystrons and focusing permanent magnets have already been fabricated by their manufacturers, and after their assembly with pulse transformers and oil tanks (shown in Fig. 6), high power tests using a water load have been carrying out. At 260 kV, the mean rf output power exceeds the design value of 30 MW when used with electromagnetic focusing, but with the permanent magnet it is about 25 MW. This decrease in the output power is due to a nonoptimal magnetic field distribution, which occasionally also results in breakdown and instability in the rf output power. Further improvements and development are necessary for the permanent magnet.
DESIGN CONSIDERATIONS FOR A DEVELOPMENTAL HIGH POWER COUPLING LOOP TO DRIVE A RESONANT LOAD

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Summary

An rf drive loop has been designed for a 400 kW, 100% duty factor (cw), 270 MHz resonant cavity load. Operating experience with a high power cw Alvarez linac at Chalk River has resulted in the evolution of design features that reduce multipactoring, field emission and rf arc track damage. The design provides means for the development of coaxial vacuum windows, the evaluation of loop conductor shapes and the investigation of rf arc propagation phenomena.

Introduction

The Alvarez accelerating structure for the high current proton linac, ZEBRA, currently under study at CRNL, will require components capable of operating at much higher average power than is found in present low duty factor accelerators. A 400 kW 100% duty factor (cw) 270 MHz resonant load is being constructed at CRNL as a test facility for the development of drift tube linac components such as tuners, post couplers, drift tube suspensions and drive loops.

A cross-sectional view of the resonant load drive loop design is shown in Fig. 1. The coupling loop is located within the tank vacuum in preference to placing it behind a domed window as the latter is susceptible to failure from multipactoring and ion bombardment damage. Multipactoring, often encountered along the evacuated portion of the drive line, can be controlled. The coaxial window geometry is simple and relatively inexpensive to replace.

The transmission line is designed for 50 ohm constant impedance, including the window which is compensated for the dielectric constant of the window material. To avoid transition discontinuities and to simplify cooling, the radial dimensions were selected to match the 230 mm (9-3/16" commercial) rigid copper rf feedline.

The tank side of the window is located 5/12 λ from the position of the detuned short - i.e., from the detuned electric field node - as determined from electric field probe measurements on a 1:1 scale model of the drive line and resonant load. With this configuration any tank detuning will cause the loop impedance to fall but the voltage at the window remains relatively large, above the higher order mode multipactoring voltage levels.

Structural Features

The loop assembly is made of interchangeable sections for convenience in the development of high power windows and the evaluation of various loop shapes.

A teflon rf window, based on a design that operates successfully at 150 kW cw on an Alvarez linac, will be used for initial tests. The window supporting section can be removed to test designs using other materials, such as ceramics, that would require different vacuum sealing methods and different diameters for impedance compensation. The tapered transition section was made relatively short and free of sharp corners or gaps that might initiate multipactoring or arc discharges. The end of the loop conductor that normally is connected to the outer conductor shell, has been fastened to a ring clamped in the outer conductor assembly to provide both electrical and vacuum connections. This arrangement allows both ends to be freed readily for replacement.

Loop coupling may be adjusted either by trimming a spacer or by rotating the loop. In the latter method, the centre conductor cooling line interferes with the tank port flange bolts restricting loop positions. However, by using a slightly rotated orientation of the flange bolt holes, almost any required loop angle may be obtained by positioning the cooling tube between a suitable pair of bolt holes on either side of the maximum position.

Aluminum was chosen as the construction material for ease of fabrication and to avoid incompatibility of the cooling water chemistries of copper and aluminum. Only the air-cooled rf feedline adaptor section is made of copper and brass.

Vacuum Seals

Because the loop and drive line are within the vacuum, the seals must have low outgassing rates and very small leakage to reduce the incidence of rf breakdown. Helicoflex seals are used in the outer conductor and port flange joints, but they do not provide an rf conduction path. Instead a short section of the joint surfaces next to the conducting wall forms a pressure contact. As a back-up measure the Helicoflex seal grooves have been designed to allow substitution of an elastomer seal.

The vacuum seal to the teflon window is made by clamping the 24.4 mm thick disc at its inner and outer circumference against a knife edge fixed on the vacuum side. The knife edge nose is rounded to ensure cold flow around the sealing surface, allowing the joint to be remade several times.
 Cooling

Both the centre and outer conductors are flood cooled with water to remove heat from transmission losses, most of which occur in the centre conductor assembly. A water flow rate of 0.1 liters/s, large enough to maintain a small temperature rise, was chosen to ensure reliable low flow protection.

The 230 mm rigid copper drive line is air cooled at a flow rate of about 24 liters/s. Window cooling is provided by directing part of the air flow leaving the centre conductor onto the window surface.

Experience with Rf Breakdown, Multipactoring and Ion Sputtering

In our early Alvarez linac designs, the drive loop supporting flange was located 100 mm from the end of the loop, resulting in a long annular gap between the loop body and the port wall. Some rf field was necessarily coupled into this gap, and in the presence of local high pressure, could initiate arcing. Figure 2 is a photograph of the end of a loop that was damaged when a leak developed at the flange joint. Such discharges may transfer to the open end of the loop and propagate towards the window. The gap may be shielded by spring contacts, although they must be designed to handle substantial currents.

At our drive levels, the voltage on the 50 ohm 15.2 cm copper drive line was well below the onset of half cycle multipactoring, but higher order multipactoring was considered possible above 15 kW. In fact multipactoring occurred at 35 kW. The resultant ion bombardment and sputtering caused conductor erosion, the deposition of a conducting copper layer on the window, and eventual track etching on the window surface. The net result was intolerable reflected power.

However, by strapping a layer of bar magnets around the periphery of the outer conductor to obtain an axial field of 5-10 mT, the electron path geometry was altered sufficiently to suppress multipactoring and allow the power to be increased gradually during conditioning. The magnetic field modified the path of any rf discharge so that the resultant outer conductor erosion was reduced. After many events, the conductor surface marking, as seen in Fig. 3, consisted of many light spiral tracks which, upon disassembly, proved relatively easy to remove.

Damage to the window was also reduced substantially. Instead of several deep tracks across the teflon window face, the entire surface was coated, lighter in the central region and much heavier with some charring near the outer edges.
As a further modification, a series of four equally spaced grooves 8 mm wide by 6.4 mm deep were machined into the vacuum face to inhibit the formation of a conducting path across the face by sputtered copper deposits. Figure 3 is a photograph of an Alvarez linac loop showing the wall and window surfaces damaged during high power operation.

Although the window surface is heavily coated and charred near the edges, the groove sidewalls and bottom are almost untouched. With the window in this condition, the mismatch seen by the source is relatively small, i.e., VSWR ≤ 1.5.

**Conclusions**

Improved loop performance has been achieved by:
- eliminating the narrow re-entrant gap between the loop and port wall
- shaping the centre conductor taper to avoid sharp edges and shaping the loop conductor to avoid a shallow crevice at the wall
- using a grooved teflon window
- immersing the evacuated section of the loop in a solenoidal magnetic field produced by bar magnets
- incorporating ports in the outer wall for installing field or light sensing probes to monitor arc propagation phenomena.

Development work is continuing.

**Acknowledgements**

R.G. Chidley and J. Ungrin have contributed substantially to the understanding and development of the cw Alvarez accelerator and its components.

**References**

1. S.O. Schriber, "The ZEBRA Program at CRNL - 300 mA-10 MeV Proton Linac", proceedings of this conference.
2. B.G. Chidley et al., "Design and Constraints for the ZEBRA Injector, RFQ and DTL", ibid.
POST COUPLER STUDIES FOR ALVAREZ TANKS TO BE USED FOR HIGH POWER OR VARIABLE ENERGY

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Summary

The on-axis electric field in a 22 cell Alvarez tank that models the 0.8 MeV to 2.8 MeV section of a 268 MHz linac has been stabilized with post-couplers at a constant spacing from the drift-tube. Measurements on field shaping with post-couplers show that a step function in the on-axis field can be produced by introducing post-coupler asymmetries. This field shaping which can be used to allow a wide range of output energy variability from an Alvarez linac can be produced with post-couplers on each drift-tube or on every second drift-tube.

Introduction

Post-couplers in a drift-tube linac are important in stabilizing the on-axis electric fields against tilts produced by mechanical errors. Recently it has been proposed that post-couplers could also be used to shape the on-axis fields along the linac length in a manner that would allow a wide range of energy variability for the output beam. Drift-tube linacs normally have a very narrow range for the output energy.

The long range goal for accelerator development at the Chalk River Nuclear Laboratories is the development of high current cw linacs suitable for electronuclear fuel breeding. Large frequency shifts can occur in such accelerator structures operated in the cw mode (100% duty factor) because of the high average power dissipated in the structure walls. One or more mechanical tuners are required in each accelerator structure to correct for frequency shifts and to ensure that each structure operates at the same frequency. On-axis fields were measured in a low power drift-tube linac model to determine optimum post-coupler dimensions that stabilize the structure against tilts introduced by adjustable tuners. During the course of these measurements, on-axis field shaping with post-couplers was investigated.

Experimental Model

On-axis fields were measured on a 22 cell aluminum Alvarez drifttube tank that was available from a previous experiment. Figure 1 shows a photograph of the 50 cm diameter 372 MHz tank, a 0.72 scale model of the 0.8 MeV to 2.8 MeV section of the 3 MeV High Current Test Facility linac. Drift-tubes were 98 mm diameter with a 11 mm diameter bore hole. The first and last full drift-tubes were 26.6 mm and 44.6 mm in length respectively. Field perturbations were introduced by adjusting the tank end plates to give a field tilt while maintaining a fixed resonant frequency.

Initial experiments on field stabilization used 19 mm (nominal 3/4 inch) diameter rods for post-couplers. This diameter was chosen to be equal to that of the drift-tube stems. Eccentric tabs with total areas 1.85 and 5.69 times the post-coupler cross-section were used for measurements involving field shaping. Three post-couplers showing the different end arrangements are shown in Fig. 2 together with the first drift tube.

Field Stabilization

Field tilt is defined as the difference in the on-axis electric field from one end of a tank to the other end divided by the average on-axis electric field. Adjustments of field tilt for the model tank were made by increasing or decreasing the length of the first cell by 2 mm or 3 mm with a movable end plate. Shifts of +1.0 MHz to -0.5 MHz in tank frequency were introduced by these adjustments. Since tilt measurements must be made at a fixed frequency the length of the final cell was adjusted to maintain a fixed frequency. The end plate shifts introduce severe distortions in the first and last cell lengths. Experimentally the tilt was found by averaging over the three cells next to the end ones.

Standard bead perturbation methods were used to sample the on-axis electric fields. First measurements made without post-couplers showed a linear dependence of the tilt on end plate frequency shift, with a slope of 57%/MHz. Ten 19 mm diameter post-couplers were then installed and located opposite the even numbered drift tubes, alternating from side to side of the tank.

Since the model represents the low energy section of a linac, cell lengths change fairly rapidly. The last drift-tube is almost a factor of two longer than the first drift-tube. Initial measurements of tilt stabilization were therefore made with a smaller post-coupler-to-drift-tube spacing at the low energy end than at the high energy end in an attempt to equalize the couplings. This approach results in the variation of two parameters namely the post-coupler-drift-tube spacing and the spacing increase along the tank length - making data analysis more complicated than necessary. An attempt was then made to stabilize the fields with a constant post-coupler-to-drift-tube gap. At a spacing of 26.5 mm a tilt stability of less than 1%/MHz was achieved corresponding to a stability improvement by a factor of 57. Individually adjusting the spacing for each post-coupler did not lead to a significant improvement in tilt stability.

Tilt stability is only one parameter that determines optimum post-coupler positions. The ratio of fields in all cells with and without post-couplers serves as a second parameter. Tilt stability may be improved by large post-coupler-to-drift-tube spacings but severe oscillations in the...
field amplitude can result along the tank. At the optimum 26.5 mm spacing the ratio of fields without post-couplers to the fields with couplers is constant within 2%.

Tilt stability measurements were also made with the two different sizes of eccentric tabs. Shifts of less than 1%/MHz were achieved in each case. The post-coupler-to-drift-tube spacing required increased from 26.5 mm to 34.2 mm for the small tabs and to 54.2 mm for the large tabs. The tabs showed minor improvements in field smoothness.

Field Shaping

A perturbation of the symmetry of a post-coupler-drift-tube geometry such as tab rotation can produce changes in the on-axis electric fields along the linac length. Recently Swenson et al. have proposed the use of perturbed post-couplers to introduce a sufficiently large step reduction in the on-axis fields that will drop the beam out of synchronism with the field in a programmed manner. This field reduction can give a wide variable-energy capability to a single-tank drift-tube linac.

Experimental measurements were done to produce such a step reduction in the model tank by rotating post-coupler tabs. Initial measurements were made with 10 post-couplers opposite the even numbered drift-tubes, as above, and with the small eccentric tabs. Rotating tabs 90° from the symmetric vertical position resulted in a very small (1%) change per coupler indicating that the tabs were too small. Large tabs were then mounted on the posts. Fig. 3 shows the results of rotating 1, 2 or 4 large tabs 90° towards the high energy downstream end of the tank. Tabs on the upstream and downstream post-couplers remained unchanged at 0°.

The peak on-axis electric field is shown plotted relative to the field with all tabs vertical. Coupler numbering refers to the drift tube opposite which the coupler is mounted. (Coupler 10 therefore is between gap 10 and 11.) The field reduction produced beyond the rotated tabs is 5%, 12% and 22% for 1, 2 or 4 tabs respectively. In addition to the field reduction in the downstream part of the tank, a field increase of about 5% occurs over several cells upstream of the ones containing rotated couplers. Only the number of cells affected changes as the number of rotated tabs increases. Similar results were obtained for the perturbation beginning in an earlier or later cell. This then would be the mechanism to produce a variable energy drift-tube linac. By pre-programming the location of the perturbation, various energies can be achieved. (A step increase can similarly be produced by rotating tabs toward the upstream end of the linac.)

Various schemes of reducing the upstream field increase have been tried without success. Figure 4 shows fields for a gradual rotation of the post-couplers by four successively larger steps (22.5°, 45°, 67.5°, 90°). The net result was to increase the number of cells across the step and to decrease field step from 22% to 16%.

Tilt stability was checked for post-couplers rotated 90° downstream. Rotating 4 tabs 90° introduced a 5%/MHz shift and rotating all 10 tabs 90° introduced a 12%/MHz shift. To stabilize the tilt to <1%/MHz with 4 tabs rotated 90° as shown in Fig. 3 required an increase in the coupler-to-drift-tube gap from 54.2 mm to 56.2 mm on all couplers. No significant change in the field pattern occurred with this spacing change.

For a second series of measurements post-couplers with large tabs were installed opposite each drift-tube. As described before, successive couplers were located at alternate sides of the tank. Tilt stabilization to <1%/MHz was achieved at a constant spacing of 52.0 mm for all 21 post-couplers. This spacing was 2.2 mm closer than that for the 10 post-coupler measurements associated with post-couplers opposite only even-numbered drift-tubes.

Figure 5 shows normalized peak on-axis electric fields for the 21 post-coupler arrangement with 1, 3 and 6 tabs rotated 90° towards the upstream end. Field reductions of about 2%, 6% and 14% respectively are produced in cells beyond the perturbed tab location. Field perturbation per tab is a factor of two smaller than the case of the same area tabs on 10 post-couplers opposite even-numbered drift-tubes. This is at least partly the result of a compensating effect on the asymmetry by the tab from the adjacent cell. Again, similar results are obtained if the location of tab perturbations is centred about different cells than shown in Fig. 5.

A field increase is again evident in gaps upstream of the rotated couplers but the number of gaps affected is less. The magnitude of the increase depends on the number of rotated couplers - an effect not observed in the 10 post-coupler measurements.

Figure 6 shows the field step produced by 6 couplers all rotated 90° compared in four successively larger 22.5° steps with the last two tabs at 90° and compared to six tabs rotated by successively larger 15° steps. Field reduction downstream of the rotated couplers is largely unchanged while the field increase upstream can be reduced by a factor of 3 using this procedure. No such reduction was observed in the 10 post-coupler case.

Figure 7 shows the normalized field produced by six successively larger 15° step tab rotations beginning at drift tubes 7, 10 and 14. Slightly larger steps are produced as the starting location moves downstream. This effect is likely the result of increased perturbation with increasing drift-tube length.

As a final confirmation of the procedure, tilt stability with the case of six couplers rotated 90° was found to be essentially unchanged from the 1%/MHz value observed with all tabs vertical.

Conclusions

In addition to their usual function of providing field stability, post-couplers can be used to introduce a step reduction in the on-axis electric field along a drift-tube linac. Unfortu-
nately a field increase is also introduced in cells upstream of the perturbed cells. The magnitude of this upstream perturbation can be reduced by introducing a gradual cell-to-cell tab rotation for the case with post-couplers adjacent to each drift-tube but remains unchanged for the case with couplers on every second drift-tube. With post couplers on each drift tube, tilt stability is not disturbed by tab rotation. This stability is partially destroyed with tab rotation when post-couplers are placed opposite every second drift-tube but can be regained by a small increase in the post-coupler-to-drift-tube spacing.

Measurements on stable field steps reported here are only associated with a rotation of the eccentric tab on the end of the post-coupler because this was the easiest procedure to perform in the laboratory. Obviously many other schemes can be employed such as movement of the post-coupler to an asymmetric location or the extension of the end of the post-coupler in an asymmetric manner. The effects the introduction of a step has on drift-tube and post-coupler stem currents and the associated consequences they have on the cylindrical outer wall joint have not been investigated. Such measurements would be difficult for low-power rf systems and would best be done on high-power rf systems that are properly instrumented.

References


Fig. 6 Reduction of upstream perturbation with gradual tab rotation. Geometry as in Fig. 5.

Fig. 5 Normalized on-axis field with one, three or six large tabs rotated 90°. Post-couplers opposite all drift tubes.

Fig. 7 Step produced by six successive 15° steps started at drift-tubes 7, 10 and 14.
VARIABLE-ENERGY DRIFT-TUBE LINACS*

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Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Summary

Practical applications of ion linacs are more viable now than ever before because of the recent development of the radio-frequency quadrupole accelerating structure, as well as other technological advances developed under the Pion Generator for Medical Irradiations program. This report describes a practical technique for varying the energy of drift-tube linacs and thus further broadening the possibilities for linac applications. This technique involves using the post couplers (normally used to flatten and stabilize the electric fields) to create a step in the fields, thus terminating the acceleration process. In the examples given for a 70-MeV accelerator design, when using this technique the energy is continuously variable down to 20 MeV, while maintaining a small energy spread.

Introduction

Practical applications of proton and ion linacs are more viable now than ever before because of the development of the radio-frequency quadrupole (RFQ) accelerating structure and other accelerator technology that we have proposed as an integrated system in our PIGMI (Pion Generator for Medical Irradiation) design. Although many of these applications would benefit from a variable-energy option, drift-tube linacs (DTL) are not noted for this property.

The only variable-energy scheme in routine use involves turning off later portions of the linac to provide a few discrete energies from multitank linacs. Many applications require more discrete energies than normally are available from this scheme. The PIGMI technology advocates single-tank, post-coupled DTLs for simplicity and reliability. Any multitank arrangement to provide energy variability is a step backward in linac technology.

Post couplers have a special property in that they can introduce a step in the electric fields. Modest perturbations to the symmetry of the post-coupler/drift-tube geometry can introduce few-percent cell-to-cell changes in the fields across the post coupler. Several such perturbations on adjacent post couplers can introduce a sizable reduction in the fields over the region of a few cells. Such steps in the fields can be used to drop the beam out of synchronism with the accelerating fields and provide a variable-energy capability for the single-tank, post-coupled DTL.

Performance

Some examples of the field distributions that could be established in a 100-cell, post-coupled DTL are shown in Figs. 1, 2, and 3. Figure 1 shows the field distributions that result when 10 adjacent post couplers, beginning at cell number 50, are set for perturbations of from 2, 3, 4, 5, and 6%. Figure 2 shows the field distributions that result when 5, 10, 15, and 20 post couplers are set for 4% perturbations, beginning at cell 50. Figure 3 shows the resulting field distributions when 10 post couplers are set for 4% perturbations beginning at cells 50, 52, 54, 56, 58, and 60.

Table I gives the field reduction factors for all combinations of 5, 10, 15, and 20 post couplers set for perturbations from 2 to 10%. In all cases where the total perturbation is large enough to drop the fields in the high-energy end of the linac below the level required for synchronous acceleration, the beam will exit the linac at a reduced energy with some energy spread. The resulting energies and energy spreads for a range of perturbations near the center of a typical 100-cell, 70-MeV DTL are given in Tables II-VI. Higher

*Work supported by the US Department of Energy.
Table I

FIELD-REDUCTION FACTORS FOR SOME COMBINATIONS OF THE NUMBER AND SIZE OF THE INDIVIDUAL POST-COUPLER PERTURBATIONS

<table>
<thead>
<tr>
<th>Step Size</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>0.98</td>
<td>0.9039</td>
<td>0.8171</td>
<td>0.7386</td>
</tr>
<tr>
<td>3%</td>
<td>0.97</td>
<td>0.8587</td>
<td>0.7374</td>
<td>0.6333</td>
</tr>
<tr>
<td>4%</td>
<td>0.96</td>
<td>0.8154</td>
<td>0.6648</td>
<td>0.5421</td>
</tr>
<tr>
<td>5%</td>
<td>0.95</td>
<td>0.7738</td>
<td>0.5987</td>
<td>0.4663</td>
</tr>
<tr>
<td>6%</td>
<td>0.94</td>
<td>0.7339</td>
<td>0.5386</td>
<td>0.3953</td>
</tr>
<tr>
<td>7%</td>
<td>0.93</td>
<td>0.6957</td>
<td>0.4840</td>
<td>0.3367</td>
</tr>
<tr>
<td>8%</td>
<td>0.92</td>
<td>0.6591</td>
<td>0.4344</td>
<td>0.2863</td>
</tr>
<tr>
<td>9%</td>
<td>0.91</td>
<td>0.6240</td>
<td>0.3894</td>
<td>0.2430</td>
</tr>
<tr>
<td>10%</td>
<td>0.90</td>
<td>0.5905</td>
<td>0.3487</td>
<td>0.2059</td>
</tr>
</tbody>
</table>

Table II

AVERAGE ENERGY AND ENERGY SPREAD IN MeV AS A FUNCTION OF THE NUMBER AND ORIGIN OF 2% FIELD STEPS

<table>
<thead>
<tr>
<th>Number of 2% Steps</th>
<th>Origin of Perturbations</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>69.7 ± 3.1</td>
<td>42.6</td>
<td>39.8</td>
<td>39.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>69.0 ± 4.4</td>
<td>43.5</td>
<td>40.8</td>
<td>40.4</td>
</tr>
<tr>
<td></td>
<td>52</td>
<td>70.3 ± 2.4</td>
<td>44.3</td>
<td>41.4</td>
<td>41.1</td>
</tr>
<tr>
<td></td>
<td>53</td>
<td>70.3 ± 1.4</td>
<td>45.5</td>
<td>42.7</td>
<td>41.9</td>
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<tr>
<td></td>
<td>54</td>
<td>70.6 ± 0.4</td>
<td>46.6</td>
<td>43.6</td>
<td>43.2</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>70.5 ± 0.7</td>
<td>47.2</td>
<td>44.2</td>
<td>43.9</td>
</tr>
<tr>
<td></td>
<td>56</td>
<td>70.3 ± 0.9</td>
<td>48.3</td>
<td>45.4</td>
<td>44.6</td>
</tr>
<tr>
<td></td>
<td>57</td>
<td>70.1 ± 0.3</td>
<td>50.0</td>
<td>46.7</td>
<td>46.1</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>70.7 ± 0.2</td>
<td>51.1</td>
<td>47.4</td>
<td>46.9</td>
</tr>
<tr>
<td></td>
<td>59</td>
<td>70.7 ± 0.3</td>
<td>52.0</td>
<td>48.6</td>
<td>48.1</td>
</tr>
</tbody>
</table>

energies result when the perturbations are moved toward the high-energy end of the linac, and lower energies result when the perturbations are moved toward the low-energy end of the linac.

In permanent-magnet focused linacs advocated by the PIGMI technology, a lower limit to the energies exists for which this scheme is suitable and below which the beam becomes unstable in the quadrupole-focusing system. In the 70-MeV linac example, this limit is about 20 MeV. For energies below 20 MeV, provisions can be made to extract the beam at some intermediate point along the structure where the low-energy beams still are stable in the quadrupole-focusing system. With beam extraction at 25 MeV, beam energies as low as 8 MeV are stable.

Table I shows that five 2% perturbations give a field reduction factor of only 0.9039, which is not low enough to drop the particles out of synchronism with the accelerating structure. The left-hand column of Table II confirms that situation, showing the average energy in each case to be close to the unperturbed value of 70 MeV. All
other combinations in Table I show an energy reduction capability. However, those combinations with field reduction factors exceeding 0.8 yield the largest energy spreads in Tables II-VI. Ten 4% perturbations give a field reduction factor of 0.6648 which will yield a relatively well-defined energy-reduction capability with root means square (rms) energy spreads of 1 MeV or less.

All of the field distributions in Fig. 1 would require proportional control of the magnitude of the perturbations on the individual post couplers. The latter scheme offers considerable mechanical, operational, and cost advantages and has enough flexibility to yield any desired energy, within the limits of the beam-transport system, to a resolution of 1 MeV or less and an energy spread of ±1 MeV or less.

Mechanical Features

A perturbation of fixed magnitude at selected post couplers can be realized by fitting each post coupler with a mechanical positioner having a well-defined home position (power off) and well-defined alternate position (power on). Both positions must be capable of fine adjustment during initial setup. The home position represents the unperturbed situation and is adjusted to achieve symmetry in the post-coupler/drift-tube geometry. In the home position, the post coupler forces a uniform field distribution across the post coupler. The alternate position represents the perturbed situation and is adjusted to achieve a certain degree of asymmetry in the post-coupler/drift-tube geometry. In this position, the post coupler introduces a step of the prescribed magnitude in the field distribution across the post coupler.
Table VI

AVERAGE ENERGY AND ENERGY SPREAD IN MeV
AS A FUNCTION OF THE NUMBER AND ORIGIN
OF 6% FIELD STEPS

<table>
<thead>
<tr>
<th>Number of 6% Steps</th>
<th>Origin of Perturbations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>34.7      ±1.0</td>
</tr>
<tr>
<td>51</td>
<td>35.3      ±0.9</td>
</tr>
<tr>
<td>52</td>
<td>36.4      ±1.0</td>
</tr>
<tr>
<td>53</td>
<td>37.1      ±1.2</td>
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<tr>
<td>54</td>
<td>38.4      ±1.2</td>
</tr>
<tr>
<td>55</td>
<td>39.0      ±1.1</td>
</tr>
<tr>
<td>56</td>
<td>40.3      ±1.1</td>
</tr>
<tr>
<td>57</td>
<td>41.0      ±1.3</td>
</tr>
<tr>
<td>58</td>
<td>41.9      ±1.1</td>
</tr>
<tr>
<td>59</td>
<td>43.3      ±1.2</td>
</tr>
</tbody>
</table>

The need for a controllable eccentricity in the post-coupler geometry was recognized in the earliest days of post couplers. Originally, the eccentricity was conceived as a way to achieve flat field distributions and effective symmetry in the post-coupler/drift-tube geometry. The original scheme was based on an eccentric tab mounted on the end of the post coupler, where the degree of asymmetry was controlled by rotation of the post coupler.

For a device requiring frequent movements and vacuum and radio-frequency (rf) contact integrity, a motion based on a flexible joint is preferred to the rotary motion of the original scheme. By pivoting the post coupler at the outer wall, only a modest flexure would be required to provide the desired asymmetry. A few-convolution bellows can provide a suitable vacuum seal and rf contact, but sliding vacuum seals and rf contacts would be unacceptable. For all stationary joints, 0-rings and Metex-rings are acceptable.

Figure 4 suggests a possible post-coupler positioner with features to enhance its effectiveness. An air cylinder with spring return is a convenient force to move the post coupler from the home position to the alternate position. Electrically operated air valves can provide a suitable interface to a control system. The mechanical linkage must have two well-defined positions, with each position capable of fine adjustment during initial setup. In addition, limit switches would provide data to the control system to confirm that the desired action has occurred.

Given a suitable mechanical positioner on each post coupler, the selection of energy from the DTL reduces to the excitation of the controllers on some preselected set of post couplers. The resulting change in the field distribution probably would change the impedance match to the rf power source. Some accommodation of this perturbation may be necessary.

Conclusions

A scheme is described in this paper to provide a variable-energy capability for the drift-tube linac, thus broadening the interest in this device for practical applications. The scheme is based on the use of post couplers to introduce steps in the accelerating fields, at specified points in the linac, to terminate the accelerator process and to produce beams of a variable energy. A relatively simple mechanical configuration for the post coupler is suggested.

REFERENCES

A variable-energy, single-section, side-coupled standing-wave linear accelerator structure is presented. This new structure provides a simple, reliable technique of continuously varying charged-particle beam energy over a wide range without degrading the energy spectrum. Theoretical and experimental results of this new technique are described. Application to medical and industrial linear accelerator technology has been demonstrated.

Introduction

Standing-wave linear accelerators are widely used for medical (radiation therapy) and industrial (radiography) applications. Most of these single-section accelerators are optimized for energy spectrum at one beam energy. It is highly desirable to obtain a beam of charged particles with a narrow spread of energy, this energy being variable over a wide range.

Radiation therapy accelerators typically produce x-rays in one of three energy ranges: 4-6 MeV (low energy), 8-12 MeV (medium energy) and 15-25 MeV (high energy). Depending upon the location of tumors, the optimum treatment can be performed by choosing the right x-ray energy. A multi-energy accelerator would allow optimum treatment at a larger range of tumor depths with a single machine. Similarly, a multi-energy industrial radiography machine would significantly increase the useful range of subject thickness.

One approach to varying the beam energy over a wide range is to cascade sections of linear accelerator guides which are independently excited from a common RF source with independent control of amplitude and phase. Another approach is the double-pass single-section linear accelerator which uses a movable reflecting magnet to obtain phase variation between passes. However, these techniques are rather complicated and the results are often costly and perhaps less reliable. Moreover, the techniques do not necessarily provide the wide range of energy variation desired without spectrum deterioration.

This paper presents a new technique which provides a simple, reliable method of varying the energy over a wide range without degrading the energy spectrum.

Structure Description

The geometry of the first few accelerating cavities of a single-section standing-wave accelerator guide, or "buncher", is designed to bunch the injected beam to minimize the energy spread for the desired accelerating electric field. For maximum efficiency, this field is nearly constant along the beam axis. The optimum bunching condition can be easily destroyed by changing the accelerating electric field for a given buncher geometry. The structure described here allows the accelerating electric field in the buncher to be kept constant while varying the magnitude and sign of the accelerating field in the rest of the accelerating guide.

The side-coupled standing-wave accelerator structure which was developed at Los Alamos has many advantages. Not the least among these is the tenacity with which the structure holds the relative fields in the accelerating cavities constant. The simplest structure using this concept is shown in Fig. 1(a). The coupling cavity which is unexcited at \( \pi/2 \) mode operation is removed from the beam axis. The technique described here is to utilize this off-axis unexcited side coupling cavity to vary the relative magnitude and/or sign of the accelerating fields of adjacent centerline cavities.

Typically, all cavities are longitudinally symmetrical to assure that the couplings between centerline and side-coupling cavities are equal, to provide constant accelerating electric field along the guide. This symmetry is indicated in Fig. 1(a).

The equivalent circuit of the structure is shown in Fig. 1(b). For \( \pi/2 \) mode operation, this equivalent circuit leads to the following relationship between coupling factors \( K_{01} \) and \( K_{12} \) and accelerating field amplitudes \( E_0 \) and \( E_2 \):

\[
\frac{E_2 - K_{01}}{E_0} = \frac{2}{K_{12} - K_{01} K_{12} Q_0 Q_1}
\]
as $KQ \gg 1$, it is clear that varying the ratio $K_{11}/K_{12}$ will result in an accelerating-field amplitude step. We have demonstrated that if this circuit is imbedded in a longer structure, the same step will result. Thus, providing independent control of accelerating fields in adjacent centerline cavities of a standing-wave accelerator guide is reduced to varying the ratio $K_{01}/K_{12}$. We have chosen to provide for this variation in the side cavity, since variation of side-cavity frequency and loss has no first-order effect on accelerator operation. Also, mechanical access is more convenient since the side cavity is located outside of the centerline accelerating cavities.

Variation of Coupling Ratio

The side-coupling cavity is magnetically coupled to the accelerating centerline cavities through the coupling apertures. The field distributions in the side-coupling cavities without coupling apertures shown in Fig. 2. If the distribution of magnetic field within the side cavity were made asymmetrical, a variation of coupling ratio $K_{01}/K_{12}$ would result.

There are several ways to induce this magnetic field asymmetry within the side cavity. One technique is to lengthen one center post and shorten the other as shown in Fig. 3(a). The resultant asymmetrical field distribution is schematically shown in the same figure. The resonant frequency of the side cavity can be held constant by keeping the proper relation between post lengths. It must be noted that if a cavity resonant mode such as the one described in Fig. 3(b) were excited, the relative sign of the accelerating fields in the adjacent centerline cavities would reverse.

Figure 4 shows the relationship of accelerating electric field ratio and side cavity post length variation for the quasi-$TM_{010}$ mode resonance case. To maintain the desired resonant frequency, one has to move both posts simultaneously. This relation is also shown in Fig. 4. By introducing this kind of side cavity in a longer accelerator at a particular location, one can produce the desired step of magnitude and sign in the axial electric field distribution, yet preserve the $H/2$ mode resonant conditions.

Figure 2. Electric and magnetic field distribution for longitudinally symmetric cavity.

Figure 3. Electric & magnetic field distribution for longitudinally asymmetric cavity.

Figure 4. Relationship of field ratio to post-length variation for quasi-$TM_{010}$ mode resonance.
Fig. 5 Axial electric field distribution for (a) high energy mode and (b) low energy mode of Clinac 2500.

Application

Two classes of standing-wave accelerator guides utilizing the concept described have been developed at Varian. They are used in the Clinac 2500 for radiation therapy and in the Linatron 200A for industrial radiography. Table I shows the basic parameters of these two machines.

The Clinac 2500 accelerator guide is capable of operating at two x-ray energies, 24 and 6 MeV, and at several electron energies up to 28 MeV. Fig. 5 shows the accelerating electric field distribution on the beam axis of the Clinac 2500 accelerator guide for the high energy mode (24 MeV) and the low energy mode (6 MeV). The control side cavity is located between the 8th and 9th accelerating cavities. High power experimental results show that the obtainable peak beam currents at 24 MeV and 6 MeV are 50 mA and 180 mA respectively.

The Linatron 200A accelerator guide is designed to operate at 2 MeV and 1 MeV. The switching side cavity is placed between the 2nd and 3rd accelerating cavities. This special side cavity, which uses the resonant-mode conversion technique described before, reverses the sign of the accelerating field. As a result, this guide is capable of operating at two different energy levels without varying the RF input power or the beam current. The Linatron 200A has demonstrated the ability to radiograph steel sections from 38 mm to 200 mm in thickness with 1% sensitivity (1-2T per ASTM E142).

Conclusion

In response to the need for a more versatile single-section accelerator guide, we developed a concept which allows control of the electric field within a guide. The concept allows a step field discontinuity between two accelerating cavities to be varied at will, in a structure in which field relationship is usually invariable. The concept was implemented in several experimental models and two forms of the concept were used in operating guides. These performed as expected. Subsequently, both forms have been used in commercial accelerators, one medical and one industrial, which have been delivered to customers throughout the United States.

Acknowledgements

The authors wish to express many thanks to V. Vaguine for his collaboration and direction, to V. Eliashberg who provided theoretical and computational studies, to A. McEuen who helped to prepare this manuscript and to L. Bean and his staff for providing machining and drafting services.

References


6. G. Meddaugh, E. Tanabe, and V. Vaguine "Variable Field Coupled Cavity Resonator Circuit" patent pending

LOOP COUPLING TO A RADIO FREQUENCY QUADRUPOLE RESONATOR (RFQ)*

D. Howard and H. Lancaster
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

Summary

Providing radio frequency energy to an RFQ resonator using a coupling loop instead of a slot gives more freedom in vane size design (smaller space occupied by the loop) and the possibility of tight coupling to ease operational problems.

Included is a discussion of various techniques to eliminate or separate the TE_{110} mode from the desired TE_{210} mode.

Results on a model designed to test these techniques will be discussed.

Introduction

The RFQ structure has attracted the attention of linac designers because of its unique ability to simultaneously bunch, focus, and accelerate low-beta ions.

The recent successes at Los Alamos National Laboratory have moved the RFQ through the stages of "exciting concept" to a practical accelerator.

Backed by a proven concept, the authors have attempted to simplify the construction and still maintain all the electrical properties of a practical accelerator by using the technique of loop coupling employed for driving most linear accelerating structures for ions. The advantages of loop coupling—small size, impedance matching, adjustable drive, phase locking, tight "resonant" coupling, etc.—have been demonstrated in the frequency range to ~400 MHz. Therefore, the purpose of these tests was to see if the RFQ resonator has properties which preclude this drive method, such as unwanted modes that are simultaneously excited with the quadrupole mode.

Besides the above-mentioned features of loop coupling, the small size of the loop would allow the utmost flexibility in vane shape design, cooling, and vacuum pumping. To explore possible problems with loop coupling, a simple model was constructed.

RFQ Test Model

The test model cavity is constructed from 8 inch-ID extruded-aluminum pipe. As might be expected, it is neither round nor longitudinally symmetrical. The pipe is "faced" to a length of 31.29 inches, and has twelve holes for inductive probes. There are three holes per quadrant which are equally spaced and longitudinally centered.

The vanes are 1/4-inch aluminum plate with the ends rough cut at 45° to the cavity wall, and are installed in quadrature with an RF gasket. The vane edges that make up the gaps are machined to make an inner radius, from the cavity center to the vane edge, of .519 inches. The vane ends are machined to be equidistant and .645 inches from the end walls.

The end walls are 1/8-inch aluminum plate with two tapped 1/4-20 holes that are placed 180° apart and centered over the vane ends to provide capacitive end tuning.

Although it is a very rough structure, the purpose of the cavity is to observe the various modes and affects upon them as modifications are made to the cavity, and different loop drive methods are employed.

Modes

Initial mode measurements are done with all probes oriented to drive or detect a longitudinal magnetic field. A sweep generator drives a center probe while other probes are checked for an amplitude response with a diode detector and log amplifier. Once the resonant frequency is determined, the cavity is driven CW while the probes are checked for relative phase and amplitude to determine the specific mode.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Science Division, U.S. Dept. of Energy under Contract No. W-7405-ENG-48.
The untuned cavity exhibited three modes\(^2\) with poor amplitude balance and no longitudinal phase changes. They were TE\(_{110}\) at 412.5 MHz, TE\(_{110}\) at 415.75 MHz, and TE\(_{210}\) at 428.5 MHz, as indicated by quadrant phases. This agrees well with the TE\(_{210}\) frequency calculated\(^3\) for the model dimensions.

When aluminum tape was added to the appropriate cavity walls in an attempt to more closely balance the quadrant amplitudes in the TE\(_{210}\) mode, the TE\(_{110}\) modes disappeared, and two dependent modes appeared at approximately the same frequencies as their TE\(_{110}\) counterparts. These modes approximate the cross section of a conical line resonator,\(^4\) and are dependent upon drive to one of the cones.

The aluminum tape was removed and closer balance was attempted by capacitively end loading the vanes by empirically adjusting the tuning slugs (1/4-20 bolts). The three original modes appeared with quadrant balance somewhat improved in the TE\(_{210}\) mode, and, as expected, the three modes were at lower frequencies.

The effective elimination or reduction of a particular mode in a resonator can result from a simultaneous excitation pattern. With drive loops in opposite resonators of an RFQ, the quadrupole mode can be enhanced, and the dipole mode reduced. Quadrupole modes with longitudinal variations (TE\(_{21n}\)) can be reduced by driving with several loops spaced longitudinally. These could be excited using a resonant manifold.\(^5\)

Model Test Results

Two methods of simultaneous drive were tried. The first, quadrature sections driven 180° out of phase, did little more than increase the amplitudes of the conical line resonator, TE\(_{110}\), and the TE\(_{210}\) modes. The second method, opposite sections...
driven in phase, removed the conical line resonator and/or the TE110 modes, and, as expected, increased the amplitude in the TE210 mode. An unexpected, but not surprising, result was the generation of TE21N, a longitudinal quadrupole mode. Since the two opposing sections are driven only at their centers, the longitudinal mode is not suppressed. Tests with longitudinally-spaced drive loops have not been done.

![Diagram of mode separation](image)

**Mode Separation**

In devices which depend on the proper excitation of several resonators (e.g., magnetrons), it is common to strap, or short together, points on the resonators with the same potential to insure proper excitation.

When properly excited and balanced, the opposite vanes of an RFQ should be at the same potential. Placing a strap between opposite vanes should not disturb the quadrupole mode, but should move the dipole mode to a far different frequency.

**Model Test Results**

One pair of opposing vanes were shorted at one end, as were their quadrature counterparts at the other end of the cavity. Shorting of both pairs of opposing vanes at one or both ends was not tried as it was felt capacitive end loading in a practical accelerator would be excessive. The result was apparent TE110 modes at each end, and longitudinal variation in the two opposing quadrants. Further investigation of this technique is planned.

**References**


5. Ferd Voelker, private communication, September 1981.
Low frequency, radio frequency quadrupole (RFQ) structures are under study at Argonne National Laboratory (ANL) as the low-velocity portion of an rf linac driver for heavy ion inertial confinement fusion. Besides offering a direct comparison with the present ANL front end, it would provide a second low-velocity Xe$^{+1}$ linac for funneling experiments at 22.9 MeV. Heavy ion RFQ accelerators are characterized by their low rf operating frequency of about 10 MHz. The large size of a manifold-fed four-vane, 10 MHz RFQ resonator structure (about 6 m in diameter) makes it unacceptable for heavy ions; therefore, alternate structures are under study at Argonne. The structures under study are: (1) a Wideroe-type structure with external stub lines, (2) a Wideroe-type structure with the stub lines internal to the structure, (3) a split coaxial line resonator with modulated vanes, and (4) an interdigital line resonator with modulated cylindrical rods. The split coaxial line resonator seems best at this low frequency. It is compact and very efficient. About 15.5 m of linac structure excited with 560 kW of rf power is sufficient to accelerate 30 mA of Xe$^{+1}$ with 97% transmission efficiency from 250 keV to 3 MeV.

Introduction

An RFQ linac$^{1,2}$ is a structure which has four-pole symmetry and produces focusing, bunching, and acceleration of charged particle beams by the use of radio frequency electric fields only. No internal static magnetic or electric quadrupoles are required in the structure proper, as is the case with a conventional rf linac. The four-pole symmetry of the device produces a strong electric quadrupole field in the vicinity of the beam aperture which can be used to focus and confine low beta charged particle beams. Because the beam focusing is performed by the rf electric field, it is possible to produce strong focusing forces in the low beta region where conventional quadrupole magnets are not feasible. It is the strongest known low beta focusing structure.$^3$ By modulating the pole pieces a longitudinal component of electric field is produced which is used to bunch and accelerate the beam. Proper shaping of the rf "focusing" lattice, bunching section and accelerating section results in a linac capable of accelerating particles of low injection energy to moderately high output energy levels with greater than 90% capture efficiency for high beam current inputs.$^3$

Structures

The problem with the use of the four-vane RFQ resonator developed at LANL at the low frequencies required for heavy ions is its large size, 6 m in diameter at 10 MHz. Therefore, alternate, more economical structures have been under study at ANL and elsewhere.$^4,5$

The structures that we have been examining are shown in Figs. 1, 2, and 3. Figure 1 shows the design of a Wideroe-type linac cavity (RFQ Structure #1) with four external stub lines. Two of the modulated vanes are supported by the stub lines and are driven at the same potential by separate rf feed loops. The other two modulated vanes are grounded to the outside shell, dividing the structure into two electrically symmetric halves. Each half can then be looked at as a separate Wideroe tank with heavy capacitive loading. Figure 2 shows the design of a Wideroe-type linac cavity (RFQ Structure #2) with four "internal" stub lines. As was the case with the preceding design two modulated vanes are supported by the stub lines and are driven at the same potential by separate rf feed loops. The other two modulated vanes are grounded to the outside shell, dividing the structure into electrically symmetric halves. Figure 3 shows the design of the split coaxial resonator (RFQ Structure #3). It has four blade-shaped beams or electrodes supporting the RFQ modulated vanes. Two diametrically opposite beams are grounded to the end plate at one end of the structure, while the other two are grounded at the other end. This can be looked at as an interdigital filter with strong capacitive coupling. It is similar to the GSI design.$^6$ However, instead of real drift tubes and fingers, it uses the LANL modulated vanes to produce the required RFQ fields. A fourth structure, a variation of structure #3 is possible. It uses modulated cylindrical rods in place of the blade-shaped support electrodes and LANL modulated vanes. However, the study of its performance characteristics is incomplete and will not be further reported on in this paper. One would however expect it to perform about as well as structure #3, but not be as mechanically rigid.

Structures #1 and #2 were analyzed using a transmission line model. The computer program POISSON$^7$ was used to determine the inter-electrode capacitance of the vane tips and hence the loading of the transmission line. The length of the structure is determined by the amount of voltage variation allowed along the line. In the case studied only 10% variation was allowed, which gives resonant structure lengths of 4 m and 5 m for structures #1 and #2, respectively. Table I gives some of the performance parameters for the ANL 6 RFQ design.$^8$ As can be seen, four Type #1 structures or three Type #2 structures are required to accomplish the approximate 45 m of structure required. The modulated vanes can be made continuous from one structure to the next by cutting holes in the end plates at the open circuit point, thus allowing no interruptions in the modulation of the vanes. The structures can be excited...
separately or from a single source by coupling the structures together by additional slots in the end plates, thus running them as a super cavity.

Structure #3 was analyzed as a multi-conductor transmission line. The voltage and current along a multi-conductor line are given by the matrix equations

\[
[V] = [V_0] \cos \beta \ell + j [G]^{-1} [I_0] \sin \beta \ell
\]

and

\[
[I] + [I_0] \cos \beta \ell + j [G] [V_0] \sin \beta \ell
\]

where

\[
[G] = [C]/(\omega \epsilon)^{1/2}
\]

and \([C]\) is the distributed capacitance matrix. Using these relationships and proper terminating conditions, it can be shown that the resonant condition for a uniform line is given by

\[
\cos^{-1} \beta \ell = 2 C_{12}/C_{11}
\]

where

\(C_{12}\) is the capacitance between conductors, \(C_{11}\) is capacitance of a conductor to all other conductors and ground

\(\beta = 2\pi/\lambda\) and \(\ell\) is length of structure

The results of this analysis agree with those using the GSI relationships and are also shown in Table I.

A model of structure #3 was constructed to test the derived relationship and is shown in Fig. 4. The outside shell is made of an aluminum tube 0.19 m in diameter and 0.5 m long. The blades are supported by copper rods 0.019 m od and 0.48 m long. They are placed 90° apart on a 0.038 m diameter circle. POISSON was used to calculate \(C_{12}\) and \(C_{11}\). The measured frequency of 58 MHz agreed to within a few percent of the calculated value using the above relationship.

**Conclusion**

The split coaxial resonator RFQ is a compact and efficient RFQ design for a low frequency heavy ion linac. A structure 1.2 m in diameter and 2 m long resonates at 12.5 MHz. Eight structures requiring about 560 kW of input rf power are sufficient to satisfy the requirements of the ANL 6 design (accelerate 30 mA of Xe\(^{+}\) with 97% transmission efficiency) from 250 keV to 3.0 MeV). The structures need to be placed close together so that the modulated vanes are not interrupted. The Wideroe-type structures are more complicated and more difficult to build. Hence, they are less attractive for heavy ions.

**Table I**

<table>
<thead>
<tr>
<th>LINAC TYPE</th>
<th>LENGTH OF ONE STRUCTURE</th>
<th>NO. OF STRUCTURES REQUIRED</th>
<th>TOTAL POWER REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 Wid. Ext. Stub Line</td>
<td>4 m</td>
<td>4</td>
<td>560 KW</td>
</tr>
<tr>
<td>#2 Wid. Int. Stub Line</td>
<td>5 m</td>
<td>3</td>
<td>900 KW</td>
</tr>
<tr>
<td>Split Coax. Resonators</td>
<td>2 m</td>
<td>8</td>
<td>560 KW</td>
</tr>
</tbody>
</table>

**References**

7. ANL version of computer program POISSON.
8. T. Wangler, LANL, private communication.
A PROGRAM DEVELOPMENT FOR SUPERFISH
Shoji Okumura
Fukui University, 910 Fukui, Japan

Summary

A new computer program is coded to calculate rf fields and resonant frequencies in axially symmetrical cavities. Algorithms for triangular mesh generation and finding the frequencies are the same as those in SUPERFISH, but the quadratic Lagrange interpolation is used to approximate the fields in triangular elements. The test runs are made for a pill-box cavity with the numbers of calculating mesh points which are equivalent to the cases for SUPERFISH. Although noticeable improvements have not yet been obtained for the frequencies, the test runs have shown that the new program gives better accuracies for the field values than SUPERFISH.

Introduction

So far a number of computer programs have been developed to evaluate rf fields and resonant frequencies in axially symmetrical cavities. The program called by the name of SUPERFISH is one of the most excellent programs and many improvements have been made for it to be able to interpret more convenient input data formats and to produce more versatile outputs. It gives the best results for the field evaluations of the fundamental mode and the accuracies decrease as the order of modes becomes higher. Even for the fundamental mode it depends on the boundaries of cavity whether the results may be so good or not. The decrease of accuracies seems to be caused by truncation errors in approximating the fields by linear functions of coordinates within the triangular elements. The use of more sophisticated approximations such as the higher-order Lagrange interpolations or C^1 approximations may be expected to improve the circumstances. However, growths of running cpu time and main memory space together with burdens in program coding make it difficult to incorporate them in the programs. The quadratic Lagrange interpolation scheme seems to be a relatively feasible method and to be the first candidate to investigate the possibility of improvements. In this approximation, the field in each triangular element is given by a linear combination of six basis functions, whose coefficients are equal to the values at the vertices or at the midpoints of the sides. The systems of linear equations are built up and solved taking the coefficients as unknowns. Therefore, the number of the unknowns on the same triangular mesh is about four times as many as those in the linear approximation used in SUPERFISH. The new program coded by the use of quadratic Lagrange interpolation is called QLFISH in this paper.

The accuracies of the calculation become higher as the number of triangular elements increase. The load of computation mainly depends on the size of the system of linear equations. So the comparisons of the accuracies between the results of QLFISH and SUPERFISH are made under a condition that SUPERFISH has four times as many as triangular elements than QLFISH. The many parts of theoretical background in this paper are based on the descriptions about SUPERFISH.

Difference Equation by Using Quadratic Lagrange Interpolation

Applying suitable normalization and excluding the time dependence term of exp(jωt), Maxwell's equation for the magnetic field \( \mathbf{H} \) in cavities can be expressed by

\[
\text{curl}(\text{curl} \mathbf{A}) = k^2 \mathbf{A},
\]

where \( k = \omega / c \). The electric field \( \mathbf{E} \) also satisfies the same equation. Using Stokes' theorem, integration of Eq. (1) over a closed surface yields

\[
\int \text{curl} \mathbf{A} \cdot ds = k^2 \int \mathbf{A} \cdot da,
\]

where \( ds \) is the infinitesimal vector tangent to the closed path along the boundary of the surface and \( da \) is the infinitesimal vector normal to the surface to the integrating surface.

The boundaries of cavity with the axial symmetry can be expressed by closed areas on the z-r plane in the cylindrical coordinate system. Assuming \( \mathbf{A} \) has only a single component \( H_1 \) having no dependence on \( \phi \), Eq. (2) can be treated as a two-dimensional problem. The triangular meshes are generated on the area in the boundaries by means of the mapping algorithm. Using the quadratic Lagrange interpolation, the field \( H_1 \) over each triangular element is given by a linear combination of six basis functions \( q_1, q_2, ..., q_6 \) as

\[
H_1 = \sum_{j=1}^{6} q_j(z,r),
\]

where \( H_1, H_2, ..., H_6 \) are the values of \( H_1(z,r) \) at the vertices or at the midpoints of the sides. The basis functions \( q_1(z,r), q_2(z,r), ..., q_6(z,r) \) are given by

\[
q_1(z,r) = p_1(2p_1 - 1), \quad q_4 = 4p_1p_2,
q_2(z,r) = p_2(2p_2 - 1), \quad q_5 = 4p_2p_3,
q_3(z,r) = p_3(2p_3 - 1), \quad q_6 = 4p_3p_1.
\]

Here \( p_1, p_2 \), and \( p_3 \) are the basis functions of the linear Lagrange interpolation which satisfy the relation

\[
P_m(z_n, r_n) = \begin{cases} 0 & (m = n) \\ 1 & (m = n) \end{cases},
\]

where \( m, n = 1, 2, 3 \) and \( (z_1, r_1), (z_2, r_2) \), and \( (z_3, r_3) \) are the coordinates of the vertices of the triangle.

Each triangular element is divided into four equal triangles by the lines connecting the midpoints of the sides. Thus the secondary triangular mesh is formed and all the vertices of this mesh correspond to the unknowns to be solved. The integrations of Eq. (2) are executed over the small areas defined by dotted lines as shown in Fig. 1. The paths go through the centroids of triangles and the midpoints of sides of the secondary triangular elements, forming dodecagons for the case they surround the primary vertices or octagons for the other cases. Substituting Eq. (3) into Eq. (2), we have linear equations which
relate the unknowns of $H_\lambda$ values for the logically near nine or nineteen verteces as

$$\sum_{j=1}^{9 \text{ or } 19} H_j(V_j + k^2 W_j) = 0, \quad (5)$$

where $V_j$ and $W_j$ are the functions of coordinates of triangular elements. If the relations are set up for all the verteces except those on the Dirichlet boundaries, we have homogeneous linear systems which have only the trivial solution unless the value of $k^2$ is one of the eigenvalues of the coefficient matrix. An assignment the constant value ($=1$) for one vertex and the replacement of the equation obtained with integrating around the vertex by the equation $H_n = 1$, lead the system to the inhomogeneous linear equations.

The equation replaced is used to determine iteratively the value of $k^2$ by the fact that the equation must be consistently satisfied by the solutions of linear systems.

The coefficient matrix of the systems of linear equations has the following form,

$$\begin{bmatrix}
A_{11} & A_{12} & A_{13} & A_{14} \\
A_{21} & A_{22} & A_{23} & A_{24} \\
A_{31} & A_{32} & A_{33} & A_{34} \\
A_{41} & A_{42} & A_{43} & A_{44} \\
A_{51} & A_{52} & A_{53} & A_{54} \\
\vdots & \vdots & \vdots & \vdots \\
A_{m-2,1} & A_{m-2,2} & \ldots & A_{m-2,m} \\
A_{m-1,1} & A_{m-1,2} & \ldots & A_{m-1,m} \\
\vdots & \vdots & \vdots & \vdots \\
A_{m,1} & A_{m,2} & \ldots & A_{m,m}
\end{bmatrix}$$

Here $m = 2L_{\text{max}} - 2$, where $L_{\text{max}}$ is the maximum $L$-value of the primary mesh. The $L$-value is the label variable of the mesh points together with the $K$-value on the logical triangular mesh. (See Ref. 1.) The values corresponding to the mesh points for $L=1$ are omitted from unknowns since they are assumed to be zero. The entries of unknown vector are $H_\lambda$ values at the secondary mesh points taking their order from low to high values for $K$ and $L$ as in the nested DO loops. The non-zero entries of submatrices $A_{ij}$'s have one or transposed one of the following forms,

Here every matrix is $(2K_{\text{max}} - 1) \times (2K_{\text{max}} - 1)$ matrix and $D$'s are the diagonal elements. The linear equations are solved by the block Gauss elimination method.

Coding of Program

The whole program consists of four programs which run sequentially. Their functions are the mesh generation, the calculation of line and surface interactions for every basis function, solving the system of linear equations and finding iteratively the resonant frequencies, and the calculation of secondary field parameters such as transit-time factors and rf wall losses. The program LATTICE in SUPERFISH was made a little modification and used for the mesh generation. Another program was developed to produce the input data for LATTICE with simple data. (The similar program has been developed and implemented in a recent LANL version of SUPERFISH) The program outputs the data which enable LATTICE to generate the meshes having various distributions of mesh density. All the programs were carefully coded to reduce running cpu time and main memory space. The integrations of Eq. (2) for the basis functions are carried out only once after the mesh is generated and the results are saved on secondary disk memories. The procedure which requires the most the main memory space is that for solving the system of linear equations. In the program six two-dimensional $(2K_{\text{max}} - 1) \times (2K_{\text{max}} - 1)$ arrays are used as buffers for this purpose. The method for iterative calculation of $k$ is based on the fact that the derivatives of the function $D(k^2)$ defined in Ref. 1 with respect to $k^2$ is -1 when $k^2$ is one of the exact eigenvalues. Any other root finding algorithms are not used since the method using the derivative of $D(k^2)$ is fast enough for the test runs.
Computational Results and Discussions

In order to investigate the accuracies attained by the programs, the fields in an empty pill-box cavity were evaluated by QLFISH and SUPERFISH and the results were compared with analytical solutions. Its dimensions are 100 cm in diameter and 20 cm in length. The results for the TM20 mode are shown in Table I for various numbers of triangular elements. Although the accuracies of the two programs for the frequencies are almost the same, the fields obtained by QLFISH have smaller mean absolute errors than those by SUPERFISH. The mean field errors become smaller for both the cases roughly proportionally to the mesh size in the radial direction. This probably happens as a special case for the pill-box cavities.

Table II shows the frequencies and the mean field errors for the lowest 10 TM modes, taking the same number of calculating points for the two programs. The field errors of QLFISH are smaller than those of SUPERFISH for all the cases, although the accuracies of the frequencies are almost the same again. It is quite interesting that the frequencies obtained by the two programs deviate from the true values by nearly equal magnitudes but with the opposite sign. In this case we get much better frequency values by taking the averages of the pair of data. As the number of triangular elements is increased, the convergent series of frequencies happens to be in one of the two cases, one is increasing and the other is decreasing. If the frequency accuracies of the two programs have the similar dependences on the number of triangular elements and we know the method to choose the opposite tendencies of convergence, we have a faster convergent series of frequencies easily by taking the average between the two results. Further investigations must be done for this problem. The run for a unit-cell of proton linac were also executed. But the error evaluations are very difficult as we do not know the exact solutions.

The disadvantages of QLFISH is that since the number of triangular elements is taken smaller comparing with the case of SUPERFISH, the curved boundaries are apt to be geometrically approximated worse by the sides of triangles. This trouble may be relieved to some extent by increasing the mesh densities in the regions of curved boundaries, which can be easily realized by using the input data generation program mentioned above.

Acknowledgements

The author wishes to thank Kazuo Hatano and Yoshio Satou for their useful discussions in this work.

References


Table I  Comparisons between SUPERFISH and QLFISH for TM20 mode in a pill-box cavity

<table>
<thead>
<tr>
<th>Number of mesh points (Kmax x Lmax)</th>
<th>Number of triangular elements</th>
<th>Calculated k2 (x 10^-2)</th>
<th>Means of absolute errors for H (x 10^-3)</th>
<th>Elapsed cpu time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 x 19</td>
<td>432</td>
<td>3.0107</td>
<td>21.07</td>
<td>1.9</td>
</tr>
<tr>
<td>7 x 10</td>
<td>108</td>
<td>2.9795</td>
<td>4.381</td>
<td>3.0</td>
</tr>
<tr>
<td>19 x 39</td>
<td>2728</td>
<td>2.9993</td>
<td>5.159</td>
<td>6.0</td>
</tr>
<tr>
<td>10 x 20</td>
<td>684</td>
<td>2.9917</td>
<td>1.397</td>
<td>14.0</td>
</tr>
<tr>
<td>39 x 79</td>
<td>11856</td>
<td>2.99639</td>
<td>0.329</td>
<td>60</td>
</tr>
<tr>
<td>20 x 40</td>
<td>2964</td>
<td>2.99456</td>
<td>0.122</td>
<td>121</td>
</tr>
</tbody>
</table>

Upper--by SUPERFISH  Lower--by QLFISH
The exact value for k^2 = 2.99548 x 10^-2
The value of H at the wall is 1.
Cpu time has only meanings of relative importance since it depends on speed of computer.

Table II  Comparisons between SUPERFISH and QLFISH for the first 10 TM0x0 modes

<table>
<thead>
<tr>
<th>Order of mode</th>
<th>exact k^2</th>
<th>calculated k^2</th>
<th>means of absolute errors for H</th>
<th>calculated k^2</th>
<th>means of absolute errors for H</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.002313274</td>
<td>0.002313215</td>
<td>0.107E-3</td>
<td>0.002313193</td>
<td>0.335E-4</td>
</tr>
<tr>
<td>1</td>
<td>0.0121885</td>
<td>0.0121924</td>
<td>0.154E-2</td>
<td>0.01218348</td>
<td>0.337E-3</td>
</tr>
<tr>
<td>2</td>
<td>0.0299948</td>
<td>0.0299933</td>
<td>0.516E-2</td>
<td>0.0299165</td>
<td>0.122E-2</td>
</tr>
<tr>
<td>3</td>
<td>0.055616</td>
<td>0.055765</td>
<td>0.837E-2</td>
<td>0.055472</td>
<td>0.175E-2</td>
</tr>
<tr>
<td>4</td>
<td>0.089173</td>
<td>0.086921</td>
<td>0.192E-1</td>
<td>0.088789</td>
<td>0.547E-2</td>
</tr>
<tr>
<td>5</td>
<td>0.130625</td>
<td>0.131652</td>
<td>0.278E-1</td>
<td>0.129797</td>
<td>0.753E-3</td>
</tr>
<tr>
<td>6</td>
<td>0.179973</td>
<td>0.181997</td>
<td>0.386E-1</td>
<td>0.178422</td>
<td>0.130E-1</td>
</tr>
<tr>
<td>7</td>
<td>0.237217</td>
<td>0.24082</td>
<td>0.528E-1</td>
<td>0.23459</td>
<td>0.146E-1</td>
</tr>
<tr>
<td>8</td>
<td>0.302357</td>
<td>0.30834</td>
<td>0.661E-1</td>
<td>0.298626</td>
<td>0.244E-1</td>
</tr>
<tr>
<td>9</td>
<td>0.375392</td>
<td>0.38462</td>
<td>0.743E-1</td>
<td>0.36936</td>
<td>0.269E-1</td>
</tr>
</tbody>
</table>

The value of H at the cylindrical wall is 1.
The numbers of mesh points are 19 x 39 for SUPERFISH and 10 x 20 for QLFISH.
Review of Induction Linacs
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Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Summary

There has been a recent upsurge of activity in the field of induction linacs, with several new machines becoming operational and others in the design stages. The performance levels of electron machines have reached 10's of kiloamps of current and will soon reach 10's of MeV's of energy. Acceleration of several kiloamps of ion current has been demonstrated, and the study of a 10 GeV heavy ion induction linac for ICF continues. The operating principles of induction linacs are reviewed with the emphasis on design choices which are important for increasing the maximum beam currents.

Introduction

The previous review of induction linacs by J. Leiss at the 1979 Particle Accelerator Conference occurred at a time when several new machines had been proposed or were in the early stages of construction. By now the ETA, Radlac, and FXR machines have been completed and are in various stages of becoming operational, and the ATA machine is midway in construction with operation scheduled a year from now. These machines have increased the operational experience level from the 1kA level of the first generation of induction electron linacs built a decade ago, to the 10kA or higher level, and will soon extend the particle energies from a few MeV to a few tens of MeV. In addition to the progress made with the electron machines, protons and light ions have been accelerated with induction machines and steady progress has been made in the conceptual design of a heavy ion induction linac inertial confinement fusion driver, for which the goal is acceleration of a kiloamp of current to energies near 10 GeV. The desired currents of the relativistic electron accelerators and the nonrelativistic ion accelerators have now reached the levels where further progress will depend in large part on the understanding and control of the transverse and longitudinal collective instabilities.

Undoubtedly the principle of induction acceleration was evident decades ago, because an induction linac is just a straightened out or linear betatron, but the first large device embodying most of the features of the present machines was the Astron injector built by N.C. Christofilos. The radial line version of the induction linac was considered for electric acceleration of electron rings at LBL and for production of high power electron beams for radiography in the U.S. and the U.S.S.R. independently in the 1960's. In the U.S. there was a hiatus of nearly a decade in new developments during which the two biggest machines at LBL and LLNL were scrapped, leaving the NBS long pulse prototype as the lone survivor. The developments in the USSR appear to have continued during this time, with the MEP 30 and LIU 1011 machines being particularly impressive. Table 1, which is an updated version of Table III of reference 1, lists some of the parameters of the present generation of machines. In addition to the efforts aimed at obtaining higher currents, there is a possibility to attain higher voltages by recirculating a beam through an induction module, similar to but with more energy gain per turn than a betatron.

Principles, Problems, and Limits of Induction Acceleration

Induction acceleration is a process of acceleration by nonresonant acceleration modules and pulsed or modulator type of power sources, rather than by the, until now, more common resonant cavity and rf source combination, in a configuration which may be iterated to high energies, even though both types of acceleration work by induction. In the ensuing discussion, emphasis is placed on acceleration instead of on source or transport problems. An induction module of the type under consideration is shown in Fig. 1. It consists of some metallic conductors which define the electric field in the accelerating gap region, a vacuum insulator separating the gap from the region marked "core," and the modulator or pulsed power source. The quotation marks around core are used because in some applications the core is a magnetic material toroid while in others it may be vacuum or a dielectric. Unlike the drive to an rf cavity which is lightly enough coupled to allow the cavity to resonate near its unloaded frequency, the drive connection to the induction module gap is very tight—directly across the gap—and therefore it has a dominant influence on the module.

Because the "core" occupies a major portion of an induction module and accounts for much of its cost, one is tempted to think that it is the seat of some very important physical processes. This misleading view is encouraged by oft-heard statements such as "the accelerating field is caused by the changing magnetic field in the core." It is more illuminating, however, to think of the core as an ac open circuit, with nothing occurring within it; core size is large simply because the available materials are far
<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Design</th>
<th>ETA/ATA</th>
<th>FRX</th>
<th>LIU 10</th>
<th>RADLAC</th>
<th>HIF Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEP 2 Injector</td>
<td>NBS</td>
<td>LLNL</td>
<td>LLNL</td>
<td>USSR</td>
<td>Sandia</td>
<td>LBL</td>
</tr>
<tr>
<td>Year Built, Proposed, or Published</td>
<td>1971</td>
<td>Eta schd. 82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Particle | 30MeV | 100MeV | 5/50MeV | 20MeV | 13.5MeV | 9MeV | 10GeV |
| Kinetic Energy | 15kA total on target, 1kA max per beam |
| Beam Current 250A | 2kA | 10kA | 4kA | 50kA | 25kA |
| Pulse Duration | 500ns | 2µs | 30ns/50ns | 60ns | 20-40ns | 15ns |
| Rep Rate (PPS) | 50 | 1 | 1000 Burst | 1 |
| Number of Switch Modules | 1500 | 250 | 10/200 | 54 | 24 | 4 | 10^4 |
| Core Type | Ni-Fe Tape | Fe Tape | Ferrite | Ferrite | Water Oil | Tape Ferrite |
| Switch | Thyratron Spark Gap | Spark Gap | Spark Gap | Spark Gap | Spark Gap | Ignitron and Spark Gap |
| Module Volt | 250kV | 400kV | 250kV | 400kV | 500kV | 1.75kV | 20-500kV |
| Core Volt | 22kV | 40kV | 250kV |
| Accel Length | 210m | 250m | 10/53m | 40m | 3m | 5km |

from ideal and a large volume is needed to create a high impedance approximation of an open circuit. In the limit of an open-circuit core it is immediately apparent that the voltage appearing across the accelerating gap is simply whatever voltage is applied at the drive terminals. By Faraday's Law of Induction, the applied voltage causes a flux change somewhere within the volume marked "core", the details of which are usually of little interest. What is significant is the total drive current going into the "core" region, because it is a measure of the difficulty of establishing the accelerating field. It is also noteworthy that the voltage across the gap can be constant in time and in space, therefore being indistinguishable in that region from a static voltage distribution, with the very important difference that this voltage may be added up along the beam direction without requiring large voltages at any one location. Conceptually, an induction linac is equivalent to a dc accelerating column. The energy associated with a magnetic field in a core is inversely proportional to the magnetic permeability - opposite to the behavior of...
the beam; the energy that does go into the "core" is usually lost. The energy supplied to the beam never passes through a state where it is all magnetic energy, as in the oscillating fields of an rf cavity, and most of the energy bypasses the core on its way to the beam.

A substantial part of the design of an induction module is addressed to making the core behave more nearly as an open circuit, or require less excitation current. Figure 2 shows examples of core currents for approximately constant voltages. The core current is rarely like that which would flow into a linear inductor because of eddy currents, magnetic viscosity, and saturation in magnetic cores, and transmission line effects in dielectric cores. A compensation circuit is often used to match the accelerating

dielectrics for which the field energy increases with the dielectric constant—and for a high current accelerator is much less than goes into the beam; the energy that does go into the "core" is usually lost. The energy supplied to the beam never passes through a state where it is all magnetic energy, as in the oscillating fields of an rf cavity, and most of the energy bypasses the core on its way to the beam.

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Table 2
Effects of various core materials on the pulse duration and core current in the module of Fig. 3 at an acceleration rate of 1 MV/m for a module 1 meter long.

<table>
<thead>
<tr>
<th>Magnetic Core</th>
<th>Nonmagnetic &quot;Core&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>$10^3$-$10^5$</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>1</td>
</tr>
<tr>
<td>$Z_0, \Omega$</td>
<td>NA</td>
</tr>
<tr>
<td>T pulse travel</td>
<td>NA</td>
</tr>
<tr>
<td>T pulse saturation</td>
<td>3µs</td>
</tr>
<tr>
<td>I core</td>
<td>2kA</td>
</tr>
</tbody>
</table>

module to its power source, which is usually a pulse forming line or network of either constant or tapered impedance. An important point to note is that the energy and current going into a core must be judged in relation to the beam current being accelerated and the value of that beam current to the user. Not every application requires an efficient accelerator. The core current in an induction linac with a magnetic core and an average acceleration rate of 1MV/meter is of the order of 1kA, therefore acceleration would be inefficient for currents of amperes and efficient for kiloamperes. Depending on the intended application and the required current levels a choice may be made as to the geometry and filling material of the region marked "core." The circuit in Fig. 3 is helpful in clarifying the operation of an induction module and the choice of the core.

The transmission line in Fig. 3 either transit-time isolates the short circuit from the gap region or provides, for a time, a high impedance to the drive line. Although several geometrical variations and embellishments are possible, especially in combining the pulse forming line and the required acceleration geometry, such as shown in Fig. 4, the basic choices may be summarized in Table 2 by considering the bent transmission line model of Fig. 3, with various core materials.

It is obvious that the efficiency increases as the beam current increases. For acceleration of very high currents the geometries of the type shown in Fig. 4, become preferable in that the power going into the core is not wasted. Additional transmission line geometries are discussed by Eccleshall and Hollandsworth in Ref. 13. The usual currents which are accelerated are more modest than those required for a good match to the dielectric core geometries because of either the output current requirements or the limits due to the beam transport system.

The reduction of the core current is a desirable goal in the majority of applications. The magnetic materials which make such reductions possible are ferrite and ferromagnetic alloys. Insofar as the magnetic properties of ferrite are well understood, the prospects of further improvements are based more on the possibility of manufacturing larger toroids than on fundamental materials improvements, even though some properties such as permeability keep improving. There is one fairly recent development in ferromagnetic materials which is extremely interesting: the amorphous glassy metals. These glasses are typically composed of 80% magnetic metal such as iron and 20% insulator such as boron. Because of the large fraction of insulator and the amorphous structure, their resistance is approximately 150µΩ·cm or about three times greater than that of transformer silicon steel. A hysteresis curve for one of the metallic glasses is shown in Fig. 5. These materials are particularly well suited for induction linac uses because the present manufacturing technique requires the material to be rapidly cooled from a melt before recrystallization can take place.
and this is possible only with material thicknesses of about 1 mil; eddy current losses, which are proportional to the thickness squared divided by the resistivity, are therefore reduced. Tests on small samples at LLNL, LBL, and elsewhere have shown that these materials are competitive with the best previously available materials such as 50% Ni 50% Fe-1 mil tape, with the promise of becoming better technically and considerably less expensive.

Collective Effects

The preceding discussion has been devoted to the "core" part of the induction module. Now, let us assume that the core is an ideal open circuit or that its impedance is folded in with the generator impedance, and consider the circuit formed by the gap electrodes and the power input line. This circuit is essentially an open-circuit transmission line with the open circuit at the gap. Looking from the gap towards the generator, there are several possibilities regarding the impedance presented to the beam: if the voltage source or generator is very stiff, it acts as a short circuit across the transmission line and the impedance has the familiar behavior of resonances when the line length is an odd number of quarter wavelengths long; if the generator impedance matches the line, then for all frequencies the beam sees a constant impedance; and if the generator impedance is higher than the line impedance, the line tends toward an open-circuited transmission line behavior, with impedance peaks when the line length is an even number of quarter wavelengths.

Usually the generator source impedance is chosen because of other considerations, with little regard of the module geometry. Unless very high currents are to be accelerated the situation may be completely acceptable. At high currents however, that is, currents near the maximum possible in the structure, the details of the gap geometry, the connections to the generator, and the stiffness of the generator become paramount.

Because almost all of the induction linacs built thus far have been for the acceleration of electrons, which are rather easily deflected by magnetic fields, the module conductor geometry consisting of a single strap threading the core is unsatisfactory because of the large transverse magnetic fields caused by currents in the strap. Instead, three or more symmetrical straps or a continuous metal conductor have been used in the gap region to minimize the steering effects from the core excitation current and the beam image current. In the limit of a continuous conductor in the gap region, the core current flows on the core side of the conductor and is well shielded from the beam, and the image current flows on the opposite side, reasonably symmetrically near the gap. Both currents combine near the drive terminals, and effectively function as sources of higher multipole fields from there, depending on the number of drive points. While alleviating the low frequency deflection and beam sweeping problem, the additional conductors introduce the possibility of harmful high frequency resonances of a new type.

The simplest equivalent circuit for the high frequency behavior of the accelerating module is a transmission line as shown in Fig. 6, where $Z_g$ includes the core, compensation, and generator impedances and $Z_0$ is the impedance of the short length of line from the gap to the drive terminals. For $Z_g < Z_0$, this line has resonances when its length equals an integral number, $n$, of half-wavelengths, similar to the resonances of a line short-circuited at both ends but with lower $Q$. The odd-$n$ modes result in a high longitudinal impedance and are the same as for the single strap example. The even modes are new, and yield a high transverse impedance. The characteristic length, $l$, is of the order of the module diameter-about 1 meter—therefore the lowest longitudinal and transverse resonances could occur near 150 MHz and 300 MHz respectively. If $Z_g > Z_0$, the resonances occur at similar frequencies except that the even-$n$ modes have high longitudinal and the odd-$n$ modes have high transverse impedances, similar to the behavior of an open-circuited line. It is unfortunate that because the induction modules resemble resonant cavities from the outside, they have been called cavities, and that the internal conductor resonances, which are due to avoidable mismatches, are confused with the resonances in empty circular cylinders whose resonant frequencies happen to fall in the same vicinity because of similar dimensions. The usual mathematical description of the interior fields in terms of normal modes appears particularly difficult to
apply to the induction modules because of the point-like drive connections and because the boundary of a magnetic core such as ferrite saturates and recedes during the pulse. Fortunately, a small amount of ferrite inserted discontinuously—so as not to be saturated by the beam current or present a high inductance to it—is almost the perfect rf absorber for high frequencies, and can be used to damp the resonances caused by geometrical and material mismatches in all of the different cavity types, thereby allowing the coupling impedance to the beam to be determined by the generator impedance at low frequencies and the gap geometry at high frequencies.

Neglecting the self-field effects, which are negligible for relativistic electrons but important for nonrelativistic ions, the stability of the beams or, more importantly, the growth rates of instabilities depend on the impedances seen by the beam at the accelerating gaps. Beam stability is the subject of the paper by Lloyd Smith in these proceedings. The problems are very similar to those facing circular machine designers about a decade ago, when they started to realize that their instabilities were dominated by the various boxes and similar objects placed in the beam line and resonating or reacting on the beam at frequencies much higher than the revolution or rf frequencies. In the induction linacs, the real or resistive part of the longitudinal impedance should be kept small for acceleration of ions whereas the transverse impedance should be minimized for acceleration of electrons. For both types of modes the generator small-signal impedance can be kept small at low frequencies by regulating the output voltage; at high frequencies, the transmission line from the acceleration gap to the drive terminal can be made lossy, thereby approximating a matched line. The best one could hope for the longitudinal impedance is a smooth increase from essentially zero at low frequencies to the characteristic impedance of the gap, \( Z_{11} = 60 \frac{g}{a} \) \( Z \) per module at high frequencies, where \( g \) is the gap length and \( a \) is the gap radius. The longitudinal impedance,

\[
Z_{11} = \frac{\int \varepsilon \, dz}{I}
\]

is the usual electrical impedance which could be measured across the accelerating gap, including, most importantly, the drive circuitry. The transverse impedance, for which several alternate definitions are possible, in most common usage is

\[
Z_1 = \frac{\int (\varepsilon + v \times B)_{\text{perp}} \, dz}{\beta I \Delta}
\]

which is a measure of transverse impulse per unit of beam displacement, \( \Delta \). At low frequencies, \( Z_1 = 60 \frac{g}{a} \) \( Z \) per module, at high frequencies in a geometry which supports a TM-like mode of oscillation, \( Z_1 = 377 \frac{g}{b^2} \) \( Z \) per module; where \( b \) is of the order of the module radius.

For all of the geometries discussed thus far, which are similar to the geometry of Fig. 1 and apply to most of the induction linacs built or contemplated, it is clear from the preceding that one would like a short accelerating gap \( g \) and a large vacuum chamber radius \( a \). Insofar as the peak electric field across a gap is usually a decreasing function of the gap distance, the accelerators for maximum current should be constructed of a large number of high-field short gaps rather than a few high-voltage long gaps, for example, 200 kV gaps of 1 cm spacing, and the impedance of the gap region smoothly transformed to the drive terminals or other high frequency absorbing material. Theoretical work is in progress now to look at the transverse instability in electron machines in the limit where a single resonant mode description is not a good model for the cavity interaction; similarly, work is in progress at analyzing the longitudinal instability of a single bunch of heavy ions. The parameters shown in Table I for ATA and HIF are near the maximum which may be obtained from machines of the "standard" type, and further progress will depend in part on the ability to understand and lower the coupling impedances.

Applications of Induction Linacs to Heavier Particles:

Insofar as particle beams have been mentioned earlier we have been mainly referring to high-current relativistic electron beams. From the description of the technology, however, it
is clear that an induction module can be used to accelerate charged particles other than electrons—for example, protons, heavy ions, or charged macroparticles, if need be. For much of an accelerator system such beam particles, are non-relativistic and the beam current that can be handled is limited by the capabilities of the beam focussing system and typically will be much smaller than the values quoted earlier for electrons. For transport of a beam in vacuum by means of magnetic quadrupole lenses the maximum current is given by Maschke's formula

\[ I_M < \frac{k}{Z} \left( \frac{e_N}{B} \right)^{2/3} \left( \frac{e_N}{B} \right)^{5/3} \tag{2} \]

where \( e_N \) is the normalized emittance and \( B \) is the maximum "pole-tip" field. In the early stages of an ion induction linac this condition—which corresponds to the near-cancellation of the magnetic restoring force by the electrostatic defocussing space-charge force—will limit the ion-beam current to the range 1-10 amps.

If one wishes, one may choose to increase the beam-current as the kinetic energy \((qV)\) is increased and still satisfy Equation 2. (Note that, non-relativistically, \( I_M \propto V^{5/6} \)). This can be accomplished by arranging for an effective ramp on the accelerating voltage profiles so that at any point in the accelerator the rear particles in the bunch will have received somewhat more energy than the particles near the front. This strategy of current amplification is possible because the ions remain nonrelativistic for a long way down the accelerator; it is not an option for electrons since they usually emerge from the gun with relativistic speeds. An effective ramp can be arranged to maintain the physical length of the bunch to be constant, in which case \( I \propto V \); alternatively the current can be increased as \( V^{5/6} \) by arranging for the physical length to decrease appropriately during acceleration.

Since Equation 2 applies to a single beam (in vacuum), another way to achieve higher current is simply to accelerate several beams in parallel, each contained by its own separate transport system but all threading the individual induction cores. There are, of course, practical limitations to this approach since addition of more beams in parallel will increase the aperture of the induction module and hence its cost. Nonetheless, studies have shown that, by judicious choice of the transverse beam (or beamlet) size and the number of such beams, a cost-effective solution exists that can accelerate greater current than that permitted by Eq. 2.

A good example of an ion induction linac design in which maximum current—handling capacity is desired is that for a heavy-ion driver for inertial fusion. Here, the accelerator system must ultimately deliver some 15kA of heavy ions \((A = 200)\), with a stored energy in the ions of 3MJ, that can produce implosion of a deuterium-tritium-filled pellet and achieve useful gain. Apart from this physics requirement, the accelerator system is also required to operate with as much beam-loading as possible in order to achieve high electrical efficiency \((\sim 20\%)\); thus it is desirable to maximize the beam current at all points in the accelerator—within reasonable cost limits. A typical scenario for 10 GeV heavy ions \((\sim 50\text{ MeV}/\text{amu})\) utilizes both current amplification and independent transport of multiple beams. The degree of current amplification that can be obtained during acceleration is limited by the single-particle dynamics of this maneuver but by the independent condition that the longitudinally-defocussing forces at the front and rear of the bunch remain within tractable limits. Figure 7 shows results of an example calculation of the current amplification that could be attained in a reference driver design; in this case, four magnetically focussed beamlets were assumed to be accelerated and attention was paid to keeping the capital cost near a minimum. One can see that the beam-current can be increased from a few amperes from the source to a few kiloamperes at the end of acceleration and that a final more drastic beam compression section is needed to obtain the last factor of

![Fig. 7 Desirable current amplification of heavy ion pulse.](image-url)
five, or so, in current as demanded by the needs of the pellet physics.

A feature of induction linacs designed to meet the needs of inertial fusion is that the capital cost is, in lowest approximation, set by the number of megajoules of beam energy that is desired. Thus if one chooses to double the beam charge and halve the particle kinetic energy to achieve the same number of megajoules, the capital cost is not drastically altered. A different situation obtains, however, in the case of a proton induction linac that might be used for producing an intense pulsed spallation-neutron source. In this case, it was found that the accelerator had relatively lighter beam-loading and the cost was dominated more by the kinetic energy desired than by the number of joules delivered. An interesting feature of this possible application is that the final proton energy (500-1000 MeV) is in the relativistic region and significant current amplification can be achieved only in the earliest part of the accelerator.

Another way of obtaining high beam-current at low ion kinetic energy is to depart from conventional vacuum beam-transport systems (quadrupoles or solenoids) and to appeal to collective focussing methods in which the electrostatic space-charge forces are off-set by neutralizing the beam with electrons. In any such scheme, it is clear that the electrons should be prevented from experiencing the accelerating field for several reasons; otherwise, because of their much greater mobility, the electrons could provide a large current-drain on the drive generator and fluctuations in the electron-current could cause erratic accelerating fields; furthermore, large currents of electrons accelerated backwards in the accelerator could result in serious component damage.

One approach could be to use Gabor lenses between induction modules and arrange for the lenses to be electrically shielded from disturbance by the pulsed accelerating field. Humphries has proposed an ingenious alternative to the Gabor lens in the form of two coaxial cylinders with the space between them occupied by electrons. In this case the ion-beam must have an annular cross-section that fits in the space between the cylinders. At the ends of each pair of coaxial cylinders a radial magnetic field is provided by two circular coils, one on the inside tip of the inner cylinder and the other on the outside tip of the outer cylinder. An accelerating voltage can be supplied by an induction module across the gap between sequential cylinder pairs. The application of an axial accelerating electric field in the presence of the radial magnetic field gives rise to magnetic insulation by neutralizing the electrons from crossing the gap and, instead, forcing them to execute an \(E \times B\) drift azimuthally around the axis. In a five-gap system Humphries et al. have demonstrated that neutralization can be achieved by injection of electrons from a pulsed plasma sources, that magnetic insulation can be effective, and that some three kiloamperes of carbon ions can be accelerated to 600 keV.

It has yet to be shown what are the limitations of such a magnetic insulation scheme. The placement of cylinders and field coils internal to the hollow beam requires that conductors must intercept the beam; how much beam-interception they cause and the magnitude of the azimuthal emittance will limit the number of accelerating stages that can be allowed. The electrons must be supplied to each pair of cylinders independently and must be replenished every pulse; since the electron charge distributions at the cylinder tips contribute to the focussing it is crucial to understand how reproducible and time-independent their behavior can be, if serious degradation of the ion-beam emittance is to be avoided.

Finally, it should be noted that the first use of an induction module to accelerate protons has been reported recently by Ivers et al. They used a low-impedance electron-beam generator to pulse both an ion-diode - to supply the protons and a downstream induction acceleration gap. A few hundred amperes of proton current was obtained in the presence of a large reverse electron stream that provided neutralization; the drive current was so large that the drain on the generator was of no consequence. This device is being modified to produce a hollow ion beam that can employ magnetic insulation in the manner proposed by Humphries.

Acknowledgments

We would like to thank our colleagues in other laboratories, Dick Briggs, George Caporaso, Stan Humphries, Bernhard Kulke, Bruce Miller, John Nation, and Mark Wilson, for supplying data on their machines and advancing the state-of-the-art.

References

2. T. J. Fessenden et al., IEEE Trans. Nucl. Sci., NS-28, 3401 (1981), and
Discussion

The emittances we see now in ETA are 0.3 to 0.4-cm radians normalized; this is about as predicted, and may be a factor of 2 to 3 above what the cathode temperature would give. One has to be very careful about bringing the beam out of the magnetic field. There is an instability lurking in the background that could cost something in emittance, but on the other hand, improvements in the cavity geometry and increase in focusing strength might keep the emittance at that level.

In the early machines, the dc-to-beam power efficiency was not a primary concern; the ERA machine had 3/4 of the power sent into resistors to stabilize the voltage. The source impedances are low and you want to throw unneeded beam away before acceleration, so ~20% efficiency is typical. With energy recovery schemes, we might reach 80%.

We do see some transfers induced by feeding power into two sides of the cavities; they are within a factor of 2 of the predictions. However, there is an 800-MHz oscillation that doesn't belong and acts as a driving term until it is damped.

We have studied the exposure of multiple beams to each other, and think an offset of the beam of about 2 mm from the quadrupole center might occur. The problems are severe at the low-energy end, less as the beam becomes more relativistic.

Spark gap development is an ongoing effort—the lifetime at Livermore now is about 2 to 3-million pulses, with a goal of 10 million. Development of cheap, interchangeable electrodes is a key aspect.

The answer as to why the electrons are not more unstable from things like the diocotron instability isn't clear. Most magnetron theories are for much more unstable flow with scalloped orbits. Here we have ordered orbits with slipping—a mild level of instability very sensitive to the applied B field. So we have an unstable system but one that can be controlled quite well. We can get the electron losses down to just a few per cent of the ion flow even in the early stages. The electrons orbit many thousands of times per microsecond, so long-pulse operation should hold no surprises on this score.
Summary

Most Rare Earth Cobalt (REC) materials have linear behavior of $B_{ij}$ vs $H_{ij}$ with permeability about 1 over a wide range of $H_{ij}$. However some of the materials with high magnetization become non-linear in the 2nd quadrant of the B-H space, while others with lower magnetization depart from linearity in the 3rd quadrant. Since the normal quadrupole design will drive many segments into the second quadrant and some even into the 3rd quadrant, the non-linear behavior of $B_{ij}$ vs $H_{ij}$ can distort the quadrupole field usually desired. Calculations have been performed using the computer code PANDIRA to explore the magnitude of the distortion caused by these non-linearities. In this paper, the usual quadrupole design is modified to use segments of lower magnetization but greater linearity in those places where segments are driven magnetically into the 2nd and 3rd quadrants. Prescriptions are given for the opening wedge angle and easy axis orientation of each segment which lead to the vanishing of the unwanted multipole components. Clearly the resulting purity of the quadrupole field comes at the expense of achieving the greatest field strength. Similar geometrical modifications can be used for other multipole designs. These techniques apply directly to the dependence on azimuthal angle for both the 2-D and 3-D multipole designs. These principles have been applied to a specific design problem.

II. Basic Quadrupole Design

A. Continuous Easy Axis Rotation

The basic 2-D quadrupole is one which consists of a ring of REC material magnetized via a pattern where the easy axis orientation is at an angle $\theta$, where $r$, $\theta$ are the conventional 2-D polar coordinates. For the case where $\nu_{ij} = \mu_{\perp} = 1$, it is easy to show that the interior field is a pure quadrupole field, with maximum field at the bore given by

$$B_{max} = 2M(1 - \frac{a}{b})$$

where $a/b$ is the ratio of inner to outer radius of the ring, and $M$ is the magnitude of the magnetization.

B. Segmented Ring

Practical designs consist of $N$ arc or trapezoidal segments of identical shape magnetized in a pattern where the easy axis orientation for the $j$th segment is at an angle $\theta_j$, where $\theta_j$ is the central azimuthal angle of the $j$th segment. Such an arrangement for 8 touching segments is shown in Figure 1.

![Eight Segment REC Quadrupole Magnet Configuration](image)

In this case the maximum quadrupole field at the bore is reduced by the form factor

$$\frac{\sin \frac{3\pi}{8}}{\frac{3\pi}{8}} \approx 0.78$$

and selected higher multipoles (10, 18, 26, ...) are also present.

In order to understand the range of values to which $B$ and $H$ are extended in a typical design, it is simplest to examine the 2-D ring with $\nu_{ij} = \mu_{\perp} = 1$ applied to a specific design problem.

I. Introduction

Rare earth cobalt (REC) materials are being used to build high field permanent magnets for a variety of applications. Among these are the use of REC quadrupoles to focus particle beams, higher order multipoles to provide compensation for non-linearities, and an array of dipoles to generate synchrotron radiation in wigglers and undulators.

In some of the applications the primary goal is maximum field strength. In others it is maximum field purity (absence of undesired multipoles). On some occasions, both maximum field strength and purity are desired. Unfortunately, those materials which have the highest magnetization have B-H curves which are not linear over the full desired range and may even have values of $\nu_{ij}$ and $\mu_{\perp}$ which are significantly different from unity. As a result, the field may have large multipole impurities.

The purpose of this paper is to explore these impurities for two dimensional quadrupoles, and to devise design principles using two different materials which provide minimum impurities and maximum field gradient. These principles will then be applied to a specific design problem.


2. Computations supported by Los Alamos National Lab.
and continuous easy axis rotation. In this case one writes

\[ v \cdot \vec{B} = 0, \quad \vec{v} \times \vec{H} = 0, \quad \vec{H} = v \phi \]

(2.3)

\[ v^2 \phi = -v \cdot \vec{H} \]

For \( a < r < b \),

\[ M_r = M \cos 2\epsilon \quad \vec{v} \cdot \vec{M} = 3M \cos 2\epsilon \]

(2.4)

\[ M_0 = M \sin 2\epsilon \]

Satisfying the boundary conditions which make \( H \) continuous, one finds within the REC normal ring

\[ B_{11}/M = \cos^2 2\epsilon (2 - \frac{2r}{b}) + \sin^2 2\epsilon (\frac{2r}{b} - 1) \]

(2.5)

\[ H_{11}/M = \cos^2 2\epsilon (1 - \frac{2r}{b}) + \sin^2 2\epsilon (\frac{2r}{b} - 2) \]

For \( r = a, H_{11}/M \) extends from \( -2 + \frac{2a}{b} \) at \( \phi = \frac{\pi}{4} \) to \( 1 - \frac{2a}{b} \) at \( \phi = 0 \). For \( a < b \), this corresponds to a range of \( H_{11} \) from \(-2M\) to \(+M\), well beyond the limits of linearity for the maximum field materials, such as that shown in Figure 2.

![Diagram](image)

Fig. 2 B(H) Curves for Different REC Materials

### III. Factors Contributing to Multipole Impurities

#### A. Permeability Greater than Unity

Most REC materials have permeabilities in the range from 1.03 to 1.20. If the permeability is the same parallel to and perpendicular to the easy axis, the formulation in the preceding section is easily modified, and the magnetic field multipole strengths are each modified by a factor proportional to \( \mu - 1 \). No new multipoles are introduced in the case of the continuous easy axis rotation, and therefore the practical consequence is that the quadrupole strength is reduced by the factor

\[ \frac{2}{\mu + 1} = 1 - \frac{1}{\mu + 1} \]

(3.1)

for \( \mu \) close to 1. For the ring with eight segments, new multipoles with strengths proportional to \( (\mu - 1) \) are introduced for \( n = 6, 14, 22, \ldots \).

#### B. Permeability Greater than Unity Along Easy Axis

The analysis is considerably more complex if \( \mu_{11} \neq \mu_\perp \). If we set \( \mu_\perp = 1 \), and \( \mu_{11} = 1 + \delta \), where \( \delta \ll 1 \), we can write

\[ v \cdot \vec{H} = 0, \quad \vec{H} = v \phi \]

\[ \vec{B} = \vec{H} + \delta \vec{H}_{11} + \vec{H}_\perp, \quad v \cdot \vec{B} = 0 \]

\[ v^2 \phi = -v \cdot \vec{H} - \delta v \cdot \vec{H}_{11} \]

(3.2)

For small \( \delta \), we can solve this equation to first order in \( \delta \) by setting \( \vec{H}_{11} \) to be the solution obtained for the continuous ring for \( \mu = 1 \). (The segmented ring introduces additional complications which are not important in the present analysis.)

If we write

\[ |H_{11}| = \frac{\vec{H}_{11} \cdot \vec{B}}{g} = \cos 2\phi \vec{H}_r + \sin 2\phi \vec{H}_\phi \]

(3.3)

we can obtain the components of the \( H_{11} \) as

\[ (H_{11})_r = \cos 2\phi \vec{H}_r + \cos 2\phi \sin 2\phi \vec{H}_\phi \]

(3.4)

\[ (H_{11})_\theta = \cos 2\phi \sin 2\phi \vec{H}_r + \sin^2 2\phi \vec{H}_\phi \]

from which we obtain

\[ v \cdot \vec{H}_{11} = \frac{1}{r} \frac{\partial}{\partial \phi} \left[ \cos^2 2\phi \vec{H}_r + \cos 2\phi \sin 2\phi \vec{H}_\phi \right] \]

(3.5)

\[ + \frac{1}{r} \frac{\partial}{\partial \phi} \left[ \cos 2\phi \sin 2\phi \vec{H}_r + \sin^2 2\phi \vec{H}_\phi \right] \]

Analysis of the continuous ring for \( \mu = 1 \) leads to the unperturbed fields within the ring

\[ H_0 = v \phi_0, \quad \phi_0 = M \cos 2(\phi - \frac{r^2}{b}) \]

(3.6)

which eventually leads to

\[ v \cdot \vec{H}_{11} = -\frac{9}{4r} M \cos 2\phi + \frac{(21 - 3b)}{4r} M \cos 6\phi \]

(3.7)

If we now solve equation (3.2) by matching fields in the regions \( 0 \leq r \leq a, a \leq r \leq b, b \leq r \), we obtain a quadrupole field at the bore modified by the factor

\[ 1 - \frac{\delta}{2} \]

(3.8)

as well as a new multipole field \( (n=6) \) of strength

\[ B_6(a) = \delta M \left[ \frac{9}{10} - \frac{3a}{2b} + \frac{3a^5}{5b^5} \right] \]

(3.9)

For \( \frac{a}{b} = \frac{1}{3} \), this has the approximate value

\[ B_6(a) \approx -0.402 \delta M \]

(3.10)

It is clear from the form of the analysis, that in a ring with \( N \) segments, additional multipoles with strengths proportional to \( \delta \) will be introduced of order \( n = N - 2, 2N - 2, 3N - 2, \ldots \), as in

The effect of having both \( \mu_{11} \) and \( \mu_\perp \) different from one produces a result approximately equivalent to that described in Section IIIA supplemented by a correction proportional to \( \mu_{11} - \mu_\perp \), which is calculated in this section by setting \( \mu_{11} - \mu_\perp = \delta \).

In this case, for convenience we have set \( \mu_\perp = 1 \). \( \mu_{11} = 1 + \delta \).
the $\mu_{11} = \mu_{1} \neq 1$ case, and $n = 6, N = 6, 2N \neq 6$, ---, the first of which is specified in Equations (3.9) and (3.10). In addition, the terms proportional to $6$ in Equations (3.8), (3.9) and (3.10) will be modified further for a segmented ring.

IV. Compensated Ring

Let us consider a ring with eight touching segments made of two different materials, as shown in Figure 3.

![Fig. 3 Modified Eight Segment REC Quadrupole to Remove Sixth Harmonic Impurities](image)

We shall assume $\mu_{11} = \mu_{1} = 1$.

The general form for the multipole expansion of the scalar potential $\phi$ in the interior region is

$$\phi = \sum_{n=0}^{\infty} \sum_{j} a_{j} \sin^{n} \theta_{j} \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{dx dy}{(x+iy)^{n+1}}$$

(4.1)

where $\theta_{j}$ is the easy axis orientation of the $j$th segment centered at azimuth $\theta_{j}$, and where the integral is taken over the 2-D region of the $j$th segment.

In the example shown in Figure 3, we have taken $a_{0} = 0$, $a_{1} = \frac{3\pi}{4}$, $a_{2} = \frac{3\pi}{2}$, $a_{3} = \frac{9\pi}{4}$, etc. It is easy to show that the multipoles $n = 3, 4, 5, 7, 8, 9$ vanish by symmetry and that the $n = 6$ multipole is given by

$$\phi_{6} = \frac{4\pi}{7\pi a_{0}} \cos 6 \theta \left(1 - \frac{a_{5}}{b_{5}}\right) [M_{0} \sin 7\psi_{0} - M_{1} \sin 7\psi_{1}]$$

(4.2)

The multipole field strength at the bore is therefore

$$B_{6}(a) = \frac{24}{7\pi} \left(1 - \frac{a_{5}}{b_{5}}\right) [M_{0} \sin 7\psi_{0} - M_{1} \sin 7\psi_{1}]$$

(4.3)

Similarly, the desired quadrupole field strength is given by

$$B_{2}(a) = \frac{8}{3\pi} \left(1 - \frac{a_{5}}{b_{5}}\right) [M_{0} \sin 3\psi_{0} + M_{1} \sin 3\psi_{1}]$$

(4.4)

If we have a material which has a linear B-H curve with $\mu_{11} \neq \mu_{1}$, we can compensate for the sixth order multipole error by choosing $\psi_{0}$ and $\psi_{1}$ such that Equation (4.3) produces an equal and opposite $n = 6$ impurity.

If we wish to use different REC materials because of the need to guarantee linearity in the B-H curve into the 2nd and 3rd quadrants, we can similarly ensure the absence of the $n = 6$ harmonic by choosing

$$\frac{\sin \psi_{1}}{\sin \psi_{0}} = \frac{M_{0}}{M_{1}}$$

(4.5)

or

$$\tan \left[ \frac{7\pi}{2} (\psi_{0} - \psi_{1}) \right] = -\frac{M_{0}}{M_{1} + M_{0}} \tan \frac{7\pi}{8} - 0.414 \frac{M_{0} - M_{1}}{M_{0} + M_{1}}$$

(4.6)

As an example, if we take $M_{0} = 12.0$ Kgauss (Material = SmCo$_{5}$) and $M_{1} = 8.0$ Kgauss (Material = Sm$_{2}$(Co+TM)$_{17}$), we are led to

$$\psi_{0} = 23.18^\circ, \psi_{1} = 21.82^\circ$$

(4.7)

in order to provide elimination of the $n = 6$ multipole.

V. Computer Model Calculations

The program PANDIRA$^{2}$ permits us to calculate the multipole fields for "real" magnet materials in any 2-D geometrical configuration with an arbitrary function for $B_{11}(H_{11})$ but with $\mu_{11}$ equal to a constant. We have performed the test calculations shown in the table to illustrate the effects of permeabilities different from unity, non-linear $B_{11}(H_{11})$ materials, and a two material configuration using the design principles for a compensated ring developed in Section IV.

These calculations were for the geometry shown in Figure 4 which is a flux plot for Case A with the ratio $a/b = 1/3$. This is one octant of an eight piece segmented ring with the pieces having an arc shape on the inside and trapezoidal shape on the outside. The form factor for the nth field harmonic for this geometry, which is shown in Figure 5, is

$$\sin(n+1)\psi_{0} - \left( \frac{a}{b} \right)^{n-1} \sin(n\psi_{0}) = 0$$

(5.1)

For $b = 3a$ and $n = 2$, there is only a 1% error if we use

$$\sin(n+1)\psi_{0} - \left( \frac{a}{b} \right)^{n-1} \sin(n\psi_{0}) = 0$$

(5.2)

For $n = 6$, the second term in Equation (5.1) is completely negligible.

The table gives the results of the computations in terms of the strength of the fundamental quadrupole and the relative strengths of the multipoles $K$. Halbach, R. F. Holsinger, "PANDIRA. "A Computer Program for the solution of Anisotropic Field Problems by a Direct Method," to be published.
In cases A-8 through D-16, harmonic errors due to $\psi_{11}$ different than unity are investigated. In case B-8, the fact that essentially no $n = 6$ error is produced even with an unrealistically high value of $\psi_{11} = 2$ is surprising. The explanation is probably that the $n = 6$ term corresponds to Equation (3.9) which we expect is largely compensated by the $N - 2 = 6$ term which is present in an 8 section quadrupole. By contrast, in case D-16 the expected $n=6$ error is present for a realistic $\psi_{11}=1.1$. In this case there is no compensating contribution from the 16 segment configuration.

Cases E-8 through G-8 show the effectiveness of the compensated ring design. In case F-8 a large $n = 6$ error results from $M_0 \neq M_1$. It is essentially eliminated in Case G-8 by adjusting $\psi_0$ and $\psi_1$ as prescribed in equations (4.5).

Finally in cases H-8 through J-8 we have calculated the errors due to truly nonlinear $B_{11}(H_{11})$ functions. In case I-8, $B_{11}(H_{11})$ is assumed linear into the second quadrant of the $B_{11}(H_{11})$ curve until approximately $H_{11} = -9.5$ K-Oersted. The material in case J-8 becomes nonlinear sooner at approximately $H_{11} = -6.0$ K-Oersted. The results show a significant decrease in quadrupole strength in addition to large non-allowed harmonic errors. It should also be noted that the allowed harmonics $n = 10$ and $n = 18$ change significantly. This would certainly be a source of error if they had been compensated for in the original configuration.

VI. Application of the Compensated Ring Design

A particular example where the compensated ring design may be applied is for REC quadrupole designs being considered for the final focus region of the Stanford Linear Collider (SLC) project.\footnote{SLC Conceptual Design Report, SLAC-229, June 1980}

One of the configurations for the final focus interaction region in the SLC is the so-called micro-quadrupole solution. A design concept for these micro-quadrupoles is shown in Figure 6. The unique requirements for these REC quadrupoles are the extremely high gradients of the order of 150 Kgauss/cm and the corresponding very small apertures of the order of 1 mm. These gradients may be achieved in principle, of course, since when an REC quadrupole is scaled down, the field strengths are unchanged and the gradient therefore is increased by the scale factor.

For the micro-quadrupole design, the maximum possible quadrupole strength is required since the very small aperture will be a difficult practical problem and the higher the strength, the larger the allowed aperture for a specified gradient. Therefore the compensated ring design would be most appropriate. Since, because of the small size, the volume of the material will be insignificant in the total cost, one would choose a very small ratio of $a/b$, e.g. $a/b = 1/10$. From Section II above, this ratio will require $B_{11}(H_{11})$ well into the third quadrant, i.e., linear to approximately $1.8M$.

A reasonable choice for the materials for the micro-quadrupole design would be a very high $B_r$ material for the "$M_0$ pieces" and very linear material for the "$M_1$ pieces." If we choose $M_0 = 12$ Kgauss and $M_1 = 8$ Kgauss from commercially available materials, the micro-quadrupole design would have the following characteristics.

- Bore radius, $a = 1$ mm
- Outside radius, $b = 10$ mm
- Quadrupole field at $r = a$, $B_0 = 14.1$ Kg
- Quadrupole gradient, $B'_2 = 141$ Kg/cm
- Field allowed error, $B^{10}_{10}$ at $r = a$, $B^{10}_{2} = -22.6\%$
The very large value of this error field is not important from the micro-quadrupole application, since the beam size of a few microns is such a small fraction of the aperture.

VIII. Conclusion

We have shown that multipole impurities are introduced by REC materials with $\nu_{11} \neq \nu_4$. We have shown that these impurities can be eliminated by choosing $\psi_0$ and $\psi_1$ to be slightly different from $22.5^\circ$, and have confirmed this by the corresponding PANDIRA calculation.

We have also shown that multiple impurities are introduced by REC materials with non-linear B-H curves. These impurities can also be eliminated by choice of $\psi_0$ and $\psi_1$ appropriate to the $M_0$ and $M_1$ materials selected. This conclusion is confirmed by the corresponding PANDIRA calculation.

The techniques which have been outlined in this paper will also work for values of $N$ higher than 8. The analysis is more complex, and it becomes necessary to choose $\alpha_j \neq 3\beta_j$ for some of the segments, but the results are similar to those obtained for the quadrupole with eight segments.

Similar techniques can also be used for the design of multipole magnets other than quadrupole.
FREE-ELECTRON LASER RESULTS*

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Summary

The Los Alamos free-electron laser (FEL) amplifier experiment was designed to demonstrate high efficiency for transfer of energy from an electron beam to a light beam in the magnetic field of a tapered wiggler. Initial results indicate an energy transfer consistent with theory. Distinct groups of decelerated electrons as well as accelerated electrons are clearly present in the energy spectrum of electrons emerging from the wiggler when the laser light is present. The observed energy decrease for the electrons captured in the decelerating bucket is \( \sim 6\% \) and the average decrease of the entire energy distribution is \( \sim 2\% \) for the conditions of these initial measurements.

Introduction

Theoretical studies predict an order of magnitude improvement in the efficiency of a FEL when the magnetic field of the wiggler is tapered. With a proper taper of the period and strength of the wiggler field, the energy transferred from the electron beam to the laser radiation can be expected to increase from a few tenths of one per cent to more than a few per cent. According to this theory, at sufficiently high laser power (few gigawatts) potential wells are formed by the laser and wiggler fields that trap some of the electrons. These potential wells and the trapped electrons can be decelerated by properly tapering the wiggler field, resulting in \( \sim 10\% \) of the trapped electrons' energy being transferred to the laser radiation. The untrapped electrons do not participate significantly to the energy exchange, and their energy is only slightly perturbed. The average deceleration of the electrons is expected to be a few per cent.

A series of FEL experiments with tapered wigglers is planned at Los Alamos. The series includes amplifier and oscillator experiments, as well as recovery of a portion of the energy remaining in the electron beam after it has passed through the wiggler. A description of these experiments has been given earlier.²

FEL Amplifier Experiment

The first activity is an amplifier experiment. The purpose of this experiment is to demonstrate high efficiency for the energy transfer from an electron beam to laser radiation in a tapered wiggl. The experiment is designed to simulate the high-power conditions that will exist near saturation of the laser gain. Measurements will be made of the electron energy loss and the increase in laser-radiation intensity.

The essential components of the FEL amplifier, as shown schematically in Fig. 1, are an electron accelerator, a beam-transport system, a wiggler, a pulsed CO₂ laser, and diagnostics for both beams after they have traversed the wiggler. The layout of these components is shown in Fig. 2.

Accelerator

The accelerator was designed and built specifically for this experiment. It consists of an injector, a fundamental-frequency buncher, a single accelerating tank, and an rf system operating at a 1.3 GHz frequency and a 20 MW peak power. The injector provides an 80-keV electron pulse with a peak current of a few amperes and a duration of 3 ns (FWHM). After bunching in a single-cavity buncher, the electrons are accelerated to 20 MeV in a standing-wave, side-coupled accelerating structure. This structure consists of 24 side-coupling cells and 25 main cells, the first 4 of which form a tapered-B section with an initial \( B \) of 0.75. The linac operates in the stored-energy mode, with a gradient of \( \sim 8 \) MeV/m.

Beam Transport

To obtain collinearity of the electron and laser beams, it is necessary to provide a bend in the electron beam line. A doubly achromatic beam-transport system consisting of three dipole magnets is used to bend the electron beam by 60°. Focusing and steering is by a pair of quadrupole triplet magnets and steering coils located at appropriate positions along the beam line. A number of view screens and current transformers are also located at convenient positions along the beam line. A beam scraper is located in the middle of the second dipole magnet where the energy dispersion is the...
largest. This scraper is used to remove the low-energy tail of the electron energy spectrum and to reduce the energy spread of the transmitted electrons to ±0.5%.

Wiggler

The wiggler provides a spatially periodic magnetic field.* It is composed of 314 nearly identical SmCo₅ permanent magnets, each 0.5 cm by 0.5 cm in cross section and 3.5 cm long. The magnets are arranged to provide 40 periods of the magnetic field, including matching fields at each end. The matching fields are produced by a one-half period section that allows a smooth transition from zero to full magnetic field at the entrance and exit of the wiggler. The peak field at the center is 3 kG and the aperture for the electron and laser beams is almost 9 mm. The wavelength of the magnetic field is tapered by ~12% to maximize energy extraction from the electron beam. The wiggler is 1 m long and is equipped with magnetic-shields and trim coils to assure the proper electron trajectory within the wiggler. Removable fluorescent screens, viewed by vidicons, are provided at the entrance, center, and exit of the wiggler to assist in the alignment and superposition of the electron and laser beams.

Laser

The CO₂ laser for the amplifier experiment consists of a reinjection oscillator/preamplifier (developed at Los Alamos for the Antares laser fusion program) and a Lumonics Model 600 amplifier. It operates on a single mode (P₂₀), has a peak power of 1 GW with a pulse length variable from 1 to 10 ns. The laser beam is transported by copper mirrors and enters the vacuum beam line through a salt window. This beam is focusable in the wiggler to a spot size close to the diffraction limit.

Diagnostics

The planned diagnostics include an electron spectrometer to measure the energy spectrum of the electrons leaving the wiggler and an optical detection scheme to measure the amplification of the laser beam. The electron spectrometer consists of a dipole magnet that bends the electron beam by 90°, a fluorescent screen and a vidicon imaging system. With this system, the electron-energy spectra taken with and without the laser signal can be compared for various initial electron energies. These data provide the details of the energy gained or lost by the electrons.

*We are indebted to Klaus Halback for his continued technical guidance in wiggler design.
The optical detection system to be used to measure amplification of the CO₂ beam is presently being developed.

Predictions

The operating conditions for the first measurements are listed in Table I. Under conditions for optimum energy extraction, ~40% of the electrons are expected to be trapped in the potential well and to be decelerated by ~7%. These lower energy electrons are expected to form a distinct peak. The rest of the electrons, which are only slightly perturbed, are expected to remain in a peak near the incident energy.

Table I

EXPERIMENTAL PARAMETERS

<table>
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<tr>
<th>Accelerator</th>
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<tr>
<td>Electron energy</td>
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<tr>
<td>Peak current</td>
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<td>Electron beam diameter</td>
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<tr>
<td>Pulse duration</td>
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<tr>
<td>Pulse energy</td>
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<tr>
<td>Focus diameter</td>
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<table>
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</thead>
<tbody>
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<td>Length</td>
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<tr>
<td>Taper (wavelength)</td>
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<tr>
<td>Wavelength</td>
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<tr>
<td>Cycles</td>
<td>40</td>
</tr>
<tr>
<td>Aperture</td>
<td>8.8 mm</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.3 T (max)</td>
</tr>
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</table>

Results

A typical electron spectrum is shown in Fig. 3. The spectrum displays the double-peaked electron-energy distribution characteristic of tapered wigglers. The high-energy peak near the original energy contains those electrons not trapped in the pondermotive potential, whereas the low-energy peak contains those electrons trapped in the pondermotive potential and decelerated with the taper in the wiggler field. For the conditions of this experiment, the trapped electrons represented ~30% of the total and were decelerated ~6%. The total extraction (corresponding to the average deceleration of the electrons) was ~2% of the initial electron energy. This is about an order of magnitude larger than was obtained in previous experiments using uniform (untapered) wigglers.

As shown in Fig. 4, the average energy extracted from the electron beam depends on the initial energy of the electrons. Maximum extraction occurs when the electrons enter at the resonant energy, corresponding to the velocity of the potential energy wells at the wiggler entrance. In fact, by injecting the electrons at too low an energy, they may be accelerated instead of decelerated, corresponding to laser absorption instead of gain.

Although the results reported here must be regarded as preliminary, they are in good qualitative and satisfactory quantitative agreement with the theoretical predictions of tapered wigglers; they demonstrate an order-of-magnitude improvement over the performance of conventional, untapered wigglers.

References


Discussion

These preliminary data indicate the main peak may have also moved down a little, rather than showing that the un-captured electrons are actually accelerated. We emphasize that these are very early results that do indicate that deceleration of a substantial group of electrons has occurred to about the right degree. Alignment and the beam being in the center of the wiggler are very crucial to the operation of the device.

In the next phase of testing, we will also use optical measurements; for example, cross-polarization techniques will be used on the laser beam itself, and a hot CO₂ cell will be used to differentially absorb the laser beam. We have not measured the micropulse current, but infer from the macropulse and the assumption that the micropulse width is 30 ps (measured on other accelerators) that the current is ~10 A.

We haven't used optical measurements yet, so we have not observed spontaneous emission or used it to tune the beam. The tapered wiggler gives a tuning advantage because it isn't necessary to have the electron beam energy exactly right—interactions occur over a wide band. We can adjust and measure the energy rather well, however.

After the optical measurements on the amplifier experiment, we will extend the system to an oscillator with a 100-μs pulse.
1. Introduction

Conventional particle accelerators make use of externally produced electric and magnetic fields to accelerate particles and to focus or contain them. Such conventional accelerators have been developed in many different configurations for many different applications ranging from high-energy physics (HEP) at particle energies of hundreds of GeV to industrial applications at a few hundred keV. There are many thousands of particle accelerators now being operated for these applications. The design and construction of particle accelerators has reached a very advanced state in the last few decades and there is considerable understanding of the performance limitations of these devices. There are now a number of serious, well thought-out proposals to design and build conventional accelerators of very high energy for applications in HEP and of very high intensity for application to controlled-fusion work and many other areas.

In comparison, the field of collective accelerators is small, with approximately a dozen small groups actively working in the United States and a roughly equal number in all other countries. Collective accelerators are by no means as far along in design as conventional accelerators, but appear to hold out great promise for improved performance.

Collective accelerators make use of the electric and magnetic fields of more-or-less purposeful assemblies of charged particles in the region of the accelerated particles, for acceleration, for focusing, or for both. That is, there are additional charges and currents in this region and in general \( v \times B \) and \( \nabla \times B \) are different from zero. In principle, very large accelerating and focusing fields are possible and the fundamental goal of collective accelerators is to make use of these large fields to build high-performance accelerators very economically.

The earliest proposals to utilize collective fields to accelerate particles were those of Harvie (1951), and Raudorf (1951) and Alfvén and Wernholm (1952). Little attention was paid to these suggestions and collective acceleration was reborn with the 1956 papers of Veksler, Budker, and Fainberg. Veksler proposed that the coherent field of an assembly of charges such as electrons can interact with a smaller number of ions so that the ions are accelerated to the same speed as the electrons. Budker proposed to set up an electron beam circulating in an external magnetic field and use the space-charge field of the electron beam to bend and focus a beam of ions circulating inside the electron beam. Fainberg proposed to use an electron beam in a waveguide to modify the dielectric properties of the guide in order that a slow wave could be set up to accelerate and focus ions. None of these concepts has survived unchanged to the present, as we shall see below. But they have all played a seminal role in stimulating work by others.

An equally great stimulation for collective acceleration has been the development of the technology of the intense relativistic electron beam (IREB). Graybill and Uglum discovered that when an IREB is injected into a neutral gas, some ions are produced and accelerated to energies greater than the injected IREB energy. A great deal of work has been done since then to develop methods of controlling this acceleration.

The state of work in the United States on collective acceleration and the state of its support led to the convening by the United States Department of Energy of a study group in the fall of 1981. The review given here grew out of the work of that study group.

For the purpose of this review, we divide collective accelerators into five general classes as follows:

1. Space-charge accelerators
2. Wave accelerators
3. Electron ring accelerators
4. Inverse-drag accelerators
5. Collective-focusing accelerators

In the following sections, we discuss these different accelerator concepts, the work in progress on them, and their applications. Finally, we outline the conclusions of the study.

2. Space-Charge Accelerators

This concept is an outgrowth of the work of Graybill and Uglum. The IREB creates a moving potential well that pulls the ions along. We can understand this potential well by considering the propagation of a relativistic electron beam intense enough for self-fields to have major effects. The electrons in the beam are moving a uniform speed \( v = c \), with \( \gamma = \frac{1}{\sqrt{1 - \beta^2}} \). The beam radius is \( a \) and the total current is \( I \). Then the self electric field is radial and the self magnetic field is azimuthal. From Gauss' law,

\[
E_r = \frac{2I}{\beta \alpha a} \cdot \frac{r}{a}, \quad r \leq a
\]

and from \( B_\theta = \beta E_r \),
This acceleration concept was discovered experimentally in 1968 by Graybill and Uglum and has developed extensively at many laboratories. A potential well that can reach a depth of more than 1 MV can be formed and ions can be attracted and accelerated. Proton energies of several times the electron beam energy have been observed. The ions can be created "naturally" by collisions of the electron beam with background gas, as in the Graybill and Uglum work; or ions can be introduced artificially, as a gas by a puff valve, or by collisions of the electron beam with an insulator anode, as in the Luce diode, or by a laser-produced plasma, as in the University or Maryland work.

The ions partially neutralize the virtual cathode and bring the limiting current $I_l$ up to the beam current. Then propagation takes place and the virtual cathode can move downstream of the anode, carrying ions with it and further accelerating them. In experiments with Luce diodes, 45-MeV protons have been observed. Multi-stage Luce diode systems have been proposed by Adamski.

It is of great interest in space-charge accelerators to control this motion of the potential well down the accelerator and several methods of doing this are under study. There are at least four devices in which a potential well is propagated at a programmed and increasing velocity by means of externally controlled elements.

In the Ionization Front Accelerator (IFA) of Olson, in one operating regime, the electron beam is injected into a tube containing a low-pressure working gas, which has been chosen to be cesium vapor. The pressure is low enough that for the duration of the beam pulse, there is not enough ionization to allow the beam current to become less than the limiting current and so to propagate quickly. Arranged along the side of the tube is a series of light pipes through which carefully timed pulses of laser light can enter to ionize the cesium. Enough ions are produced upstream of the virtual cathode at the head of the beam to neutralize the beam space charge in that region and reduce the potential to zero. Downstream of the beam head, there is little beam present and the potential is also essentially zero there. Thus the potential well in the beam head provides an accelerating bucket that has a sharp gradient at the upstream side. By gradually advancing the region of ion creation by successive laser light pulses, the well can be guided forward at a predetermined rate to accelerate ions. Scaling studies indicate that, for example, protons of GeV energies could be produced in a compact IFA.

A slow-wave structure to control the motion of the potential well is being studied at the University of Maryland. This structure is initially charged to a high potential by the electron beam (or externally) and discharged to ground when the potential well arrives. The discharge pulse and thus the potential well travel with a velocity that is determined by the pitch angle of the slow-wave structure.

Fisher proposes to inject ions from a pulsed wall plasma to speed up the virtual cathode in a time-programmed manner. With the present equipment, he has achieved 10-MeV protons and feels it can be extended to 100 MeV.

$$\Phi = \frac{I}{\beta_0} \left(1 + 2 \ln \frac{b}{a}\right)$$

Equation (4) apparently gives results within 25 to 30% of observation.

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$$B_0 = \frac{2I}{\rho_0} \cdot \frac{r}{a}, \quad r \leq a$$

$$= \frac{2I}{\rho_0} \cdot \frac{a}{r}, \quad r \geq a$$

There are two limiting currents, an electrostatic one and a magnetic one. For the electrostatic limit, consider the electron beam to be enclosed in a conducting cylinder of radius $b$. Then the electrostatic potential difference between the center of the beam $(r=0)$ and the wall is

$$\Phi = \frac{I}{\beta_0} \left(1 + 2 \ln \frac{b}{a}\right)$$

When the electrostatic energy $\Phi$ equals the electron kinetic energy $(y-1)e\,mc^2$, where $m$ is the electron mass, the total energy of an electron is equal to its rest energy, its speed is zero, and it can no longer propagate. This occurs at a current

$$I_L = \frac{I_0 \beta(y-1)}{1 + 2 \ln \frac{b}{a}}$$

where

$$I_0 = \frac{mc^3}{e} = 17 \text{ kA}$$

is a universal current. This simplified derivation does not include self-consistent effects that will cause $y$ to vary across the beam ("shear") and various somewhat phenomenological improvements have been derived. Equation (4) apparently gives results within 25 to 30% of observation.

The radius of curvature of an electron in the magnetic field of equation (2) inside the beam is $r = \rho_0/eB$, and when $\rho < a/2$, an electron will turn around inside the beam and not propagate. There is therefore a magnetic limiting current

$$I_A = I_0 \delta y$$

the Alfven-Lawson current. For most cases of physical interest, the magnetic limiting current is much greater than the electrostatic limiting current.

An electron beam accelerated from a cathode to an anode will not propagate past the region of the anode if its current is greater than $I_l$. Space charge will therefore accumulate, creating a potential well for positive ions, a "virtual cathode." This kind of potential well is the basis of space-charge collective accelerators.
Because it is unusual in having several features externally controllable, the Collective Particle Accelerator (CPA), now under test by Friedman, is an especially interesting concept. In this, a hollow electron beam is injected below the limiting current, passed through a chopper to create a sequence of rings of charge which then enter a guide field made up of discrete short solenoids. As the train of rings passes down the rippled guide field, their radii throb alternately inward and outward. This produces an axial electric accelerating field that can be decomposed into two waves, a slow forward wave \( v < c \) and a backward wave that can be either slow or fast, depending on the choice of parameters. The phase velocity of the accelerating wave can be controlled by varying either the inter-ring spacing or the inter-magnet spacing and its amplitude can be varied by changing either the beam current or the magnetic-field strength. Note that the mechanism proceeds by the action of discrete rings of charge, each of which retains its identity, and thus is quite different from the wave accelerators discussed below. The electron rings also produce radial focusing of the ions.

3. Wave Accelerators

An electron beam can be thought of as a plasma. Because the beam is not electrically neutral, an external magnetic field is needed to hold it together. The plasma properties can be summarized in a dielectric constant \( \varepsilon \), which becomes anisotropic when the external field is applied. The propagation of waves is affected by the dielectric properties of the medium. Further, the waves are split into "fast" and "slow" modes and Doppler-shifted by the beam motion. In Fig. 1 (taken from Ref. 18 with permission) are shown the roots of the dispersion relation, the axially symmetric modes of waves on an electron beam in a magnetic field. In Fig. 1, A identifies the four modified electromagnetic modes, B the two Doppler-shifted plasma or space-charge wave modes, C the Doppler-shifted upper (fast) branch of the upper-hybrid mode (also called the "cyclotron" mode) and D the Doppler-shifted lower (slow) branch of the cyclotron mode.

The plasma waveguide proposed by Fainberg and studied by his group was the first accelerator concept to utilize waves on an electron beam. A further important concept has been added to use a negative-energy wave train grown on the electron beam to accelerate protons, thus pumping energy from the electron beam into the protons.

There are two experiments in progress to study the potential for application of variable phase-velocity wave trains to collective acceleration. Both have recently succeeded in demonstrating the excitation and growth of the wanted waves and the suppression of other unwanted modes, but have not yet reached the point of injecting and accelerating ions. Although each of these experiments utilizes waves of very different character, one a cyclotron wave, the other a space-charge wave, both have the feature of exploiting a negative-energy mode. Thus, the greater the number of ions accelerated, the larger the amplitude of the accelerating field grows, until nonlinear saturation occurs. Large-amplitude wave excitation creates a longitudinal modulation of the space-charge potential and, hence, a sequence of accelerating buckets that propagate along the beam with the phase velocity of the wave. Acceleration of the ions is achieved by arranging for the phase velocity to increase from some initially low value at injection.

Auto-Resonant Accelerator. This system utilizes a cyclotron wave (the Doppler-shifted cyclotron mode) which has the attractive feature that the phase velocity can be made very small; thus ions can be picked up from rest by simply injecting a puff of gas at the appropriate place. The phase velocity of this wave is given by

\[
\nu_{ph} = \nu_e'/(1 + \frac{eB}{\gamma \mu_0 c}),
\]

where the electron velocity \( \nu_e \) is close to the speed of light, \( eB/\gamma \mu_0 c = \Omega \) is the cyclotron frequency chosen for exciting the wave, and \( \nu_o \) is the impressed frequency. By choosing a high field (high \( \Omega \) and relatively low frequency \( \nu_o \), the phase velocity can be made initially small \( (\ll c) \) for ion pickup. Thereafter the magnetic field can be diminished in a tapered way, the phase velocity increased and the ions accelerated.

A proof-of-principle experiment is underway at Austin, following extensive theoretical analysis. The procedure is to pass the beam \( (2.5 \text{ MV}, 20 \text{ kA}) \) through a double-helical resonant excitation section driven at \( \omega/2\pi = 250 \text{ MHz} \) to excite the wave. Next comes a dissipative helical growth section which loads the wave and thereby causes it to increase in amplitude. This has now been accomplished (and incipient non-axisymmetric modes suppressed) and potential wells of about 200 kV demonstrated, in modest magnetic fields \( (\approx 2 \text{ kG}) \). Because the phase velocity is not small, the next step will be to pass the beam into a tapered solenoid \( (\text{from } 2 \text{ kG up to } 20 \text{ kG}) \) to slow down the wave to the point where ion pickup is possible. Finally the flared-field accelerating section will be added. It may be noted that high phase velocities are more difficult to achieve in practice for this concept.
Space-Charge Wave Accelerator. The second wave system being studied for acceleration employs a negative-energy slow space-charge wave grown on the beam during its propagation through a slow-wave excitation structure. The behavior of slow space-charge waves has been long studied in the case of vacuum tubes, but there are some differences for relativistic high-current beams. The expression for the phase-velocity is

\[ \omega_p \chi = v_p / \left( 1 + F_0 \right), \]

where \( \omega_p \) is the impressed frequency, \( \omega \) is the beam plasma frequency (relativistic) and \( F \) is a plasma-frequency reduction factor that depends on the ratio of the beam diameter to pipe diameter.

It was pointed out by Sprangle et al. at NRL that an accelerator could be built by injecting a beam of constant diameter into a pipe whose walls converged in tapered fashion towards the beam (Convergent Guide Accelerator, or CGA). In this geometry, \( F \) can be made to decrease with distance in a programmed way and, accordingly, the phase velocity \( v_p \) increased gradually as needed. Sprangle et al. gave arguments showing that such an accelerator could give 0.5 A of protons at 300 MeV in a length of 15 m. This concept has been extensively developed by Nation’s group at Cornell.

Upon analysis, however, it turns out that one cannot practically realize low values for \( v_p \) in contrast with the cyclotron wave case. As \( v_p \) tends to zero, the beam current \( I \) approaches the limiting current \( I_l \). For this reason, values of \( v_p \) below 0.2 c appear to be more difficult. There is interesting recent theoretical work considering the nonlinear regime. In this work, Hughes and Ott predict a significant decrease in the phase velocity of the slow space-charge wave at large wave amplitudes.

Experiments by Nation with a 250-kV electron beam have shown successful growth of a slow wave in an iris-loaded structure at frequency of 1.1 GHz. The growth was rapid; accelerating fields of 6 MV per meter were generated. Below \( v = 0.2c \), operation is so close to the limiting current that the system is highly erratic. A linear induction accelerator is presently being built as an alternative to the present Luce diode injector.

A program to use a cyclotron as an injector has been considered at NRL, but has been deferred.

4. Electron Ring Accelerators

The electron ring accelerator (ERA) was proposed by Veksler in 1967.\(^2\) There is a circulating electron beam of toroidal geometry in a magnetic mirror and ions are trapped in it. Acceleration takes place by means of an electric field or changing magnetic field along the axis of the toroid, perpendicular to the plane of the electron ring. The objective of the ring geometry is to preserve the stability of the electron beam. A space-charge electric field (the "holding power") that would accelerate the ions of several hundred MeV per meter was originally considered feasible, but the estimated maximum holding power has decreased as a result of extensive work.

At the 1971 High Energy Accelerator Conference in Geneva, V. P. Sarantsev reported the acceleration of \( \alpha \)-particles to 30 MeV. This result was apparently not reproducible. Enthusiasm for the ring accelerator was further damped by theoretical analysis of instabilities, which showed that the holding power was limited to about 50 MV/m. The accelerator would therefore not be of great interest for high-energy physics. The ERA program at Berkeley was terminated in 1975. However, three active groups continued to investigate the ERA: At Garching in West Germany, the University of Maryland in the United States, and Dubna in the USSR.

Since 1971, ERA research has concentrated on improving the quality of the rings at Dubna and Garching or on a different approach to forming the ring at Maryland. A small-scale ion-acceleration experiment at Garching confirmed the basic principle by accelerating ions to a few hundred keV.

In 1978, the Dubna group reported new results on ion acceleration. They have accelerated about 5 \( \times 10^{11} \) - \( \times 10^{12} \) ions at a rate of 4 MeV/nucleon, and heavier ions at a rate of 1.5-2 MeV/nucleon. The acceleration was over a length of 50 cm. At the end of the compression, the magnetic field was 15 kG and the electron energy was 20 MeV. The electron ring contained about 10\(^4\) electrons within a final major radius of 3 cm and a minor radius of about 2 mm.

Since 1978, the ERA programs at Garching and Maryland have been discontinued. The Dubna group has continued, devoting effort to acceleration of neon, argon, krypton, and xenon ions to 3.2 MeV/nucleon and to the use of electric fields rather than magnetic expansion for acceleration of the ion-loaded ring. They reported recently\(^6\) that they have accelerated rings with electric fields and that they are authorized to build a heavy-ion ERA to reach 20 MeV/nucleon as an injector to higher-energy heavy-ion accelerators.

5. Inverse-Drag Accelerator

Veksler proposed in 1956\(^8\) that an electron "medium" (a bunch) traveling at large velocity with respect to charged particles could give energy to the charges through coherent scattering and through inverse Cherenkov radiation.

No significant experimental work has ever been carried out on this inverse-drag acceleration mechanism. But Irani and Rostoker have shown\(^8\) that the bunches do not hold together long enough for any useful acceleration to take place, at least in a linear geometry. It is therefore believed by almost all workers that inverse-drag accelerators have severe difficulties in principle.

6. Collective Focusing Accelerators

The first proposal for an accelerator using collective fields for focusing particles was that of Budker.\(^3\) The radial electric field of an intense electron beam in a circular accelerator was to be used to bend an ion around the circle. As the ion beam gained energy, it would move radially outward toward the large electric fields at the edge of the electron beam. The Budker proposal was found to have difficulties of principle. For example, the betatron wave numbers of the ion beam increase as
the beam moves radially outward and many resonances are crossed. Work on the Budker collective focusing has not been carried on.

There are several more recent concepts that are being actively studied. Among them are:

**Pulselac**

The basic acceleration scheme is a conventional one using pulsed drift tubes to accelerate a long slug of ions. Ions are accelerated into a drift tube and, when the head of the beam reaches the downstream end, the voltage is removed from the drift tube and the succeeding one switched on. Instead of using conventional focusing, Humphries et al.\(^2\) have arranged to inject electrons into the drift tubes to provide charge neutralization and transverse focusing of the ion beam; a convenient arrangement is an array of field-emission points. The key of the scheme, however, is to prevent the electrons from crossing the accelerating gap between successive drift tubes, so that they do not constitute an inordinate current drain on the power supply. This is accomplished by magnetic insulation; a magnetic field is applied in such a direction that the electrons perform magnetron orbits (with an \(E \times B\) drift) but can never cross the gap and so drain the voltage generator. Obviously, fresh electrons must be injected into successive drift tubes.

Creating such a situation requires the drift tube to consist of two concentric tubes with an annular ion beam contained between them. Conductors wound around the outer radius at the tips of the outer tube and around the inner radius of the inner tube can provide a magnetic field to meet the requirement of magnetic insulation. A useful feature of this arrangement is that the \(E \times B\) drift can carry the electrons around the axis again and again and again; thus charge accumulation, which can be troublesome in other geometries, is avoided.

A set of plasma guns arranged in an annulus supplies about 3,000 to 4,000 \(A\) of carbon ions for injection; a 5-gap pulsed drift-tube system now in operation produces at its exit an impressive 3,000 \(A\) of carbon ions at an energy of 600 \(keV\), with good emittance. These results seem to indicate that the mobile electron species can adjust its distribution in a benign way to provide focusing that is both strong and approximately linear.

Injectors have been developed, for example 5-ka, 120-kV nitrogen beams with 0.5 usec pulse; carbon beams at 2 kV have been post-accelerated in a second independent gap at 200 keV. A radial magnetic field gap has been shown to confine electrons stably at a field stress of 0.5 \(MV/cm\). Neutralization of beams in transport regions with a space-charge balance of better than 0.2 percent has been demonstrated. Most of the elements of a possible 5-TW/cm\(^2\) inertial-fusion test system have been tested.

**Toroidal Electron-Focused Ion Accelerator**

This concept, proposed by Rostoker, is closely related to the Budker proposal. Several novel features are included, however, that make the idea seem attractive. The basic idea is to create a bumpy toroidal magnetic field, i.e., a string of mirrors that closes on itself, and to inject a dense cloud of electrons with predominantly transverse velocities (i.e., no toroidal component). The electrons form a deep potential well into which ions are injected; the ions are then accelerated by pulsing a transformer, exactly as in a betatron. Ions are focused up to a charge density about 10\% of the electron charge density.

The key to the operation is the local trapping of the electrons in the multiplicity of mirrors. When the induced electric field is created, few electrons are accelerated because the loss-cone is sparsely populated. This has been verified in a small experiment at Irvine. Suppression of the toroidal electron current is essential to avoid taking all the energy from the generator. The design draws heavily on results from an early collective device\(^3\) (HIPAC) at Avco-Everett in which the technique for injection of electrons with high transverse energy was developed. In addition, work on HIPAC succeeded in mapping out the regions of potential instabilities (diocotron, magnetron, electron-resonance) and, as a result of that work, the proposed design pays careful attention to avoiding these hazards. This scheme has no particular advantages over a conventional accelerator for bending an ion beam, but it has considerable advantage for focusing or increasing the space-charge limit. For the acceleration of a large number of ions, the CFIA could provide reduction of major radius, compared with a conventional accelerator, by a factor of \(\sqrt{5}\).

A table-top experiment is underway to demonstrate proton acceleration to a few MeV. The electron guiding field will be about 1 cm in minor and 1 m in major diameter. So far, collective focusing fields of 150 \(kV/cm\) have been achieved.

The technology of electron injection and trapping has been developed. An electron line density of \(8 \times 10^{11}\) electrons/cm has been injected, trapped and contained for a few milliseconds. An induced toroidal field of 10 \(V/cm\) has been applied. It has produced a toroidal electron current corresponding to less than 0.5 percent of the trapped electrons and is also below the noise threshold. The electron-focusing structure has been established and experiments on injection and acceleration of ions have just started.

7. Possible Applications of Collective Accelerators

Historically, many collective accelerator concepts were created with the thought of accelerating particles to very high energies in a simple, elegant (and therefore inexpensive) manner. The intended application motivating this work was high-energy physics, where achieving very high energy particle beams has become limited by the economics of size and construction rather than the technology. The early promise of very high accelerating-voltage gradients in collective devices, gradients not apparently achievable in conventional radio-frequency structures, was the key technical factor. But the success of circular accelerators in reaching the particle beam energies and intensities needed for physics research has forestalled the use of linear devices, except in very high energy electron linacs. The present generation of proton synchrotrons can reach 1000 \(GeV\) energies in a structure 6000 meters long, and thus...
any linear device must be capable of an accelerating gradient of at least 160 MV/m sustained over kilometer distances in order to compete. We have therefore concluded that the acceleration of charged particles to very high energies is an unlikely application of collective accelerators.

There are, however, many other applications of great interest at lower energies, as can be seen in the accompanying table, which summarizes the study group's views on applications. This includes the use of collective acceleration and collective focusing devices as the early, lower-energy stages of the multistaged devices employed in facilities for high-energy physics. The areas of most promising application are those that require relatively high intensity beams of ions with energy less than about 1 GeV and having low pulse-to-pulse repetition rate. Some of these applications are appropriate for collective devices now being developed.

8. Conclusion

It is concluded that the basic physics of all the known collective-accelerator concepts appears to be sound, with the exception that in the inverse-drag accelerator, particle bunches do not stay together long enough to be accelerated in a linear geometry. Even here, it is possible that this difficulty can be ameliorated in toroidal geometries.

Most collective-accelerator concepts are in the proof-of-principle stage and require more work before construction of a prototype. Collective-focusing devices, especially PULSELAC, are closest to the prototype stage. When these concepts are further developed, there are applications of interest for which they are appropriate.

A perhaps surprising result of the collective-accelerators study is that the electron ring accelerator, abandoned in the United States, is alive and well and competitive with other devices. It is further developed than other concepts and its difficulties are therefore better known. But it is comparable in performance to other devices and the work of the Dubna group has shown that it is viable.

The field of collective accelerators is young and it is difficult to guess what directions will be prominent in the future. But, as a field, it is characterized by creativity, vigor and dedication. Conventional and collective accelerator workers will undoubtedly learn much from each other's work.

REQUIREMENTS FOR APPLICATIONS AND SUITABILITY OF COLLECTIVE ACCELERATOR CATEGORIES

<table>
<thead>
<tr>
<th>Application</th>
<th>Particle</th>
<th>Kinetic Energy</th>
<th>Peak Power or Intensity</th>
<th>Duty Factor or Average Power</th>
<th>Accelerating Gradient</th>
<th>Space Charge</th>
<th>Wave Acceleration</th>
<th>Collective Focusing Acceleration</th>
<th>EEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEP Direct</td>
<td>p</td>
<td>1000 GeV</td>
<td>10¹¹</td>
<td>NA</td>
<td>&gt; 100 MV/m</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Likely</td>
</tr>
<tr>
<td>HEP Injector</td>
<td>n</td>
<td>500 GeV</td>
<td>10¹¹</td>
<td>NA</td>
<td>&gt; 2 MV/m</td>
<td>Potential</td>
<td>Potential</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td></td>
<td>p</td>
<td>200 MV</td>
<td>20 MV</td>
<td>0.2%</td>
<td>&gt; 2 MV/m</td>
<td>Potential</td>
<td>Potential</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>Inertial Fusion</td>
<td>A = 10-30</td>
<td>0.1 GeV</td>
<td>100 TW</td>
<td>20 MW</td>
<td>&gt; 2 MV/m</td>
<td>Promising</td>
<td>Promising</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>Magnetic Fusion</td>
<td>A &gt; 1</td>
<td>120 keV</td>
<td>NA</td>
<td>-100/10-100 MeV</td>
<td>NA</td>
<td>Unlikely</td>
<td>Potential</td>
<td>Unlikely</td>
<td>Likely</td>
</tr>
<tr>
<td>Nucleon Physics</td>
<td>A &gt; 1</td>
<td>3-10 GeV</td>
<td>NA</td>
<td>-100/100 kV</td>
<td>50 MV/m</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Likely</td>
</tr>
<tr>
<td>Nucleon Physics</td>
<td>Heavy Ions</td>
<td>&gt; 10 MeV/A</td>
<td>NA</td>
<td>NA</td>
<td>&gt; 100 MV/A</td>
<td>Promising⁷</td>
<td>Promising⁷</td>
<td>Promising⁷</td>
<td>Promising⁷</td>
</tr>
<tr>
<td>Ion Sources</td>
<td>A &gt; 1</td>
<td>&gt; 10 MV/A</td>
<td>10¹¹</td>
<td>100%</td>
<td>&gt; 2 MV/m</td>
<td>Promising⁵</td>
<td>Unlikely</td>
<td>Potential⁵</td>
<td>Likely</td>
</tr>
<tr>
<td>Pulsed Neutron</td>
<td>p,d</td>
<td>1 GeV</td>
<td>3 10¹¹</td>
<td>10⁻⁴/5 kW</td>
<td>&gt; 2 MV/m</td>
<td>Promising⁵</td>
<td>Potential</td>
<td>Unlikely</td>
<td>Likely</td>
</tr>
<tr>
<td>Material Studies (PLS)</td>
<td>d</td>
<td>30 MeV</td>
<td>100 WA</td>
<td>100%</td>
<td>&gt; 2 MV/m</td>
<td>Promising⁷</td>
<td>Promising⁷</td>
<td>(Potential)†</td>
<td>Unlikely</td>
</tr>
<tr>
<td>Industrial Studies</td>
<td>A &gt; 1</td>
<td>1 MV/A</td>
<td>NA</td>
<td>10-100 MW/A</td>
<td>NA</td>
<td>Unlikely</td>
<td>Potential</td>
<td>Potential†</td>
<td>Likely</td>
</tr>
<tr>
<td>Medical Therapy</td>
<td>A &gt; 1</td>
<td>300 MV/A</td>
<td>NA</td>
<td>NA</td>
<td>30 MV/m</td>
<td>Promising</td>
<td>Promising</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>Medical Isotope Production</td>
<td>A &gt; 1</td>
<td>10 MV/A</td>
<td>10¹¹/12 sec</td>
<td>NA</td>
<td>&gt; 2 MV/m</td>
<td>Promising</td>
<td>Promising</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>Fusion Breeding</td>
<td>d,p</td>
<td>1 GeV</td>
<td>0.2-1 A</td>
<td>300 MW</td>
<td>&gt; 2 MV/m²</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Likely</td>
</tr>
<tr>
<td>Fusion Breeding (Tritium)</td>
<td>d,p</td>
<td>100 MV</td>
<td>10⁶</td>
<td>10⁻⁶</td>
<td>&gt; 2 MV/m²</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Likely</td>
</tr>
</tbody>
</table>

NA = Not applicable or pertinent

¹Energy of Fermilab Tevatron
²Energy of upgraded SLC linear accelerator
³Parameters of existing injector linacs (PHL, BNL)
⁴Parameters of TTPF injectors
⁵Low duty-factor applications only
⁶As part of a hybrid system
⁷Applicable if linear operation (100% duty factor) not needed
⁸Nominal requirements for this potential application

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References


Discussion

F COLE paper--discussion of R. FAEHL movie on collective effects:

The diagnostics in the movie were not good enough to tell precisely what fraction of the ions achieved an energy higher than the electron energy, but it appears that even though the fraction might be small, the quantity is still copious.
PARTICLE SIMULATIONS OF RADLAC

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Abstract

A crucial problem in high-current radial line electron accelerators is radial oscillations of the beam in the foilless diode injector and in the accelerating gaps. This problem is studied via 2-1/2-D particle simulations (quasistatic and electromagnetic) in cylindrical r,z geometry, with emphasis on contouring the applied magnetic field for optimum transport. The results are generally optimistic for future systems; however, further work is needed on designing the injector.

The Radlac Device

A schematic of the linear radial line electron accelerator is shown in Fig. 1. The advantages of such a system in comparison to conventional linear induction accelerators are that high currents (10-100 kA) can be accelerated to tens of MeV, and it permits the use of known technology for pulsed transmission lines. Output beam parameters of 25 kA and 9 MeV were achieved in experiments performed in 1980.

Simulation results for a typical diode source in cylindrical r,z geometry are shown in Fig. 2. The applied magnetic field $B_0$ of about 18 kG is primarily axial, but was contoured according to a modified version of the theory of Ref. 3. For a voltage of 4 MV, the current was 87 kA. Although the radial oscillation amplitude is small (considerably smaller than for the same case with a uniform 18 kG field), it is larger than if a uniform 35 kG field were applied. Further, the larger fields are better at mitigating the troublesome problem of shank emission. However, the larger

Figure 1. Schematic of a Radlac electron accelerator.

In attempting to reach higher powers, two old problems resurfaced which require theoretical treatment. These are the issues of azimuthally symmetric radial oscillations and azimuthally asymmetric instabilities. In this paper, we shall consider only the former problem, since the off-axis diocotron has been discussed in a recent publication, and the latest results on other instabilities will be given by B. B. Godfrey elsewhere in these proceedings.

The Foilless Diode Injector

Care in the design of the beam source is especially crucial in Radlac, since simulations show that small radial oscillations tend to be magnified by the accelerating gaps. The ideal injector would produce a cold, symmetric, annular electron beam of at least 4 MeV. (We consider only thin annular beams because of the higher space charge limit.)

Simulation results for a typical diode source in cylindrical r,z geometry are shown in Fig. 2. The applied magnetic field $B_0$ of about 18 kG is primarily axial, but was contoured according to a modified version of the theory of Ref. 3. For a voltage of 4 MV, the current was 87 kA. Although the radial oscillation amplitude is small (considerably smaller than for the same case with a uniform 18 kG field), it is larger than if a uniform 35 kG field were applied. Further, the larger fields are better at mitigating the troublesome problem of shank emission. However, the larger

Figure 2. Electron trajectories from foil­
less diode simulation; K = cathode, A = anode. Applied voltage 4 MV, beam cur­
rent 87 kA.
fields are impractical here from field energy and beam canonical angular momentum considerations. Hence, unlike the case of a single accelerating gap, the problem of injector-induced oscillations is presently considered to be only partially solved.

One possible solution is a large field which decreases adiabatically from the diode to the first gap. Simulations show the beam expanding as $B_{0}^{-1/2}$, however, as expected. Several other cathode designs have been considered, but none have been found to be clearly superior. Parametric deamplification via wall rippling seems impractical for this system. Giving the beam an initial radial momentum has not been studied extensively for diode injectors, but a practical design at high current appears difficult.

The Accelerating Gaps

A previous paper showed how to virtually eliminate oscillations in a single gap by contouring the applied $\vec{B}$ field. That the same technique works for three gaps is shown in Figs. 3 and 4. In Fig. 3, a 50 kA beam acquires oscillations which grow larger after each gap; contouring the field appropriately reduces the oscillations to a very low level (Fig. 4). Adding a realistic random radial velocity spread to the injected beam does not change the result of Fig. 4 appreciably; so the method presumably works for a beam from a "real" injector. We are only considering the first three gaps of the system because after a few gaps the increased beam energy makes the cyclotron wavelength much larger than the axial gap dimension; it is unnecessary to carefully contour $\vec{B}$ in subsequent gaps.

Another method for reducing the oscillations is to increase the wall radius after each gap. According to our simulations, this helps considerably but is not as effective as magnetic contouring (at least for the case of Fig. 3).

We have developed a simple envelope theory for the multigap problem, based on the radial equation of motion for the edge electron. This model yields the envelope $R(z)$ if the field $B_{0}(z)$ is given and if a separate Poisson solver is available to obtain the gap fields for an ideal non-oscillating beam at the given current. Figure 3 shows $R(z)$ for the uniform 20 kG field; the agreement is excellent, and since $R(z)$ can be obtained at a tiny fraction of the cost of a particle simulation, we are using the envelope model as a design tool for Radlac systems. The envelope approach fails, however, for currents exceeding the space-charge limit, or when one must calculate the internal beam dynamics, and cannot be used in warm-beam problems.

Figure 3. Three-gap simulation electron map for 50 kA beam from 4 MV diode with $B_{0} = 20$ kG (uniform). Each gap has spacing 4 cm, voltage 3 MV. The beam is initially in the slow-rotational mode equilibrium. Some beam loss occurs after the third gap. The solid curve is from an envelope calculation.

Figure 4. Simulation for the case of Fig. 3, except the applied $\vec{B}$ is contoured according to the theory of Ref. 3.

The multigap simulations in the figures were done with a quasistatic code, raising the question of the magnitude of electromagnetic (inductive and displacement current) effects. Using a new electromagnetic code MAGIC with an implicit Maxwell solver, the time development of multigap...
systems with the parameters of Fig. 3 was studied. The applied voltages were ramped in time up to constant values, as was the injected beam current, and the system settled into a "quasisteady" state. There was no essential difference in the beam behavior between these runs and the corresponding quasistatic cases, and we conclude that purely electromagnetic effects are not important in determining the motion of azimuthally symmetric beams through several accelerating gaps in Radelac. (This result says nothing about $\theta$-dependent instabilities.)

**Conclusion**

Azimuthally symmetric radial oscillations in Radelac systems have been studied via 2-D particle codes. Except for the question of designing the optimum injector, the results suggest that the problem may be handled successfully by a combination of magnetic contouring and variable wall radius.

However, we have only discussed the oscillations in terms of ideal gaps. Actual gaps must be designed with image displacement/beam breakup problems in mind, and with the constraint of preventing electron leakage, while still controlling radial oscillations. It is hoped that experiments in the near future will answer the question of whether all requirements can be met simultaneously through a multigap system.

**Acknowledgments**

The contoured field used in Fig. 4 was obtained by M. R. Franz of the Air Force Weapons Laboratory. Many useful discussions were held with R. J. Adler and B. B. Godfrey.

**References**

Experimental studies of beam focusing with the first solenoid lens in the University of Maryland electron beam transport experiment (at 5 kV, 230-310 mA) are reported. At zero magnetic field, the density profile and beam envelope are in agreement with theory. When the beam is focused with the lens, it becomes hollow, develops halos near the waist, and shows images of the anode mesh downstream from the waist. When the beam is reduced, the beam is less hollow, the halos are smaller, and the images improved. These effects are attributed to lens aberration, nonlinear space-charge forces, beam rotation, and transverse velocity components.

Introduction and General Considerations

The motivation for the Maryland-Rutherford electron beam transport experiment, design features, and preliminary results with two solenoid lenses were discussed in three previous papers. To repeat briefly, the main objective of our project is to study the causes of emittance growth and instabilities that limit the beam current and the brightness in a periodic focusing channel. Our initial goal is to determine the behavior of an unbunched, long beam in transverse phase space; the study could be extended later to the more complex case of a bunched beam.

The main impetus of our work is to check whether the instabilities predicted by recent theoretical and numerical studies can be observed experimentally. In addition, we want to study other effects that deteriorate the beam quality such as aberrations due to external fields and nonuniform space charge densities. An electron beam in the range of a few kV was chosen for reasons of small scale and low costs. Periodically spaced short solenoids are being used to focus the beam in the first phase of our project.

Theoretically, the radius, a, of a beam in a solenoidal focusing system is determined by the envelope equation (paraxial approximation, Larmor frame)

\[ \frac{d^2 a}{dz^2} + \kappa(z) a - K = \frac{a^2}{a_0^2} = 0, \]

where \( \kappa(z) = \sqrt{2B_0/2e}\gamma \), \( B = B(z) \) = magnetic field on the axis, \( K = (1/\gamma)(2B_0^2/3) \) = generalized perveance, \( I \) = beam current, \( I_0 = 4\pi e_m e_0^2/\gamma = 1.7 \times 10^{-4} \) amperes for electrons, \( \gamma = m_0 c/rms \) emittance, \( q \) = particle charge, \( m_0 \) = rest mass, and \( \gamma = (1 - \beta^2)^{-1/2} \).

When the focusing system is periodic, with period \( \Delta z = S \), the beam physics is determined by the "tunes," or phase advances, \( \phi_0 \) and \( \phi_0 \), of the particle oscillations with and without space charge, respectively. Equation (1) can then be solved by the smooth-approximation technique and, for a channel with acceptance \( \alpha \) and matched conditions, one obtains the following relations\(^8,9\)

\[ I = I_0 \left( \frac{3}{2} \frac{\alpha}{a_0^2} \right)^{3/2} (1 - \epsilon^2/\alpha^2), \]

\[ \frac{\alpha}{a_0} = \frac{\gamma}{\sigma_0} \left( 1 + \frac{u^2}{u} - u \right), \]

where \( \alpha \) = average beam radius, and \( u = KS/(2\alpha c) \). Graphs and formulas for the factor \( \sigma_0 \) can be found in Ref. 9.

For a source with brightness \( B \), one has

\[ I = Be^2, \]

and the actual beam current corresponds to the intersection of curves (2) and (5) as illustrated in Fig. 1. The acceptance \( \alpha \) of a channel can be defined by a suitably placed hole of radius \( a \). Any emittance growth will reduce the brightness and hence the beam current through the hole (see dashed curve in Fig. 1). A measurement of the beam transmission thus provides a first indication on the existence of instabilities or other effects. Further refinements require beam profile and emittance measurements.

Theory and numerical simulations predict quadrupole (envelope) instabilities when \( \alpha > 90^\circ \) and sextupole (third-order) instabilities when \( \alpha > 60^\circ \). There are also intensity thresholds, i.e., lower limits for \( \alpha_0 \), that depend on the form of the particle distribution function and on coupling between transverse and longitudinal modes. For a K-V distribution, for instance, one has the stability requirement \( \sigma_0 > 0.4 \) and \( \sigma_0 < 60^\circ \). In our experiment, we plan to vary both \( \sigma_0 \) and \( \alpha \) over a wide range to cover all possible instability modes predicted by theory. The use of grids to accomplish this is being studied at the Rutherford Laboratory.

Electron Beam Apparatus

The three major components of the apparatus are the electron gun, the solenoid focusing system, and the diagnostic chamber, as described previously. The experiment is designed to proceed in stages: several electron guns producing different beam characteristics will be tried; the various beam profiles in free space are measured first; then solenoid lenses will be added, one at a time, until the full length of the focusing channel (approximately 30 lenses) is completed.

In preliminary studies with a home-made...
The electron gun, we measured the free-space beam envelope expansion and focusing with one and two lenses. Subsequent measurements of the radial current density with a Faraday cup revealed that the beam becomes hollow when it is focused. This led us to start a more systematic study of the beam properties with only one solenoid lens.

The experimental configuration for the measurements is shown in Fig. 2. The electron gun is the same as that in Ref. 3, except that the cathode-anode gap is only 1.6 cm and the beam current is 310 mA (versus 230 mA) at 5 kV. The diameter of the cathode is 1 cm and the anode aperture is covered with a fine tungsten mesh. The center of the solenoid is 8.6 cm from the anode. A fluorescent screen at the end of a hollow tube, can be moved along the beam axis; the screen pictures of the beam, which can be seen through the tube, are recorded with the aid of a TV video-tape system.

Experimental Results

The radial density profile near the anode, fluorescent screen pictures, and the beam envelopes for various peak magnetic fields (from 0 to 380 G) of the full-size beam were already published in our previous paper. We have now also measured the radial density profiles versus distance along the axis for various magnetic fields. Figure 3(a) shows three profiles at a distance of 20, 22, and 24 cm, respectively, with a fixed peak magnetic field of B0 = 117 G. The most notable feature in the hollow structure of the profile even though the beam prior to entering the lens has a peaked, almost Gaussian, shape (see Ref. 3). However, it appears that with increasing distance, the hollow feature gradually disappears. The asymmetry in the profile curves is caused by misalignments in the system and possibly some nonuniformity in cathode emission.

We do not fully understand yet why the beam becomes hollow. However, qualitatively, we attribute this phenomenon to a combination of lens aberrations, nonlinear space charge forces, trajectory rotation in the solenoidal magnetic field, and the relatively low temperature of the beam. (The emittance is \( \varepsilon = \varepsilon_0 \sqrt{2kT/eV} = 3 \times 10^{-3} \) m-rad, where \( \varepsilon_0 = \text{cathode radius} = 0.5 \text{ cm} \), \( kT = \text{cathode temperature} = 0.12 \text{ eV} \), \( eV = \text{gun voltage} = 5 \text{ kV} \).

From the qualitative analysis, one concludes that the radial profile should be less hollow when the beam radius is reduced since all of the mentioned effects increase with radius. We therefore inserted a thin mask into the beam behind the anode, with an aperture of 0.5 cm thus reducing the beam size by a factor of two. An important additional feature of the mask are two 0.5 mm pinholes outside of the reduced beam aperture but inside of the full-size beam radius, as shown in the upper left corner of Fig. 4.

We should note that the mask reduces the current \( I \), and hence \( K \), by a factor of 4 and the emittance by a factor of 2. Consequently, in a periodic channel, the space charge parameter \( u \) would decrease by a factor 2 and the tune shift ratio \( \sigma/\sigma_0 \) would increase.

Some experimental results obtained with the reduced beam are shown in Figs. 3(b), 4, and 5. First, in Fig. 3(b), we see, by comparison with 3(a), that the beam profile is considerably less hollow than in the case of the full-size beam confirming our expectations. In Fig. 4, the envelopes for the reduced beam are plotted for different magnetic fields. Computations show that only the free-space curve \( (B_0 = 0) \) agrees with the envelope obtained from integration of Eq. (1). The phosphor screen, pictures taken at a fixed axial position of \( z = 16 \) cm with varying magnetic field strength, are seen in Fig. 5. We note that all of the features discussed already in Ref. 3 are present here as well, in particular, halos near the waist and images of the anode mesh downstream from the waist. However, in contrast to the full-size beam, the halos are less pronounced and the images are sharper. Of particular interest is the fact that the images of the anode mesh first show shadows of the wires; but then, as the magnetic field is increased, they become bright.

Equally noteworthy is the behavior of the two beamlets defined by the pinholes. Since they are launched from a region outside of the reduced beam radius, the defocusing force due to the space charge \( (F = I/r) \) is less than on beam electrons near the edge \( (r = a) \). Thus, the two beamlets enter into the beam (near \( z = 18 \) cm), as indicated schematically in Fig. 4 for the outer beamlet, (b). When the magnetic field is turned on and increased, the two beamlets cross the axis and emerge on opposite sides of the beam, as can be seen in the photos of Fig. 5. One can also see a coma-like distortion of the beamlet cross section.

In conclusion, we found that the beam, focused by only one solenoid, shows a variety of effects some of which were unexpected. While we do have some qualitative explanations, more experimental studies as well as numerical simulation will be required to obtain a full understanding. Thus, in parallel with the construction of the periodic solenoid channel, we plan to devote some time to more detailed studies of beam behavior in a single lens.

With regard to the periodic channel, we plan to increase the effect of emittance versus space charge, and thus the tune \( \sigma \), by lowering the gun voltage, decreasing the beam perveance, and using beam masks and special grids. The first results with the grids at the Rutherford Laboratory are already quite encouraging: it was demonstrated that the beam radius can be increased easily by a factor of two with proper grid voltage and polarity.

References


I = I_0 \beta \gamma n_0 / S, B_2 < B_1.

Fig. 1 Channel acceptance, Eq. (2), and brightness, Eq. (5), define actual beam current, I = I_0 \beta \gamma n_0 / S, B_2 < B_1.

(A) BEAM WITH R = 0.5 cm
(B) BEAM WITH R = 0.25 cm

Fig. 2 Experimental setup with magnetic field profile.

Fig. 3 Radial density profiles for full-size (a) and half-size (b) beam at B_0 = 117 G, V = 5kV.

Fig. 4 Envelopes at various magnetic fields for reduced beam size. Insert shows beam mask with two pinholes.

Fig. 5 Phosphor screen pictures at z = 16 cm for B_0 = 0, 117 G, 176 G, 264 G, and 322 G.
Discussion

The experimental beam envelope curves show that violent effects occur when the beam radius is only 40% of the lens radius. (1 cm out of 2.5 cm.) The experimental envelopes agree with integration of the envelope equations only without the magnetic field. So there is more physics than the envelope equations contain, and we hope to get that from numerical simulations.

We started with a solid beam and see hollowing and later reforming to a core again. If one wanted to use the higher space-charge limit of the hollow beam, one should start with an injected hollow beam.
Summary

Several limitations of the benefits of the race track microtron (RTM) as an economic c.w. electron accelerator are discussed. For beam blowup some final results of our investigations for the Mainz Microtron are given. The other two effects presented more generally are beam diffusion by imperfections of the optical elements of a RTM and the deterioration of transverse phase space by synchrotron radiation.

Beam blowup (BBU)

Our model of "circulative" BBU in RTM's is discussed in detail in ref.1,2,3 and a survey of the properties of the BBU-modes in the biperiodic on-axis coupled MAMI-RF-structure was given there. In the meantime the transverse shunt impedance of the three dangerous modes at 4.2, 6.8 and 11.2 GHz has been remeasured with a very precise mechanical and RF-setup of the perturbation apparatus and a detailed space harmonic analysis to get the transit time factor. The results are compiled in Table 1 with the old estimates for given in brackets (for reference: $v_{acc} = 2449.3$ MHz with $r_0 = 67$ MeV/m).

$$v\text{(MHz)} \begin{array}{ccc} 4187 & 6785 & 11215 \\ r_0' \text{(MeV/m)} & 16.8 \pm 0.9 & 0.78 \pm 0.05 & 0.19 \pm 0.02 \\ \text{(18)} & \text{(3.6)} & \text{(1.9)} \end{array}$$

Tab.1

It is clear that (even noting that the BBU-threshold-current $I_t$ is going down with the $1/v$) the only BBU-mode remaining dangerous is the one at 4.2 GHz. We therefore redid our model calculations for the product $I_t r_0'$ as a function of $v_{acc}$ in a narrow frequency band around 4.2 GHz, taking as an input the detailed setup of the RTM's under construction at Mainz (e.g. $\beta < 1$ for the 14 MeV-RTM and as focusing scheme only two lenses at the ends of the linac axis for all three RTM's). The results are given in Fig. 1 and 2 for MAMI I and II.

![Fig. 1 Blowup threshold for 14 MeV stage](image)

One should note that a single spike of $I_t r_0'$ with a FWHM < 0.3 MHz (Fig. 2) naturally isn't a limitation for the current, it should be easy to get away from it by small changes in machine parameters (e.g. linac temperature, focal lengths). Nevertheless in MAMI II $r_0'$ will be reduced by a factor of ten, splitting the BBU-resonance of the linac.

We tried to verify this calculations qualitatively with the 14 MeV-RTM already operating by looking for the amplification of beam noise in its linac. By an RF-cavity on the injection path the beam was magnetically deflected $\pm 0.3$ mrad with $v = 4175 - 4205$ MHz and this "beam noise" was detected by a similar cavity at the output end of the RTM. Up to a machine current of 60 pA (limited by the present status of the gun) it was impossible to find any resonance of beam noise at 4187 MHz, in qualitative agreement with the results in Fig. 1 ($I_t = 1$ mA).

![Fig. 3 Setup for beam noise measurement](image)

However if one wants to build a very high current machine, the most radical approach to avoid BBU is to use a single-mode RF-structure. In Ref.3 we proposed a "pipe-cavity" for such a structure, but it was clear that a drawback of this geometry is that by lack of rotational symmetry the accelerating field may act on the beam like an RF-quadrup-
pole (cf. Fig.4). With the precision perturbation setup the quadrupole asymmetry of our pipe-cavity indeed was measured to be \( \delta(r) = \frac{E_{\text{max}}(r)-E_{\text{min}}(r)}{E(0)} = 2.5 \times 10^{-3} + 8 \times 10^{-4} \) at \( r = 5 \) mm \( (E: z\text{-component of electric field}) \), which means that a 10 m linac built of these cavities would have a focal length of 20 meters at 100 MeV. However it turned out that essentially by changing the distance between the shorting rods concentrating the RF-field near the nose cones this asymmetry can be canceled within a measurement error of \( \pm 3 \times 10^{-4} \) (the shunt impedance goes down from 60 to 50 M\( \Omega \) by these operations) (Fig. 4).

**Fig. 4** Pipe cavity optimized for field symmetry

**Beam Diffusion by Field Imperfections**

In c.w. recycling accelerators one has typically a large \( \beta \)-function, low bending radii and large bending angles. This coincidence makes a beam sensitive to field errors in the optical elements. In a cyclic machine, like a storage ring, this would not necessarily jeopardize stability. A recycling machine, however, is not really cyclic since the orbits differ from turn to turn. The influence of field perturbations then generally adds up turn by turn and might result in considerable phase space deformations. In the following a simple model is used to give a rough estimation of this effect of “beam diffusion”.

Generally, if a beam intersects a region of erroneously perturbed field its particles at different locations \( x \) across the beam would experience different deflections \( x' = f(x) \). Let’s look at one particle intersecting many stochastically varying perturbations. Under the simplifying assumption of a smooth focussing force a particle goes around in circles of radius \( R_0 \) in the \( x-x' \)-plane (Fig. 5) if no field perturbations are present. If the particle intersects a field perturbation \( f_1(x) \) at a moment when it is in point \( A \) it will be lifted by the amount \( \Delta x_1 = f_1(x) \) and will from there on go around in a circle of different radius. Later on, when in point \( B \), it might intersect another perturbation \( f_2(x) \) which would shift it to \( B' \) and so on. If \( \Delta f(x) \ll \bar{x} \) the change of the radius is given by \( \Delta x = \bar{f}(x) \cos \varphi \).

By representing \( f(x) \) by a power series \( f(x) = \sum a_n x^n \) and assuming that the effects of its different terms superimpose independently (which, again, is true if \( \Delta f(x) \ll \bar{x} \) one gets \( \Delta x_n = a_n x_n \bar{x} \sin \varphi \) cos \( \varphi \) (where \( \bar{R} \sin \varphi = \bar{x} \)). Here \( a_n \) represents a dipole-like perturbation, \( a_1 \) a quadrupole, \( a_2 \) a sextupole etc.

If there are many successive perturbations of stochastically varying strength one should speak in terms of the mean squares. Integrating over \( \varphi \) yields: \( \langle \Delta x^2 \rangle_n = \bar{x}^2 a_n^2 K_n^2 \) (where \( K_n^2 = 1/2, 1/8, 1/16 \) for \( n = 0, 1, 2 \)).

\( \bar{x} \) will be subject to one-dimensional Brownian movement following the Fokker-Planck equation

\[
2 \Delta p/\Delta n = a^2 (\Delta x^2 + p)/\Delta x^2 \quad (1)
\]

where \( n \) is the number of perturbations and \( p(\bar{x},n) \) the probability density.

Since the field distributions are always smooth the particles of the beam would not move independently. Thus the phase space boundary would not really diffuse by Brownian movement but it would - while staying sharp - slowly change its original shape, keeping the surrounded area constant (Liouville).

The range of this deformation may be estimated by solving for \( p(\bar{x},0) = \delta(\bar{x} - \bar{x}_0) \) as initial condition.

If the deformations are not too large, \( \bar{x}^2 a_n \) may be replaced by \( \bar{x}^2 \) and drawn before the differential operator, thus allowing the well known solution

\[
p(\bar{x},n) = \exp (\bar{x}^2/2a^2)(\sigma/2\pi)^{1/2} \quad (2)
\]

where \( \sigma \) may be interpreted as a measure for the amount of the deformation (Fig.6).

In case of a dipole magnet, for instance, the \( a_n \) are given by the field derivatives with \( a_n = (\partial^2 \bar{R} / \partial B \partial\lambda)(\partial^2 B / \partial x^2) \) where \( \lambda \) is the orbit length.
through the perturbation considered and $R$ the bending radius. In case of short range stochastical field errors, $A_s$ is of the order of the gap width and, when inserting its mean square into eq. (2), $dn$ is to be replaced there by $ds/A_s$. In case of a long range field error (e.g. a pole face tilt in a long bending magnet) $x$ and $\beta$.

$$\Delta x' = \frac{\Delta r}{R} \sin \varphi = \frac{\Delta E}{E} \sin \varphi$$

$$\langle \Delta x'^2 \rangle = \frac{N}{2} \frac{\langle \Delta E^2 \rangle}{E^2}$$

$$N = \text{Number of Quanta} = \frac{572}{\sqrt{3} \times 137}$$

$$\langle \Delta E^2 \rangle = 3.58 \times 10^{-14} \frac{\chi^2}{R^2} [\text{EV:mm}]$$

Fig. 6 Deformation of phase space boundary by different multipole terms

might change significantly within the magnet. Then the integrand of (2) becomes

$$\langle (\partial B/\partial x)^2 \rangle (\delta x_0^2 + \delta B_0^2) (\partial B/\partial x_0)^2.$$
FOCUSING CONSIDERATIONS IN THE RACE TRACK MICROTRON AND DOUBLE-SIDED MICROTRON

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Summary

We have developed general designs for quadrupole multiplet systems for use in both the Race Track Microtron (RTM) and Double-Sided Microtron (DSM). The quadrupole multiplet consists of five quadrupoles forming two mirror symmetric optical systems; furthermore, both systems are telescopic in the bending plane and exhibit dispersion zeroes in the centers of the second and fourth quadrupoles. The systems perform achromatic transformations and either rotate the incoming beam phase ellipse by $90^\circ$ or introduce focussing into the system. Alternate telescopic systems utilizing three quadrupoles can be used at higher energies. Compact systems can be constructed using permanent magnets. We present examples of these systems as applied to the proposed Argonne National Laboratory 2-GeV RTM-DSM configuration.

I. Introduction

The crucial requirement for both the RTM and DSM is longitudinal phase stability. Nevertheless, effective transverse focussing schemes are required for the multiple passes through these devices. The beams should be dispersion free in the linac(s). The planned ANL RTM-DSM complex is shown in Fig. 1. The DSM traveling wave linacs each boost the electron energy by 25 MeV per traversal while 6 MeV is gained per turn in the RTM. Referring to Fig. 1, 5 MeV electrons are injected into linac 1 and alternately accelerated and focussed in a system of six 3.0 m long rf sections and seven periodic quadrupole triplets situated between the rf sections and at the ends of the structure. The 30 MeV electrons are bent $20^\circ$ left by a septum magnet (which is the first dipole of the chicane system for returning high energy electrons); after passing through a $170^\circ$ isochronous bending system, the electrons are injected into the RTM where the energy is boosted to 180 MeV after 25 turns. This beam is then re-injected into the 180 MeV short straight section (SSS) of the DSM and is then accelerated up to a maximum energy of 2005 MeV in 36.5 turns.

In this document, we specifically discuss the active focussing systems that are required in the return paths of the RTM and short straight sections of the DSM. We do not discuss correction devices for maintaining phase stability. In Sec. II, we examine the geometry and requirements of each system. The theory is presented in Sec. III, and several examples are developed in Sec. IV. Concluding remarks are added in Sec. V.

II. Geometry and Focussing Requirements

Figures 2(a) and 2(b) exhibit plan views of one orbit through the RTM and one-half turn through the DSM, respectively. The system between the entry (1) point of the RTM and isochronous dipole (2) is a design furnished by Dr. Michael Tish. Points A and B represent the centers of the DSM linacs.

*Work supported by the U.S. Department of Energy.
and exit (f) points must perform an achromatic transformation. We require nominal beam waists at the linac centers \( \beta = \beta_A, \alpha_A = 0 \), and at the midpoint \( \beta = \beta_2, \alpha_2 = 0 \); the system must be variable so as to affect other conditions, however. It must also be compact -- the spacing between adjacent orbits is \( \lambda/\pi \) for the RTM and \( \lambda/(\pi - 2) \) for the DSM where \( \lambda \) is the rf wavelength (\( \lambda = 0.125 \) m).

The choice of dipole entrance angle \( \theta_1 \) in Fig. 2(b) has been studied intensively. Entrance and exit angles of \(-45^\circ\) produce \(90^\circ\) bends, a parallel to parallel transformation in the bend plane, and severe vertical defocussing. The minimum energy is near 200 MeV, however. Attempts to lessen this defocussing using external negative fields, i.e., reverse field stripes, are planned. However, they give rise to a path length problem. Presently, we plan to use \( \theta_1 > 30^\circ \) with a small quadrupole between the \(90^\circ\) dipoles and linacs. This decision was partly historical because the early AML design accelerated directly up from 5-2005 MeV in the DSM. The positive \( \theta_1 \) value reduces the vertical defocussing but causes a horizontal crossover downstream of the dipole. Stability studies have indicated an acceptable value of \( \beta_A = 1.5 \) m for both the RTM and DSM.

### III. Beam Transfer Theory

A mirror symmetric system will be located between, e.g., points (1) and (3) in Fig. 2. Then the \( 2 \times 2 \) transfer matrices from points i to f are given by

\[
M_{fi} = \begin{pmatrix} r & s \\ t & r \end{pmatrix}
\]  

(1)

in both transverse planes. The horizontal plane behavior in the interior section (1 to 3) is constrained to be telescopic and to have unity diagonal elements because of the achromatic requirement and

\[
M_{31}(x) = \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix}
\]  

(2)

The matrix (2) can be written in the form

\[
M_{31}(x) = \begin{pmatrix} \sqrt{\frac{\beta_3}{\beta_1}} f(\psi_{\alpha_1}) \sqrt{\frac{\beta_3}{\beta_1}} \sin \psi \\ 0 \end{pmatrix}
\]  

(3)

where the betatron phase shift is given by \( \tan \psi = (\alpha_3 - \alpha_1)/(1 + \alpha_3 \alpha_1) \) and \( f(\psi,\alpha) = \cos \psi + \alpha \sin \psi \). If \( \beta_1 = \beta_3 \) and \( \alpha_2 = -\alpha_1 \), we have \( \sin \psi = 2\alpha_1/(1 + \alpha_1^2) \) and \( a = 2\beta_1\alpha_1/(1 + \alpha_1^2) \). We can rewrite Eq. (2) as

\[
M_{31}(x) = \begin{pmatrix} 1 & \frac{a}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{a}{2} \\ 0 & 1 \end{pmatrix}
\]  

(4)

We find that \( a/2 \) is the distance to the horizontal waist as measured from points 1 or 3. The unity matrix in Eq. (4) represents a mirror symmetric focussing system acting in the \( x \) (bend) plane from a distance \( a/2 \) downstream of point 1 to \( a/2 \) upstream of point 3.

The chosen value of \( a = 2B_1\alpha_1/(1 + \alpha_1^2) \) results in a \(90^\circ\) beam ellipse rotation in going from point i to f (see Fig. 2(b)), i.e., \( \beta_f(x) = \beta_f(x) \) and \( \alpha_f(x) = -\alpha_i(x) \). This can be altered by changing the value of \( a \); then \( \tan \psi = a/(\beta_1 - \alpha_1) \), \( \alpha_3 = \alpha_1 - \gamma \alpha_1 \) and we obtain

\[
\beta_3 = \beta_1 \left( \frac{1 + \tan^2 \psi}{(1 + \alpha_1 \tan \psi)^2} \right)
\]

(5)

This change still maintains the achromatic transformation of Eq. (2).

## IV. Optical Systems

Two configurations have been adopted to deal with the RTM and the \( \theta_1 = -45^\circ \) optics of the DSM: (1) a five quadrupole design, and (2) a three quadrupole system. Both use a quadrupole singlet at the center symmetry point 2. For the RTM, the \( x \) transfer matrix for one turn \( M_{AA}(x) \) is a drift (ignoring acceleration) of length \( (2 + a) \). The \( \beta_A \) function will grow rapidly unless \( a < -2 \); thus, one must have \( \sin \psi < 0 \) (from Eq. (3)). This can be accomplished with the five quadrupole design. In the DSM, a similar system is used for energies below 1300 MeV; the triplet will suffice at higher energies.

Figure 3 shows the thin-lens analogues for the two systems along with the behavior of the dispersion \( \eta \) ray. The lens positioning relative to the horizontal waist location \( a/2 = \beta_1\alpha_1/(1 + \alpha_1^2) \) is indicated. For the RTM \( \alpha_1 < 0 \), thus \( a/2 < 0 \) is required. The multiplet is adjusted to form beam

![Fig. 3 Thin-lens Equivalents for Quadrupole Multiplet and Triplet Focussing Systems as Discussed in the Text](image-url)
waists and $\eta' = 0$ at point 2, and $\eta = 0$ in Q2 and Q4. The tune can be varied by changing Q2, Q4 without affecting the dispersion ray. In the DSM, the value of $a/2$ increases with energy; Q1 and Q5 must remain inside of these locations and their strengths increase quadratically.

For 1300 to 1800 MeV, the lower scheme in Fig. 3 is adopted. The quadrupole strengths are varied to obtain $r_2 = 0$, and an x waist $a_2(x) = 0$; the optimum location of Q1 (and Q3) minimizes $|a_2(y)|$. Above 1800 MeV, $a/2$ exceeds the distance between points 1 and 2 which is given by $s_{12} = 5.585 - \lambda(E-30)/(50(\pi-2))$ for even energies and by $s_{12} = 5.53 - \lambda(E-55)/(50(\pi-2))$ for odd energies. We treat this case by reversing the quadrupole polarities to $H,V,H$.

A program has been written to study the DSM optics over the entire range 200-2000 MeV. Quadrupoles are treated as thin lenses; dipoles use the standard transformations and Enge short-tail fields for reduced vertical focussing at the edges. A one dimensional minimizer is used to optimize quadrupole locations; information on each orbit is available. We show in Fig. 4 the quadrupole pole-tip fields required for a bore radius of 1 cm and length of 10 cm; $\Theta_1$ was taken as 30°. The discontinuities occur when $a/2$ occurs in the centers of Q1 and Q2, respectively.

We have calculated beam envelopes using the program TRANSPORT. In Fig. 5, we show DSM sample results for 430 MeV/c optics. The initial conditions were $E_A = 1.50 m$, $\Theta_A = 30^0$, and a geometric emittance of 5/430 $\pi$ mm-mr. Beam waists occur at the midpoint; the dispersions (not shown) behave similarly to those shown in Fig. 3(a). Envelopes have also been generated for the low-energy orbits in the RTM. They exhibit the same trends as those observed in Fig. 5. Similarly, high-energy orbits have been evaluated for the triplet geometry.

![Fig. 5 Sample Transport Beam Envelopes for 430 MeV/c Electrons in a DSM SSS](image)

**V. Conclusions**

More work remains to be done on these systems. The general stability problem must be addressed in regard to choices for $\Theta_1$, and the option of different values for $E_A$. The cumulative effect of perturbations in the DSM short-straight sections needs to be understood. The beam breakup threshold remains to be evaluated; the maintenance of beam waists in the linacs minimizes these effects.

**References**


AUTOMATIC BEAM-STEERING OF THE MAINZ MICROTRON

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Introduction.

The Mainz Microtron (MAMI) will consist of three cascaded Race-Track Microtrons with a Van De Graaff as injector. The first stage, delivering an output energy of 14 MeV, has been working for about two years in the Institut für Kernphysik in Mainz. The second stage is presently under construction and will increase the output-energy to 180 MeV.

A principal problem with these microtrons is the precise positioning of each individual turn to the middle-axis of the accelerating rf.-section. Therefore in front of and behind the section monitors for detecting the beam-position in each of the 20 turns of the first stage has been installed. A computer reads out this data and determines the setting of the 80 steering coils in the return-tracks of the beam (two coils in horizontal and vertical direction for each turn). The following describes the details of the hard- and software of this system shown in fig.1.

The Position-Monitors and Steering Magnets.

The beam-monitors consist of square rf.-cavities, in which the electron beam excites a rf.-wave of the accelerator-frequency (TM210-mode). Two antennas are positioned in such a manner, that a beam deviation off the middle-axis in x- and y-direction produces independent signals. To get the signals from each revolution the beam is marked with short pulses of about 8 kHz repetition rate. When such a pulse runs through the microtron it passes the monitors in each turn and produces a signal change, which depends on the beam-deviation.

After some rf.-electronics and differentiation, we get the signals on the oscilloscope (Fig. 2). Every peak on the photographs corresponds to one turn, its amplitude is proportional to the beam-intensity and in the position signals also to the deviation in the turn.

These signals are fed into a fast 12 -fold CAMAC-ADC, where the contributions of the individual turns are cut out by appropriate gate-signals, generated by a programmable delay-generator. Special electronics provides for the repetitive starting of the ADC for all turns, so that the computer can average the digitalized data thus reducing noise contributions. After calculating the new settings of the steering coils in a complex algorithm the computer delivers this data via CAMAC to a multiplexed digital/analog-converter with sample and hold circuits, which supplies the steering magnets.

The Mathematical Description of the Transversal Microtron-Optics.

In the optimisation algorithm the microtron is described in a first order matrix-formalism for particle beam-optics. The beam is represented by a vector \( (x, y, x', y') \), where \( x, y \) are the deviations from the nominal position, \( x', y' \) are the corresponding angular-deviations. Due to the special optics there is no coupling between horizontal and vertical beam position. Therefore the problem is reduced to only one direction \( (x, x') \). So the \( i \)-th turn of the microtron can be described by the equation:

\[
x_i = A_i x_{i-1} + S_i (u_i - \overline{u}_i),
\]

where \( x_i \) is a vector, which contains the beam-deviations measured by the two monitors, \( u_i \) is the actual setting of the two steering magnets and \( \overline{u}_i \) is the optimal setting, which is not necessarily zero, because of errors in real optics. \( A_i \) is a matrix standing for the condensed optics of one turn, \( S_i \) describes the optical behaviour from the steering magnets to the following monitors. To describe all turns \( i=1,\ldots,20 \) of the microtron,
the above equation is recursively inserted in itself getting a system of equations:

\[
\begin{pmatrix}
X_1 \\
\vdots \\
X_n
\end{pmatrix} = \begin{pmatrix} S_1 & A_2 S_1 & S_2 & & 0 \\
A_2 S_1 & A_3 S_1 & A_2 S_2 & A_3 S_2 & & \ddots \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
A_n \cdots A_2 S_1 & A_n \cdots A_3 S_2 & \cdots & & & S_n
\end{pmatrix} \begin{pmatrix} u_1 \\
\vdots \\
u_n
\end{pmatrix} - \begin{pmatrix} \bar{u}_1 \\
\vdots \\
\bar{u}_n
\end{pmatrix},
\]

\(n = 20\) is the number of turns.

or in short form:

\[x = C (u - \bar{u})\]

The following algorithms are based on the above equation.

**One-Step-Algorithm.**

One could think of an algorithm for steering as follows:

\[\omega = - C^{-1} x,\]

where a correction \(\omega\) for the steering magnets would be calculated from the measured beam-deviations \(x\). Theoretically this algorithm should converge if repeated often enough, but in practice noise caused by many sources prevent the algorithm from converging. Averaging of the data improves this only to some extent but takes too much time.

**Least-Square-Fit Method.**

An improved algorithm, which takes the noise much better into account, interprets the problem as a minimization-task of a statistical function. We choose a function, which describes the difference between the measured deviations \(x\) and the corresponding theoretical values \(x^{(\text{th})}\), calculated with a parametrized model of the microtron (analogous to a \(X^2\)-minimization).

\[\chi = (x - x^{(\text{th})})^T (x - x^{(\text{th})}).\]

This function is minimized by setting the derivative to zero. This leads to the one-step algorithm described before. In order to take more than one step into account a number of measurements is added:

\[\sum_{j=1}^{k} (x^j - x^{(\text{th})})^T (x^j - x^{(\text{th})}).\]

The index \(j\) indicates the number of the measurement. Minimizing in standard way with the optimal settings for the steering magnets \(\bar{u}\) as minimization parameters leads to

\[u^k = \frac{1}{k} C^{-1} \sum_{j=1}^{k} (Cu^j - x^j).\]

In order to cancel out the deviations between model and reality the steering magnets are set to the computed value for \(u\) after each measurement.

So we get:

\[u^{k+1} = \frac{1}{k} C^{-1} \sum_{j=1}^{k} (Cu^j - x^j).\]

\(k\) now indicates the iteration step. This iteration, where all data have the same weight, could already be used to optimise the beam-position, but it is desirable to supply new data with more weight than the older one. The simplest way to do this is the multiplication of the sum-elements with a power-series. The factor is \((1 - \varepsilon)\), where \(\varepsilon\) is a small number between 0 and 1. \(\varepsilon\) gives the rate of "forgetfulness" of the algorithm. So we find:

\[u^{k+1} = \frac{1}{k} C^{-1} \sum_{j=1}^{k} (1 - (1 - \varepsilon)^k (1 - \varepsilon) . (Cu^j - x^j).\]

The fraction at the left hand side of the sum is for normalization-purposes.

Programming the algorithm is very easy and doesn't need much computer-memory due to the simple form of the matrix \(C\).

**Practical Experiences.**

Fig. 2 shows photographs of the analog position- and intensity-signals of the monitors before and after optimisation.

Before optimisation the beam makes only a few turns and then disappears in the wall of the beam-pipe. After optimisation the beam gets through the whole microtron and the position signals are very small. This means the beam is close to its optimal position. The optimisation-program has been successfully used for about 1 year in microtron operation of the first stage. At present the beam-position-optimisation takes about one minute, but an optimized version of the program could reduce this time to a few seconds.

**Optimisation of Other Parameters.**

The speed of the optimisation-process depends on how accurately the system can be described by the mathematical model. There are certain parameters, which are not known well enough. For example in our microtron we didn't know the scaling of the position monitors (what deviation gives which signal) and due to technical reasons we didn't know the exact focal length of the solenoids.

So it was desirable to find a way to get these parameters by looking at the transversal behaviour...
of the beam.

For the solution of this problem the same procedure is used as before. The differentiated function must be solved for the parameter-vector we try to optimise. This only is possible with a linear dependence of the theoretical deviations on the parameters. As the focal length of the solenoids appears in the 40th power in our microtron-description it is necessary to make a first order Taylor-expansion of x and find the correct result by iteration of the expanded equation. For one step we get:

\[ \delta p = \frac{a(x)^T}{a \delta p} (x - x(th)) \]

where is the derivative of the theoretical data , and is the measured data. gives a correction of the parameter-vector, which improves the model for calculating .

For our problem we write the monitor scaling values and the focal length into the parameter-vector. Then we make two measurements with different steering-magnet-settings with the difference . In this case the microtron-behaviour can be described by:

\[ \Delta x(th) = C \Delta u \]

Now the function is minimized by repeated improvement of the model C with

\[ \delta p = \left[ \frac{\partial C}{\partial p} \right]^{-1} \left[ \frac{\partial C}{\partial u} \right] \Delta u \]

until becomes small. Fig.3 shows a picture of a measured and a computed signal after parameter-optimisation.

**Discussion**

We haven't had a problem with the TM11 mode because our structure doesn't support it.

If we were to build a whole array of these, we would feed them upside down, similar to a Cornell proposal.

We have started some studies on system stability to alignment errors and drifts. The only thing that looks serious is to create nondispersive beams in the linacs. The transverse optics appears to be quite insensitive, but the longitudinal is a serious problem. The beam dispersion has very low tolerances and requires a very sophisticated diagnostic system.

We have allowed for a factor of about 400 in emittance growth for synchrotron radiation loss.

We can steer the beam to within 0.5 mm of the linac center line; this is limited by the 6-bit accuracy of the steering coil readout and could be done better in principle.

We have only one bunch belonging to a given turn in the linac section at the same time. We find that the digital calculations compare well with the beam simulation method.

We calculate the extracted plasma sheath profile by assuming it follows the spherical curvature of the electrode; this is another case where the beam-simulation codes give you a check. We haven't done any calculations or experiments on the shape of the extraction electrodes inside the plasma chamber.

Although it would be desirable to determine the optimal steering-magnet settings and the other parameters in one procedure, it is not practical because this algorithm needs more computing time and due to strong intercoupling of parameters it takes much more time for it to converge. So we have chosen to keep both procedures separate and use the data of the one procedure as input for the other. Once determined, monitor-scaling and focal length are stable enough to be used as input for the beam-position-optimisation procedure for some time.
The design of high-perveance extractors is dominated by the space-charge forces in the beam and by the aberrations caused by fringing fields at the apertures. Computer programs were developed for various extractor geometries that incorporate these effects. Basically the approach was to find a Laplace solution, external to the beam, that matches smoothly to the Child-Langmuir potential distribution in a laminar-flow ion beam. The electrode shapes calculated are not unique but do provide the desired beam optics. The application of this technique to the development of electrodes for a 250-mA, 75-keV hydrogen-ion extractor is discussed. For this application spherical geometry was used. The beam obtained was of high quality, that is, low emittance and small angular divergence.

Explanation of Problem

In the design of high-perveance ion extractors for producing a high-quality beam for injection into a linac or radio-frequency quadrupole (RFQ), the geometry of the extractor electrodes becomes critical. For use in an RFQ, a high-quality beam might be defined as a circular ion beam with high current density, laminar flow, and relatively low energy. Also, it is highly desirable that there be a minimum variation of current density with radius. The use of a cusp-field ion source is most helpful in maintaining a uniform current density. To reduce the effective emittance of the extracted ion beam, it is necessary to maintain laminar flow and to minimize all nonlinear effects in the extractor field.

Assuming that the emission surface of the ion-emitting plasma resides at high voltage, then the aperture at ground potential, through which the accelerated ions must pass, is responsible for introducing a significant radially outward deflection to the emergent ions. This exit-lens effect is given by

\[ r' = r/f = \frac{k E_m r}{4\phi} \]

where

- \( r' \) = angular change in radians,
- \( E_m \) = maximum electric field at ground electrode,
- \( r \) = radius of ray at ground electrode,
- \( \phi \) = energy of ions at ground electrode,
- \( k \) = empirical correction to Davidson/Calbick equation (often \( \approx 1.8 \)),
- \( f \) = focal length of thin lens.

For high-current beams, this effect can easily lead to divergences of many degrees. A method extensively employed by designers of high-intensity electron guns and by workers with high-perveance ion extractors is to extract particles from an emitting surface in an initially spherically convergent geometry. Two beneficial effects ensue: (1) the diameter of the ground aperture is reduced, hence the maximum divergence angle is decreased; (2) the convergence angle can be selected to compensate for the divergent effect of the exit lens, giving a smaller diameter beam that emerges essentially parallel.

There are computer simulation codes such as SNOW\(^1\) that permit an evaluation of the feasibility of any selected electrode geometry. Although this method is generally preferable to the actual construction and trial-and-error testing of different electrode geometries, it can be somewhat awkward and time-consuming in practice. Electrolytic tank and other analog methods have been described in the literature\(^2\). What was desired, however, was a well-defined digital-computer technique that would accept as inputs the required ion beam parameters and produce as outputs the electrode profiles needed to produce this beam.

Approach

A series of computer programs has been written that aids in the design of extractor electrodes. Assuming that a uniform current density is available on a spherical emission surface, then a laminar-flow uniform-density spherically convergent ion beam can be produced if the potential variation within the accelerated ion beam varies only with the spherical radius. That is, the solution to Poisson's equation within the beam is given by

\[ \frac{\partial^2 V}{\partial r^2} + \frac{2}{r} \frac{\partial V}{\partial r} = -\rho/\varepsilon_0, \]

where

\[ \rho = \frac{J(r)}{2\pi r^2} = \frac{J_0 r_{c}^2 r^2}{2\varepsilon_0 \sqrt{2e(V_0 - V)}}, \]

- \( J \) = current density,
- \( r_{c} \) = radius of emission surface,
- \( J_0 \) = current density at emission surface, and
- \( V_0 \) = voltage at emission surface.

This differential equation can be solved numerically, by a fourth-order Runge-Kutta method. In practice, the design with the computer programs...
involves selecting current density, total current, ion mass and charge, extraction voltage, and a range of convergence half-angles to be considered. The code will calculate at selected intervals for convergence angles, the divergent effect of the exit lens, and required inner and outer radii for the ground and emission electrodes, respectively. The maximum electric field near the ground electrode is also determined. From this output, the designer may then select a series of parameters for input into the second program.

This second program will accept as inputs the various selected beam parameters and will output the cylindrical coordinates of the equipotentials (electrodes) that will establish the required potential distribution along the beam boundary. Several methods of formulation of this program were tried, but all techniques suffer from one basic limitation. The problem as posed is one of solving Laplace’s equation in a region where the potential is not specified at all points of a closed region.

Instead, the initial conditions are given only as specification of potential variation along the beam boundary, that is, along only a small fraction of the region’s boundary. Because this incorrectly or incompletely poses the boundary conditions for an elliptic differential equation, of which Laplace’s is one example, the resultant solution is often multi-valued and poorly behaved. Within a range of input conditions (namely for low perveance, that is, \( \gtrsim 1 \text{ u Perv} \)); this simple method can provide electrode profiles that produce a high-quality extracted beam.

Most commonly the following series was fitted to the potential distribution along the beam edge using a least-square routine.

\[
V(r, \theta) = \sum_{n=0}^{N} A_n r^n + B_n r^{-n-1}.
\]

It is assumed that the potential at any \( r \) and \( \theta \) is given by

\[
V(r, \theta) = \sum_{n=0}^{N} \left[ A_n r^n + B_n r^{-n-1} \right] \frac{P_n(\cos \theta)}{P_n(\cos \theta_0)},
\]

where the \( P_n(\cos \theta) \) are the Legendre coefficients of the first kind.

Another method based on the Langmuir-Blodgett (LB)* expression for the space-change limited flow between two spheres was developed to determine the electrical shapes for spherically convergent beam extraction. The potential distribution along the beam required is

\[
V = V_0 \exp \left[ \frac{4/3}{a/a_1} \right],
\]

where \( V \) is the LB potential and \( V_0 \) is the extractor potential.

Where \( G \) is defined by

\[
G = \ln(r/R_2),
\]

\( R_2 \) = the radius of the plasma emitting surface,

\( R_1 \) = the extractor electrode radius, for

\( r = R_1 \),

\( \alpha = \alpha_1 \).

The solution consists of development of the potential in the Laplace region outside the beam from the boundary conditions, given by the LB potential, and additionally that \( \frac{\partial V}{\partial \theta} = 0 \) for \( \theta = \theta_0 \); \( \theta_0 \) is the convergence angle of the beam. The form of the Laplace solution used is

\[
V(r, \theta) = A_0[P_0(\theta) + b_0 Q_0(\theta)]
\]

\[
+ \sum_{n=1}^{N} \frac{A_n}{r^n} \left[ a_{n-1} P_{n-1}(\theta) + b_{n-1} Q_{n-1}(\theta) \right],
\]

where \( P_n(\theta) \) and \( Q_n(\theta) \) are Legendre polynomials of the first and second kind, respectively. The \( A_n \) were determined using a Taylor series expansion of the LB potential:

\[
V(R) = \sum_{n=0}^{N} \frac{1}{n} \nu(n) (x-x_0)^n,
\]

where the derivatives \( \nu(n) \) were calculated from analytic expressions generated using the LB potential. This Taylor expansion is reduced to the Laplace form by using the binomial expansion of \((x-x_0)^n\); that is,

\[
A_n = \sum_{m=0}^{n} \frac{(-1)^m}{m!} \nu(m+n) x_0^{m+n},
\]

thus

\[
V(R) = \sum_{n=0}^{N} A_n \frac{R_0}{R} x_0^n.
\]

The coefficients \( a_n \) and \( b_n \) of Eq. (3) were determined from the boundary conditions \( \frac{\partial V}{\partial \theta} = 0 \), and also that the Laplace solution reduces to the LB potential at the boundary. Mathematically

\[
a_n P_n(\theta_0) + b_n Q_n(\theta_0) = 1,
\]

\[
a_n P_n(\theta_0) + b_n Q_n(\theta_0) = 0,
\]

for every \( n \). Thus

\[
a_n = G - 0.3 G^2 + 0.075 G^3 - 0.00143 G^4
\]

\[
+ 0.002161 G^5 - 0.0002679 G^6.
\]

\[
R_2 = 0.3 G^2 + 0.075 G^3 - 0.00143 G^4
\]

\[
+ 0.002161 G^5 - 0.0002679 G^6.
\]
The denominator in Eq. (7) is the Wronskian and does not vanish for \( 1 < \theta < \mu \).

Electrode shapes calculated using this method for a 75-kV, 250-mA, single-gap hydrogen ion extractor agree well with the shapes calculated using the least-squares method described in this paper. The method is probably limited to low-perveance beams \((<1 \text{ Perv})\) and to systems described adequately by the LB potential. Attempts to generalize the approach to include the effect of the exit lens on the potential distribution along the beam were unsuccessful.

Efforts are continuing on an extension of a method described by Harker, which should avoid the ill-conditioning by converting the elliptic differential equation into one of hyperbolic form by a suitable conformal mapping and use of an imaginary third coordinate axis. It is hoped that computer programs eventually will be developed whose validity is completely general.

Acknowledgments

The authors wish to note the earlier work done by D. W. Mueller on spherical extractor design, which is reported in another paper in these proceedings. We would also like to thank those who assembled the extractors for testing--especially E. A. Meyer and B. A. Sherwood.

References


ION SOURCE DEVELOPMENT AND INJECTOR DESIGN FOR ZEBRA

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Summary

The requirement for high and variable current in ZEBRA, and the acceptance limits (on both energy and phase space distribution) of the RFQ place stringent demands on the injector design. For variable current, the ion source extraction voltage must be varied over a wide range (I = y^3/2) to maintain a matched beam, however the RFQ has a limited range of injection energy. The 75 keV injection energy made necessary by current limits in the RFQ will require that care be taken to ensure reliability. Beam spill limits in downstream structures and RFQ beam dynamics require minimal beam halo and precise control of the phase space distribution. Following a discussion of these problems, and the approaches being taken at Chalk River to solve them, a conceptual design for the ZEBRA injector is presented.

Introduction

The injector for ZEBRA^1 must provide a proton current variable from less than 60 mA to more than 375 mA with less than a 15% variation in output energy. The beam is to have very low halo (< 2%) and should "uniformly" fill a defined ellipse in phase space throughout the full current range. Space charge limits in the RFQ^1 have forced the injector voltage to 75 kV from the original 50 kV value. This higher voltage increases the potential for damage by high voltage transients caused by sparking. To produce an injector with the required performance, an extensive development program is underway at Chalk River. This program covers development of plasma sources and extraction columns, studies of the transport of high-current space charge neutralized beams, design of injector packages and control systems, and development of beam simulation codes.

Ion Source and Injector Development

Two facilities are currently in operation. The Ion Source Test Stand (ISTS) is being upgraded to provide 900 mA at 80 kV. In addition a 50 kV, 100 mA supply will soon be available for development of tetrode extraction columns. The main feature of ISTS is an Emissance Measuring Unit (EMU) with a dynamic range of ~ 10^5. Power dissipation in the EMU dump limits beams to ~ 8 kW for typical beam sizes (~ 80 mm dia). However a straight through dump can handle 35 kW and work is underway to design a 75 kW dump. The Injector Test Experiment (ITE) can provide 750 mA at 50 kV. The ITE beam line has a 60° bending magnet with adjustable entrance and exit angles and a simple pepperpot-plate emittance device in the proton beam line. This facility will be used to commission injector packages (as for the RFQ1 experiment) and for beam transport studies and development of beam diagnostics.

A desirable plasma source would provide a uniform (± 2.5% over a 30 mm diameter extraction area) high current density (~ 400 mA/cm^2) cool (T_e < 0.2 eV) plasma with high proton percentage (~ 90%) and would have high arc and gas efficiency. Component lifetime should give over 500 hours of full power operation with no significant degradation in performance. At Chalk River, a program is underway to develop such a source. Initial development has been done on a duoPIGatron source with a plain PIG region. The duoplasmatron feed provides a good environment for either a standard oxide cathode or a refractory compound hollow cathode and provides a good electron source. The magnetic field in the PIG region can be controlled to optimize operation over a wide current range. A current density of 445 mA/cm^2 with acceptable uniformity over a 20 mm diameter extraction array (derived from extracted beam measurements) can be achieved with a 14 A, 100 V arc. For a properly tuned source, noise levels are less than 3%. With this source, proton fraction is approximately 45% at full current. This fraction is unacceptably low. To facilitate parametric studies and optimization, a new source has been designed and fabricated.

Studies of duoPIGatron sources with both axial- and orthogonal-cusp PIG regions have begun. Initial results indicate that, for the beam current range of interest, these sources have lower arc and gas efficiency than the simple duoPIGatron. To provide more basic measurements on the source plasma and to provide better input values for codes such as BEAM^2, a system is being constructed to traverse double floating Langmuir probes across and into the source plasma and to sweep these probes to give values for electron density and temperature. A spectrum analyzer is being used to study the noise spectrum of the source plasma and to help determine the mechanisms producing the noise.

The extraction column must not only provide a high-brightness, low halo beam, but it must also operate reliably. Catastrophic breakdowns leading to complete loss of beam are not the only problem - small "tics" in the column will yield, momentarily, a poor quality beam that increases beam spill in the downstream part of the accelerator. For good quality beams, the geometry in the beam region is extremely critical. Small aberrations that would not be noticed in most accelerators are intolerable in a high current beam. The best approach to electrode design is a) calculation of the optics of a proposed design using a simulation code like BEAM, b) modification of the design to reduce aberrations, and c) experimental verification of the design by emittance measurements. This technique has yielded designs that provide beams with 2% or less halo and very high brightness.
Most of the work to date has been done on triode columns that are more appropriate for beams of up to 50 keV. However, with the increased energy required for ZEBRA, tetrode columns are being considered. So far only computer simulations of tetrode columns have been performed, however a power supply that will permit testing of tetrode columns is on order.

Experience at Chalk River, and elsewhere, has identified a number of factors affecting reliability. The major factor is the generation of x-rays by backstreaming electrons, especially as voltages increase above 40-50 kV. Two approaches can be taken to ameliorate this problem. Generation of backstreaming electrons can be reduced by a) reducing beam spill on electrodes, b) reducing the gas pressure in the column and c) provision of effective suppression of electrons from the beam plasma. The deleterious effect of the x-rays can be reduced by proper shielding of ceramic insulators and by proper choice of electrode materials. For example, on the present extraction column, use of a molybdenum-faced accel electrode increased the usable voltage by up to 50%, and the extractable current by 75%. Proper cooling of electrodes is also important - present designs use a conduction cooled accel electrode designed to ensure good cooling, and an internally cooled ground (decel) electrode. Thick copper walls in the electrodes provide not only improved cooling, but also good x-ray shielding.

Transport of high-current, high-current-density, space-charge neutralized beams is a major concern for ion sourcers. The deleterious effects on beam emittance of magnetic transport elements are being studied at Karlsruhe and Darmstadt. At Chalk River large amplitude (> 20%) modulation at ~ 100 kHz on a drifting beam was observed when the extraction voltage was varied 10% from the proper value. One of the required diagnostics in a high current injector will be a spectrum analyzer - for both beam generated and plasma-source-generated noise. Development of non-destructive beam diagnostic devices, for example J.S. Fraser's tomographic scanner, is well underway. However the processes in the beam, especially a beam comprised of many beamlets, are not well understood. Further development of non-destructive beam diagnostics is required before significant headway can be made in the study of beam transport.

The ZEBRA Injector

In addition to the considerations above, three additional requirements for the ZEBRA injector are receiving special attention. The first is the requirement for a 10-fold variation in output current within a limited energy range. Since the matched curve for an extraction column varies as $V^{3/2}/m^{1/2}$, and current variation by scraping off part of the beam leads to a large halo growth, other techniques must be used. One possible solution would be to use a biased RFQ, however this would add to problems in the RFQ design and to difficulties with matching to the drift-tube-linac acceptance. Another possible solution would be use of a two-stage injector. This requires two high-power, high-voltage power supplies, one of them floating. Furthermore the injector becomes much more complex and the transport elements required between the two columns may lead to unacceptable emittance growth. The proposed design uses a single stage injector with two tricks of ion sourcers to provide the required current variation within given voltage constraints. If excess gas is fed to the plasma source, much of the $H_2^+$ is converted to $H_3^+$. This not only reduces the proton current, but also increases the effective mass of the extracted beam, reducing the matched current at a given voltage. This secondary effect could be further enhanced by feeding a small amount of a heavier gas, such as argon, to the source. Preliminary studies using excess hydrogen indicate a reduction in proton current by a factor of four should be achievable using this technique. A further reduction by a factor of 2-3 can be achieved by using a neutralizer tube between the source and magnet. The neutralizer converts ions to neutrals that will pass through the mass separation magnet unaffected. Emittance measurements on the ion fraction of such a neutral beam show that the emittance is not significantly degraded by scattering - in fact the effects of scattering seem to be more than compensated for by reduced space charge blow-up. However, alignment is critical as any scraping by the neutralizer tube leads to an increase in halo.

Beam dumps are a second area of injector design receiving special attention. The ion source produces a 50-60 kW beam. With reasonable care in controlling beam size, this leads to power densities in the range of 1-2 kW/cm². This power density can be handled by properly designed copper swirl-tubes as used on ITE. They are easy to fabricate, have a reasonable safety margin, and have proven to be trouble-free. It may be necessary to plasma spray the swirl tubes with a thin layer of molybdenum or tungsten to reduce erosion of the copper by sputtering and other processes.

The third area is associated with damage from spark induced transients. No matter how well an extraction column is designed, it will spark eventually. When it does, all nearby electronic equipment suffers. Extensive shielding, filtering and transient suppression will only reduce the damage, not prevent it. On present systems, the power supplies in the high voltage dome are the most affected. Computer data acquisition and control systems, as will be required on the ZEBRA injector, are especially sensitive to damage and perturbation by high voltage transients. The solution to this sensitivity is to put as much of the electronics as possible at ground potential. Because the power supplies for the source are SCR regulated, most of the supply can be at ground by replacing the output transformer in the supply with a high voltage isolation transformer (see Fig. 1). This has the added advantages of reducing the amount of telemetry across the high voltage interface and of keeping the links between the computer and the power supplies at ground. Cost of the isolation transformer is increased but the total system cost will likely be reduced if only in the costs of required spare parts. The high voltage dome will be more compact, especially as all the
gas handling system, except the metering valve, will also be at ground. The only components in the dome would be passive filters on the outputs of the power supplies, and a small number of V/f converters to telemeter source parameters to ground. If required, a rugged active crowbar for the arc power could be installed.

Figure 2 shows the conceptual design for the injector. The plasma source is an orthogonal cusp DUPIGatron with a lanthanum hexaboride hollow cathode. The tetrode extraction column has either seven or thirteen apertures - the number will depend on the required uniformity in illumination of the phase space ellipse. Beamlet steering by either aperture displacement or electrode curvature will be used to reduce the effective emittance of the multi-aperture beam. Gross alignment is achieved by a gimbal below the source; fine steering can be achieved by coils wound on the upper end of the 1 m long neutralizer tube. Mass separation is achieved by a 30 cm radius, n=1/2, shaped-pole double-focusing magnet similar to that on the FMIT injector. Separate swirl tube dumps are provided for the straight through beam and the H²⁺ and H³⁺ components. Most of the remaining vacuum chamber is protected by water cooled liners to reduce heating from stray beam. Vacuum valves are installed just below the ion source (to reduce downtime for source changes and maintenance) and at the exit of the injector. Viewports are provided for optical measurement of beam size, position and intensity profile. Vacuum pumping is provided by a combination of turbomolecular and cryopumps. In spite of massive oil contamination on ITE, no deleterious effect on ion source performance has been seen. However, there are concerns about the effect of oil vapor in the RFQ. At the exit of the injector, there are a baffled conical tube to aid in differential pumping of the RFQ, a plugging swirl-tube dump to permit run-up and operation when the RFQ is unavailable, and a weak solenoidal electron trap to decrease perturbation of space charge neutralization by fields in the RFQ. Diagnostics consist of combined tomographic and optical beam size and position scanners at the exit of the ion source and near the injector exit. Simple spectrum analyzers are employed on the beam dumps. A full computer control system for automatic run-up and for data logging is included.

This design, with modifications prompted by the development programs underway at Chalk River and elsewhere, should satisfy the requirement for the ZEBRA injector. A test of these ideas will be carried out on the 50 keV, 110 mA (H¹⁺) RFQ1 injector to be operating in early 1983.

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References

Discussion
The 100-kHz modulation that we see when we scrape the beam is not present when the scraping iris is not inserted. We look at the entire beam hitting the dump at the end in this observation. We have bent the beam a little so part goes on the dump and part on a protective plate; again, without the iris, we don't see the modulation. We also put an antenna in and didn't see it. There are a lot of things in the short transport that are still not understood.
THE IMAGE DISPLACEMENT INSTABILITY IN RADIAL LINE ACCELERATORS

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Introduction

The radial line linear induction accelerator is a viable method for producing short pulse, high current, high energy electron beams. In the radial line accelerator, pulsed power technology is applied to an electron beam in series by a linear array of modules. The high voltage breakdown problems associated with pulsed power are then reduced because the electron beam is the only component affected by the full accelerating field. The primary difficulty encountered in producing intense beams from such linacs is beam stability.

We are interested in current levels useful for a variety of applications, including plasma heating, free electron lasers, simulation of radiation effects, and collective ion acceleration. In particular, we note that the combination of high current and energy have been demonstrated to be extremely desirable for collective ion acceleration.

The instabilities in the accelerator fall into several categories. For azimuthal mode number \( m > 1 \), the diocotron and resistive wall instabilities occur. Nonlinear effects due to beam drift motion occur for all \( m \) values. Zero frequency oscillations and the Klystron instability are \( m = 0 \) effects.

In this work we confine discussion primarily to the \( m = 1 \) instabilities induced by an accelerating (or nonaccelerating) gap in the drift tube, the beam breakup instability and its zero frequency analog, the image displacement instability. These instabilities are particularly dangerous in high current accelerators where they can rapidly amplify an initial small transverse displacement of the beam to such an extent that it strikes the drift tube wall.

Below, a recently constructed radial line accelerator is briefly described. The beam breakup and image displacement instability theories are then presented, and sample calculations indicating their rate of growth in various cases are given. We have experimentally observed the image displacement instability, and results from the experiment as well as from corresponding three-dimensional numerical simulations are discussed.

The RADLAC Accelerator

Figure 1 is a schematic of the 10 MeV, 30 kA RADLAC accelerator developed jointly by the Air Force Weapons Laboratory and Sandia National Laboratory. The center conductor of each line is charged by a Marx generator to 3 MeV. When a cavity switch is closed, the full voltage appears across one side of the line only (for 12 ns in RADLAC). Sequentially triggering the radial lines accelerates the passing beam to its final high energy.

In order that the beam current be well below the spacecharge limit in the accelerator drift tube, the electron beam is injected at 2 MeV and with an annular crosssection. Focusing is provided by a solenoidal magnetic field, \( B_z = 10 \text{ kg} \).

Instability Theory

Several simplifying assumptions are invoked to reduce the beam transverse dynamics to a tractable form. Each axial segment of the beam is assumed to displace rigidly in the transverse direction, and the displacement is taken to be small compared to the drift tube radius, \( b \). In turn, the drift tube radius is much smaller than the betatron wavelength, \( \lambda_c = 2\pi \gamma m c^2 \). The beam axial velocity is \( v = c \), with \( \gamma = (1 - v^2/c^2)^{-\frac{1}{2}} \gg 1 \). Any axial relative displacement of the beam segments is ignored.

With \( \xi = x + iy \), the equation of transverse motion for the beam centroid is found to be

\[
\frac{a}{ \partial z} \frac{a}{ \partial z} \xi - i \omega_c \frac{d}{ \partial t} \xi = \frac{2I}{b^2 m c^2} \left( \frac{e}{2} \xi + \frac{ieB}{c} \right) + \sum_j \kappa(z - z_j) \left( \frac{21}{mb^2 c} \xi + \frac{ieB}{c} \right)
\]

(1)
Note that $B_j$ excludes the image displacement portion of the magnetic field, which is the $2\mu_0 m b^2 c$ term. $B_j$ is the transverse magnetic field of a single TM10n mode of the accelerating cavity in the $j$th gap at frequency $\omega$ and quality factor $Q$. The gap width is $t$. The growth of $B_j$ can be derived from a cavity normal mode relation with the source resulting from an off-axis beam:

$$\frac{d^2 B_j}{dt^2} + \frac{\omega}{Q} \frac{d B_j}{dt} + \omega^2 B_j = i \frac{Z_j \omega^2 \xi(z_j)}{Q \kappa c}$$

We note that both $\xi(z_j,t)$ and $I(t)$ have Fourier components at frequency $\omega$.

Several constants are built into the structure of equations (1,2). The image displacement force constant $f$ measures the ratio of the transverse force in the gap to the transverse electric force in the drift tube. It is typically of order $-1/2$. The accelerating gaps do not have to be resonant for reasons of efficiency, in contrast to those of RF linacs. However, the requirements for voltage standoff, power feeds, etc., result in enough wave reflections to justify modeling the gap regions as a lossy cavity. Thus, $Z_j$ (the cavity transverse impedance) and $Q$ must be found. Given these constants and the initial time dependence of $I$ and $\xi$, a complete linear description is defined.

We must estimate the growth of these instabilities in order to design future accelerators. To do this, equations (1) and (2) have been integrated numerically for a few sets of idealized conditions.

The image displacement results for a 100 kA beam are summarized in Table I. The effect of a small change in focusing magnetic field can be very large in terms of instability growth, illustrated by cases 1-5 and 6-7. In all cases, the effect of acceleration is to reduce growth. Even with acceleration, however, a resonance in growth as a function of $B_z$ is observed in case 6. Case 2 illustrates a prohibitively large growth of 1600 $(2.1 \times 10^7)$ for 10 nonaccelerating gaps.

Cases 1-5 are without acceleration, and cases 6-10 include acceleration at the gaps. $\Gamma$ is the growth for ten gaps.

<table>
<thead>
<tr>
<th>Case</th>
<th>$B_z$ (kg)</th>
<th>$(t/b^2)$</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>0.8</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>19.88</td>
<td>0.8</td>
<td>1600.0</td>
</tr>
<tr>
<td>3</td>
<td>19.74</td>
<td>0.8</td>
<td>340.0</td>
</tr>
<tr>
<td>4</td>
<td>19.01</td>
<td>0.8</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>19.47</td>
<td>0.8</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>20.0</td>
<td>0.8</td>
<td>470.0</td>
</tr>
<tr>
<td>7</td>
<td>20.46</td>
<td>0.8</td>
<td>48.0</td>
</tr>
<tr>
<td>8</td>
<td>20.0</td>
<td>0.29</td>
<td>4.5</td>
</tr>
<tr>
<td>9</td>
<td>19.83</td>
<td>0.29</td>
<td>7.3</td>
</tr>
<tr>
<td>10</td>
<td>20.46</td>
<td>0.29</td>
<td>1.6</td>
</tr>
</tbody>
</table>

$\Gamma$ is the total instability growth for 10 gaps relative to the initial displacement. Cases 4-7 include acceleration effects.

Table II. Calculated Beam Breakup Instability Growth

<table>
<thead>
<tr>
<th>Case</th>
<th>$B_z$ (kg)</th>
<th>$Z_j/Q$ (ohm)</th>
<th>$T_R$ (cm)</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>20</td>
<td>10</td>
<td>350.0</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>20</td>
<td>20</td>
<td>200.0</td>
</tr>
<tr>
<td>3</td>
<td>20.0</td>
<td>40</td>
<td>10</td>
<td>350.0</td>
</tr>
<tr>
<td>4</td>
<td>20.0</td>
<td>20</td>
<td>10</td>
<td>350.0</td>
</tr>
<tr>
<td>5</td>
<td>20.0</td>
<td>40</td>
<td>10</td>
<td>350.0</td>
</tr>
<tr>
<td>6</td>
<td>19.83</td>
<td>20</td>
<td>10</td>
<td>4.2</td>
</tr>
<tr>
<td>7</td>
<td>19.83</td>
<td>20</td>
<td>10</td>
<td>3.1</td>
</tr>
</tbody>
</table>

$\Gamma$ is the total instability growth for 10 gaps relative to the initial displacement. Cases 4-7 include acceleration effects.

Image Displacement Experiment

An experiment has been performed in a nonaccelerating structure to investigate the image displacement effect. It addresses several of the issues not included in the simple theory of the last section, particularly short wavelength effects. A side view of the experimental structure is shown in Figure 2. Nonaccelerating gaps were used in the experiment so that the size and cost of the experiment could be minimized.
The foils shown in Figure 2 suppressed competing instability effects, including beam breakup and zero frequency radial oscillations. The $m = 1$ magnetic field penetrates through the foil in less than a nanosecond, and the defocusing electric field is increased by a factor of $-2$.

In a periodic configuration the momentum changes due to each gap will always add in phase for $\lambda \sim L$ where $L$ is the distance between gaps. Thus, if we vary $\lambda$ we expect to see resonances for $\eta \lambda = L$ where $n$ is an integer. The obvious method of diagnosing the experiment is the use of magnetic loop pairs. However, for the parameter regime $\lambda \sim b$, these understate the beam offset. Witness plates (i.e., the damage of a target in the beam path due to the beam) are a less accurate alternative method. They have the disadvantage of registering a pattern which is a complicated function of the beam energy deposition. A particular difficulty of witness plates is that they may not detect differences between the magnetic and geometric beam centroids.

The beam offset as a function of magnetic field for the geometry of Figure 2 is shown in Figure 3, where the dots depict the experimental points, and the solid curve is the linear theory corrected for finite gap effects and spatial transients.

The points attached to a vertical line are of particular interest -- they indicate that the beam was so poorly defined that only a lower bound on the offset was available. This, we believe, is the first experimental observation of the instability.

A second effect was observed with magnetic probes. The beam drifts in $\eta$ through the gaps at a frequency $-(B_0(b)/B_2)(c/b)$, where $B_0(b)$ is the beam self-field measured at the drift tube wall.

An experimental configuration similar to that of Figure 2 was studied with the three-dimensional particle-in-cell simulation code IVORY. Typical code results are shown in Figure 4 for an axial magnetic field somewhat lower than achievable in the experiment. The plots of particles in the $r-z$ and $\eta-z$ planes are shown. The $\eta-z$ plots indicate the particle drift while the three $r-z$ particle streamlines indicate the resonant particle betatron motion, and mixing of the azimuthally symmetric and image displacement oscillations. We anticipate that this new code will be a powerful tool in the study of collective particle effects in intense beams.

Acknowledgement
This research was supported by the U.S. Air Force Weapons Laboratory. We are indebted to R. B. Miller for valuable discussions.

References
Summary

A severe problem in the design of double sided microtrons (DSM) which could supersede the race track microtron (RTM) in the 1-2 GeV range mainly because of its smaller magnet weight is the strong vertical defocusing in the bending magnets. Several possibilities to overcome this difficulty are discussed and a special beam optical design making use of the large longitudinal stability of the DSM is presented.

Introduction

The acceleration scheme of the double sided microtron (fig.1) has been mentioned by several authors many years ago but it was not considered to be promising because of its extremely critical beam optics. Because of the demand for a cw accelerator in the 1 GeV range its properties were recently investigated in more detail and a possible way to overcome the beam optical difficulty was shown 1. After that the DSM has been proposed in a different design as a 2 GeV cw electron accelerator 2.

Fig.1 Scheme of DSM and RTM

General Properties

In tab.1 the general properties of the DSM and RTM are summarized. The bending system of the DSM originates from the 180° magnets by cutting two 90° segment magnets from each of them which leads to a reduction of the active pole face area by a factor \((\pi - 2)/\pi = 0.36\) and consequently to a large saving of iron. Therefore, the end energy of a DSM is about twice the end energy of the RTM for the same magnet weight. Because of the coherence condition and the geometry of the system the energy gain per linac and the distance between successive turns is increased by the factor \(\pi/(\pi - 2)\) for the DSM. By the fact of having two accelerators on the circumference the longitudinal stability is considerably larger. While the horizontal beam transformation in the segment magnets is simply parallel to parallel a severe problem, however, is given by the strong vertical defocusing in the fringe fields (fig.2). Since the DSM would be a relatively large device with about 20 m linac length stable particle motion seems not to be possible with focal length below about 1 m. As one can see from the diagram in fig. 2 acceleration would therefore only be possible with an uneconomical high injection energy of about 1300 MeV.

Tab.1 Main parameters of DSM and RTM

<table>
<thead>
<tr>
<th></th>
<th>DSM</th>
<th>RTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>pole face area ((R_p = pole radius))</td>
<td>(2(\pi - 2)R^2_p)</td>
<td>(2\pi R^2_p)</td>
</tr>
<tr>
<td>end energy for a total iron weight of 320 t</td>
<td>1.5 GeV</td>
<td>0.8 GeV</td>
</tr>
<tr>
<td>distance between subsequent turns ((m = 1; \lambda = 12.24 cm))</td>
<td>(m\lambda/(\pi - 2))</td>
<td>(m\lambda/\pi)</td>
</tr>
<tr>
<td>energy gain per turn ((B = 1.5 \text{ tesla}; \lambda = 12.24 \text{ cm}; m = 1))</td>
<td>48.3 MeV</td>
<td>8.8 MeV</td>
</tr>
<tr>
<td>first order longitudinal stability range for the synchronous phase ((m = 1))</td>
<td>(-51.9^\circ &lt; \phi &lt; 0^\circ)</td>
<td>(-32.5^\circ &lt; \phi &lt; 0^\circ)</td>
</tr>
<tr>
<td>transverse beam optics</td>
<td>vert.defoc.</td>
<td>hor.neutral</td>
</tr>
</tbody>
</table>

Reduction of Vertical Defocusing

A modification of the field distribution in the 90° segment magnets for a reduction of vertical defocusing leads in general to a non linear relation between path length and particle momentum (fig. 3). The coherence condition which requires a path length increase of one (or several) wavelength \(\lambda\) from linac to linac for successive turns can nevertheless be maintained if the momentum gain \(\Delta p\) varies in the right manner during the acceleration. The possible variation of \(\Delta p\) is determined by the allowed range of the synchronous phase \(\phi\). In a DSM longitudinal oscillations are stable as long as \(\phi\) moves between \(0^\circ\) and \(-51.9^\circ\) (the strong instability around \(\phi = 1/3\) is not important if the synchrotron frequency changes continuously in this region). Therefore, \(\Delta p\) and with it the longitudinal dispersion \(\Delta s/\Delta p\) may vary between 100% and 63%, in
Fig. 3 Possible variation of the longitudinal dispersion in a DSM principle, during the accelerating process. If the variation is smooth enough one can find input phase and input energy combinations for which the synchronous phase varies slowly and without oscillations.

In fig. 4 a, several two-dimensional field distributions are shown and the vertical focusing strength as well as the longitudinal dispersion as functions of the particle momentum \( p \) obtained from a ray tracing program are given. For the field curves 1 and 4 both with reverse field stripe and field gradient the focal length is always larger than 1 m for energies above 100 MeV. Of course, the longitudinal dispersion is no more constant so that a lower limit for the injection energy for the distribution 2 (without gradient) and limited energy ranges for the curves 1, 3 and 4 are defined.

Vertical beam optics can be further improved by adding a second reverse field stripe at a certain inclination angle in respect to the main pole edge which has more effect at medium energies (fig. 4 b). Unfortunately, the variation of \( \Delta s/\Delta p \) is relatively large in this case so that the possible energy range of the DSM is significantly reduced. Moreover, additional effort is needed in the horizontal plane to correct for the bending angle and for the angular dispersion.

The use of pole face rotations on the entrance and exit of the 180° bending systems represents another very effective possibility for the reduction of vertical defocusing without influence to the longitudinal dispersion. As one can see from the diagrams in fig. 4 c, however, the resulting horizontal focusing is rather strong and additional measures are required for horizontal focusing and achromatic transformation. On the other hand, it would be obvious in this case to maintain a constant betatron frequency in the horizontal plane also.

Beam Optical Design Example

In fig. 5 the scaled scheme of a 1.3 GeV-DSM and its beam optical properties obtained from a ray tracing simulation program are represented. The rest defocusing of the two-dimensional field distribution 1 (fig. 4 a) is compensated by a

---

**Fig. 4** Focusing strength and longitudinal dispersion as functions of the particle momentum for different field configurations \( (B_0 = 1.24 \text{ Tesla}) \)

---

**Fig. 5** Scaled scheme of a 1.3 GeV-DSM and its beam optical properties.
Conclusion

The problem of beam focusing in a DSM may be solved provided that the injection energy is not too low and the tolerances in the optical elements can be kept sufficiently small. The acceptance is much larger than the emittance to be expected from a RTM-injector. However, the problem of alignment and setting of the numerous quadrupoles is not yet discussed and would, at least, require a powerful beam diagnostic and control system. Further attention must be paid to beam diffusion effects by quantum synchrotron radiation and field imperfections.

References


Fig. 5 Scaled scheme of a 1.3 GeV-DSM with phase space areas at input and output energy

done only with two singulets in the middle of each linac. The vertical acceptance is limited by geometrical aberrations in the segment magnets to about 0.8 π mm mrad at 176 MeV. The influence of chromatic aberrations is relatively small so that betatron oscillations are stable for the phase space area shown even for Δp = ± 0.5 MeV/c. Due to the reverse field and the field gradient in the dipoles the synchronous phase is shifting from - 100° to - 400° during the acceleration with only a small change in the longitudinal acceptance area.
RESISTANCE DRIVEN BUNCHING MODE OF AN ACCELERATED ION PULSE*

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Summary

Amplification of a longitudinal perturbation of an ion pulse in a linear induction accelerator is calculated. The simplified accelerator model consists only of an applied field ($E_0$), distributed gap impedance per meter ($R$) and beam-pipe capacity per meter ($C$). The beam is treated as a cold, one-dimensional fluid. It is found that normal mode frequencies are nearly real, with only a very small damping rate proportional to $R$. This result is valid for a general current profile and is not restricted to small $R$. However, the mode structure exhibits spatial amplification from pulse head to tail by the factor $\exp(RCLv_0/2)$, where $L$ is pulse length and $v_0$ is drift velocity. This factor is very large for typical HIF parameters.

Introduction

An induction linac driver for HIF involves the transport of an intense ion pulse through several kilometers of accelerator structure; this is long enough that the pulse is strongly coupled to itself via its interaction with the vacuum pipe and acceleration gaps. A longitudinal bunching instability is intrinsic for this system, and unless suppressed by appropriate design it will generate an unacceptably large momentum spread.

The field in the gaps may be considered to act continuously and is programmed to axially confine as well as accelerate the beam. Spontaneous bunching is opposed by the local increase in space charge, and mode growth is not expected from this interaction alone. The resistive character of the gap impedance is destabilizing, and application of the growth rate formula derived for circular machines gives an exponentialation length of only hundreds of meters for typical parameters. That treatment, however, is not applicable to a finite length pulse in a straight system since the growing wave moves backwards in the pulse and is expected to convert to a decaying forward wave at the pulse tail. Qualitatively, we expect a distorted mode structure, with amplitude which is large in the tail and small in the head. This may be viewed as the result of a balance between resistive drag on the mode peaks and repulsion by the excess space charge in the tail. Momentum spread on the order of 1% may be sufficient for stability, but even this amount may be too large to meet final focusing requirements.

System Model

To avoid confusion about currents all quantities are defined in the laboratory frame. The pulse line density is $n(t,z)$ and it drifts in the $+z$ direction with velocity $v(t,z)$. Since thermal effects are neglected the (non-relativistic) equations of motion are

$$\frac{dn}{dt} + dnv/dz = 0,$$

$$\frac{dv}{dt} + vdv/dz = qE/M,$$

(1)

(2)

and the electric field consists of applied and beam induced components:

$$E + E_n - Rqnv - (q/C)n/dz = 0.$$  

(3)

As mentioned, $R$ and $C$ are the continuous representation of the effect of gaps and pipe. The capacity is taken to be that of the co-axial beam of radius $a$ and pipe of radius $b$:

$$C = 4\pi\epsilon_0/[2\log(b/a) + 0.5].$$  

(4)

For simplicity the unperturbed velocity $v_0$ is held constant and $E_n$ is just the field required to cancel the field induced by the unperturbed current profile, i.e. the net unperturbed field vanishes.
The assumed parameters are (C.S.W.):
\[ R = 200 \Omega /m, \beta/a = 1.5, N = 200 \text{Hps}, q = 2e, L = 20 \text{m}, \]
and total ion number \( N = 10^{15} \). Velocity is taken to be the final value \( v_0 = 0.3c \), so we have the typical HIF parameters: \( T = 9.06 \text{ GeV}, W = 1.45 \text{ MJ}, I = 1.44 \text{ kA} \). In order to reach the required power on the pellet (~100TW), the pulse must be subdivided or compressed by a factor of \( x = 15 \); this would be done subsequent to acceleration and is not considered here.

It is important to note that there is some latitude in the selection of parameters. The value \( v_0 \) is fixed within a factor of two by geometry, and \( v_0 \) is similarly restricted by the target gain requirement. Considerable reduction of \( L \) is possible, but at increased cost since space charge density is thereby increased. In principal \( R \) can be reduced, however the driver efficiency is also reduced. To see this we note that in the simplist model of the gaps, efficiency is 100% if the impedance is matched to the current and accelerating gradient, i.e. if
\[ R = E_0 / I = R_m \quad \text{(5)} \]

For the typical value \( E = 10^6 \text{V/m} \) we have \( R = 949 \Omega /m \) at \( I = 1.44 \text{ kA} \), and higher values at lower \( I \). The assumed value \( R = 200 \Omega /m \) (which is used only at the final current) is therefore a moderate mismatch. More generally the efficiency (for the simple gap model) is
\[ \eta = 4(R/R_m) \left( 1 + R/R_m \right)^{-2} \quad \text{(6)} \]

with value \( \eta = 0.695 \) for the assumed parameters. Since non-zero \( R \) drives the bunching mode it may be desirable to consider a mismatch as great as \( R = 10 \), which yields \( \eta = 0.331 \).

It is very convenient to make use of the variable
\[ x = z - v_0 t \quad \text{(7)} \]

which measures distance with respect to the pulse tail \( (x=0) \), with the head at \( x=L \).

We use \( x \) and \( t \) as the independent variables of the calculation - this has the appearance of a Galilean transformation, but current is still defined in the laboratory frame. Eqn (3) yields for given profile \( n_0(x) \)
\[ E_n(x) = R n_0 v_0 + (q/C) \frac{dn_0}{dx}. \quad \text{(8)} \]

Perturbed System

We consider a longitudinal perturbation \( n = n_0 + \Delta n, \Delta n = \delta n \), \( v = v_0 + \Delta v, E = \delta E \). Then using the variables \( (x,t) \), eqs (1-3) yield
\[ \delta n/\delta t = -\Delta n/\delta v/\delta x, \quad \text{(9)} \]
\[ \delta v/\delta t = q \delta E/M, \quad \text{(10)} \]
\[ \delta E = -R q (v_0 \delta n + n_0 \delta v + q/C) \delta n/\delta x. \quad \text{(11)} \]

The analysis is simplified by using the Lagrangian displacement variable \( \xi(t,x) \):
\[ \delta v = (\partial \xi / \partial t) x \quad \text{(12)} \]
and this is the point of departure from previous work. Eqns (9-11) become
\[ \delta n = -\partial_0 \xi / \partial x, \quad \text{(13)} \]
\[ \partial_0^2 \xi/\partial t^2 = q \delta E/M, \quad \text{(14)} \]
\[ \delta E = R q (v_0 \partial_0 \xi / \partial x - \partial n_0 / \partial t) + (q/C) \delta^2 n_0 \xi / \partial x^2. \quad \text{(15)} \]

Eliminating \( \delta n \) and \( \delta E \), and grouping dimensional factors, we have
\[ \frac{1}{v_0} \frac{\partial^2 n \xi}{\partial t^2} = \eta \frac{n_0 \xi}{\pi} \left[ \frac{1}{2} (\partial^2 - 1) \frac{q \partial_0 \xi}{\partial x} \frac{\partial^2 \xi}{\partial x^2} \right]. \quad \text{(16)} \]

Here \( \eta = N/L \) is the mean density and we define
\[ \epsilon^2 = (q^2 e_0 M v_0^2 C) = 2.24 \times 10^{-5} \quad \text{(17)} \]
\[ r = (RCv_0)^{-1} = 0.655 \text{ m} \quad \text{(18)} \]

The variable \( x \) is compared with lengths \( L \) and \( r \). Time \( (v_0 t) \) is compared with the system length \(~4.5 \text{km})\), and a natural frequency \((e/2r)^{-1} = (277 \text{m})^{-1}\). If values of \( v_0 \) other than \( 0.3c \) are considered, then the product \( Rv_0/L \) should be held fixed to realize constant fractional mismatch of impedance.

The boundary conditions are \( n_0 \Delta \xi = 0 \) at the pulse ends. This makes the perturbed potential energy finite as \( \xi = 0 \). In the special case of flat top \( n_0(x) \), \( n_0 \xi \) must go smoothly to zero at the pulse ends even though \( n_0 \) has a step. If \( n_0 \) goes smoothly to zero at the ends then \( \xi \) may be finite there.

Mode Structure

Equation (16) is of an inconvenient form for analysis because of the first derivative in \( x \). This is removed by defining
\[ \psi(t,x) = n_0 \xi \exp(\lambda x/L), \quad \text{(19)} \]

where
\[ \lambda = L/2r = LRCv_0/2 = 15.3. \quad \text{(20)} \]

We are removing a mode distortion factor (which is large for the assumed parameters). Eq. (16) gives
\[ \frac{1}{v_0} \frac{\partial^2 \psi}{\partial t^2} = \frac{\epsilon^2 n_0 \partial^2 \psi}{\pi (\partial x^2)} - \psi - \frac{1}{v_0} \frac{\partial \psi}{\partial t}. \quad \text{(21)} \]
Note that the time derivative in Eq. (21) is small of order ε and therefore the last term on the right may usually be neglected; this is done in most similar derivations and is equivalent to dropping the term proportional to dv in Eq. (11). If that term is dropped then Eq. (21) is of self-adjoint form and mode frequency (which is real and positive) can be evaluated for general $n_0(x)$ using a variational technique.

Here we estimate mode frequency for general $n_0(x)$. Let $\psi = g(x) \exp(-ik\nu_0 t)$; then eqn (21) yields

$$-(\frac{\omega}{\varepsilon})^2 g = \frac{\partial^2 g}{\partial x^2} - \frac{g}{4\epsilon^2} + \left(\frac{10}{\varepsilon}\right) g.$$  \hspace{1cm} (22)

Multiplying all terms by $(Lg^*\tilde{n}/n_0)$ and integrating over $x$ we obtain the quadratic in $\omega$

$$A\left(\frac{\omega}{\varepsilon}\right)^2 + B\left(\frac{\omega}{\varepsilon}\right) \left(\frac{L}{4\epsilon^2}\right) + C = 0,$$  \hspace{1cm} (23)

where $A$, $B$, and $C$ are the positive quantities

$$A = \int_L \left[\frac{dx}{L} |\tilde{g}|^2 \right], \quad B = \int_L \left[\frac{dx}{L} |\tilde{g}|^2 \right], \quad C = \int_L \left[\frac{dx}{L} \tilde{g}^2 \right].$$  \hspace{1cm} (24)

The eigenfrequencies are

$$\omega = -\left[\frac{\epsilon^2 - A}{2\epsilon^2} \right] \pm \left[\frac{\epsilon^2}{2A} \left(\frac{\epsilon^2}{A} - \frac{\epsilon^2 - A}{2\epsilon^2} \right) + \left(\frac{\epsilon^2}{A} \right) \left(\frac{\epsilon}{A} \right) \left(\frac{\epsilon}{A} \right) \left(\frac{\epsilon}{A} \right) \right]^{1/2}.$$  \hspace{1cm} (25)

For a flat top profile the normalized eigenfunctions are

$$g_m(x) = \sqrt{2\pi} \sin(m\pi x/L),$$  \hspace{1cm} (26)

with $m$ any positive integer. In this case we have

$$A = B = 1/2, \quad C = m^2 \pi^2/2.$$  \hspace{1cm} (27)

For general $n_0(x)$ we expect $A/B$ to be of order unity and $C/A$ to be of order $(m^2 \pi^2)^2$, so we have

$$\omega = \left[\frac{\epsilon^2}{2\epsilon^2} \right] \pm \left[\frac{\epsilon^2}{2A} \left(\frac{\epsilon^2}{A} - \frac{\epsilon^2 - A}{2\epsilon^2} \right) + \left(\frac{\epsilon^2}{A} \right) \left(\frac{\epsilon}{A} \right) \left(\frac{\epsilon}{A} \right) \left(\frac{\epsilon}{A} \right) \left(\frac{\epsilon}{A} \right) \right]^{1/2}.$$  \hspace{1cm} (28)

For the nominal parameters scale lengths are

$$2r/e^2 = 58.6 \text{ km}, \quad L/e = 4.23 \text{ km},$$  \hspace{1cm} (29)

$$2r/e = .277 \text{ km},$$  \hspace{1cm} (30)

and their relative ordering is maintained for lower $v_0$ if $v_R$ is fixed. We therefore expect frequencies clustered near $(277m)^{-1}$ at low mode number $(m<10)$ and increasing proportional to $m$ for $m > 10$. The damping length (58.6km) is of negligible consequence.

**Discussion**

The most important feature of the mode structure is the distortion factor [eq. (19)].

An initial perturbation must be expanded in the normal modes $g_m$:

$$n_0 = \exp(-xL) \sum A_m g_m(x) \cos(\omega_m \nu_0 t),$$  \hspace{1cm} (30)

with coefficients

$$A_m = \int g_m(x) n_0 \psi(x,t=0) \exp(xL/L).$$  \hspace{1cm} (31)

For mode numbers close to that of the initial disturbance $A_m$ contains the factor $e^A$. In particular, the flat top profile yields, for a perturbation $n_0 \psi(t=0)=\sin(\pi x/L)$,

$$\frac{A^2}{A} = e^A - 1 - \frac{\lambda}{A} \left[1 + \left(\frac{\lambda}{2\pi}\right)^2\right].$$  \hspace{1cm} (32)

This amplification factor is nearly $3 \times 10^5$ for low mode number (nominal parameters). The result is that the small disturbances due to field errors in the gaps produce very large disturbances in the pulse tail after a drift length of $\sim 300m$. This disturbance is oscillatory with a spectrum of frequencies and eventually converts to a large momentum spread or loss of particles from the pulse ends.

Several possible cures are apparent. First, it is clear that sufficient velocity spread will damp the disturbance. A simple estimate based on a continuous pulse with a Lorentzian velocity distribution gives the requirement (hwhm)

$$\Delta v/v_0 \geq e^{-\sqrt{\frac{\lambda}{\pi}} - .0104},$$  \hspace{1cm} (33)

which is on the borderline of acceptability for final focusing requirements. If spread is used for mode suppression and is initially too low, it seems likely that the system will "overshoot" by a large factor when it generates spread velocity by mode distortion.

A second class of cures consist of the use of feedback or high frequency filtering of $\delta E$ in the accelerating modules - this is not considered here.

Finally, one may design the system such that the factor $\lambda=RCLv_0^2/2$ is only of order unity. A possibility would be $L=10m, R=250m, I=2.88$ kA. Then $\lambda=956$, but the efficiency drops to $\eta= .251$ and there is an increased cost for transport.

**References**

2. D. Neuffer, ibid, p.246.
DESIGN OF AN ELECTRON BEAM SPECTRAL MODIFICATION SYSTEM

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and
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ABSTRACT

We report the design of a spectral modification system (SMS) for use with the proposed NEAL linac-pulse stretcher ring, cw electron beam facility. The SMS allows tailoring of the energy distribution of electrons in beams produced by a pulsed linac operating in the transient beam loading (TBL) regime. Modification of the energy distribution of electrons injected into the pulse stretcher ring will increase the duty factor of current extracted from the ring and improve the efficiency of the extraction process. Physically, the SMS consists of an anisochronous, achromatic magnetic lattice followed by a pair of traveling-wave accelerating sections. For beams in the energy range of 500 MeV to 4 GeV, TBL ripple on the energy envelope of microsecond long beam spills is expected to be reduced from 1/5 peak-peak to less than 0.01% while the desired width of the energy profile due to the phase extent of the microbunches in the beam spill is preserved.

INTRODUCTION

The recently proposed NEAL accelerator is composed of a pulsed linac and a pulse stretcher storage ring (PSSR).1 Attainment of a high duty factor and a large efficiency in the pulse stretching operation rely on a good match between the temporal and spectral characteristics of the linac beam and the admittance of the PSSR. For monochromatic extraction of current from the PSSR in the energy range of 500 MeV to 2.0 GeV, it is required that the linac generate 1.2 μs beam spills with a spectral width which is variable between about 0.2% at the low energies to about 2.0% at the higher energies. Achromatic extraction from the ring has been proposed for beam energies greater than 2 GeV, dictating a linac beam spectrum whose width of less than 0.1%.

This paper reports the design of a spectral modification system (SMS) to be used for tailoring of the spectra of the linac beam spills beyond the control which can be expected with the use of delayed klystron triggering and through the variation of the phase extent of the microbunches.2 The SMS can be used as a Ripple Suppressor to remove ripple on the beam energy envelope caused by transient beam loading in the linac due to peak beam currents > 200 mA. It can also be used as an Energy Compressor when narrow spectra are required.

Figure 1 illustrates the components necessary for the SMS. A triplet of magnetic dipoles

[M1, M2, M3] followed by a pair of accelerating sections (A1, A2) are placed at the end of the linac. The magnets form an achromatic, anisochronous, horizontal bump in the beam trajectory to disperse the beam longitudinally according to energy. A pair of accelerating sections is used to differentially accelerate the dispersed beam, thereby achieving either ripple suppression or energy compression. The hardware of the SMS is quite similar to that of existing energy compression systems.3

ANALYSIS

Linac beam spills comprise a pulse train of N electron microbunches, each microbunch having the same amount of charge in the identical distribution and each microbunch riding along the crest of the RF acceleration wave in the linac at the same position as any other microbunch. It is assumed that changes in the energies of electrons in the microbunches due to TBL is constant across a single bunch but may vary from bunch to bunch.

The energies of electrons in the linac beam spill are given as \( E_n(\theta,t) \):

\[
E_n(\theta,t) = \sum_{n=1}^{N} E_n(\theta,t)
\]

where \( E_n(\theta,t) \) is the energies as a function of rf phase, \( \theta_n \), and time, \( t \), of electrons of the nth microbunch. \( E_n(\theta,t) \) is defined as

\[
E_n(\theta,t) = E_1 \cos(\theta) \delta(t-t_n) + E_1 \delta(t-t_n) \]

where \( E_1 \) is the maximum energy available for electron acceleration in the linac; \( \theta = \) the phase position of electrons within the nth microbunch, \( \theta_1 < \theta < \theta_0 \), with \( \theta_0 \) the phase of the tail of the bunch and \( \theta_1 \) the phase of the head of the bunch; \( E_1(\theta) \) is the change in the energy of microbunches due to TBL; and \( \delta(\cdot) \) is the Dirac delta function with \( t_n \) the temporal location of the nth microbunch within the beam spill.
When the beam described by Eqs. (1) and (2) is transported through the SMS, the energies of electrons leaving the SMS are given by

$$E_o(\theta,t) = \sum_{n=1}^{N} n E_n(\theta,t)$$

$$= k(E(RF,t) - E_{sms}) - e_{RF} \sin\left[ \frac{\theta_{sms} - \theta}{E_{sms}} \right]$$

(3)

where $e_{RF}$ is the energy gain available in the SMS; $k$ is the SMS dispersion constant; $E_{sms}$ is the centroid energy of the magnet chicane; and $\theta_{sms}$ is the phase of the SMS RF with respect to the linac RF phase. Specification of the SMS parameters ($e_{RF}$, $k$, $E_{sms}$, and $\theta_{sms}$) determine the operating behavior of the system.

As a Ripple Suppressor, the SMS is required to preserve the desired energy width of the beam spill, determined by the phase extent of the microbunches, while reducing the ripple on the energy envelope caused by transient beam loading. In the case of energy compression, the SMS should reduce the full width of the beam energy spectra to be less than some tolerable energy spread, $\Delta$. With these constraints in mind, the values of the SMS parameters have been determined and are listed in Table I.

**COMPUTER MODELING AND SIMULATIONS**

In order to evaluate the foregoing analysis, the linac beam spill is assumed to be 1.2 $\mu$s long and the transient RF filling time of the linac is 0.87 $\mu$s. $E_b(t)$ has been modeled as a sinusoid during the transient period:

$$E_b(t) = (-0.5 \times 10^{-3} E_1 \sin(\omega t))(U(t) - U(t-0.87 \mu s))$$

(4)

**TABLE I. SMS Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Ripple Suppression</th>
<th>Energy Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{RF}$</td>
<td>Available energy gain in SMS acceleration sections</td>
<td>$\Delta_{tbl}$</td>
<td>$\Delta$</td>
</tr>
<tr>
<td>$k$</td>
<td>Dispersion constant of the SMS magnetic chicane</td>
<td>$[\theta_1 - \theta_2][\cos(\theta_2) + \cos(\theta_1)]$</td>
<td>$E_1[\theta_1 - \theta_2][\cos(\theta_2) + \cos(\theta_1)]$</td>
</tr>
<tr>
<td>$E_{sms}$</td>
<td>Centroid energy of the magnetic chicane</td>
<td>$E_1[\cos(\theta_2) + \cos(\theta_1)]$</td>
<td>$E_1[\cos(\theta_2) + \cos(\theta_1)]$</td>
</tr>
<tr>
<td>$\theta_{sms}$</td>
<td>Phase of the SMS RF WRT linac RF phase</td>
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<td>$2.0$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>RF phase of beam</td>
<td>$0^0 &lt; \theta_2 &lt; \theta_1$</td>
<td>$\theta_2 &lt; \theta_1 &lt; 0^0$</td>
</tr>
</tbody>
</table>

$\Delta_{tbl}$ = maximum magnitude of TBL energy ripple.

$\Delta$ = maximum tolerable final energy spread after energy compression.
In order to examine the effect of the SMS on the energy distribution of the beam spill, an initial electron phase distribution of $p_0(\theta)$ has been assumed:

$$p_0(\theta) = A|\theta - \theta_3| \exp[(\theta - \theta_3)^2/2\sigma^2]$$

(5)

where $A$ is a normalization constant, $\theta_3 = 6.0^\circ$, and $\sigma = 1.85^\circ$. $p_0(\theta)$ is plotted in Figure 3 for $0^\circ < \theta < 6^\circ$. Figure 4(a) illustrates the energy distribution of the linac beam shown in Figure 2(a) having the phase distribution of Figure 3. Figure 4(b) illustrates the energy distribution of the same beam spill after the SMS. In Figure 4(b), the full width of the distribution, has been reduced to that expected for a $6^\circ$ bunch, $\Delta E = 5.5 \times 10^{-3}$, and the shape of the energy distribution is identical to that of the initial phase distribution.

Figure 5 illustrates the behavior of the SMS when used as an Energy Compressor. Figure 5(a) is a plot of an input beam spill for the case of $E_1 = 1.0$, $\theta_1 = 0.0^\circ$, and $\theta_2 = -2.5^\circ$; Figure 5(b) depicts the same beam after compression in the SMS. As seen from Figure 5, the SMS effectively removes the TBL ripple and compresses the total spectrum.

Fig. 3. The initial phase distribution particles within the microbunches comprising the input beam spill.

Fig. 4. The energy spectra of the beams (a) before and (b) after Ripple Suppression.

Fig. 5. Energy compression: (a) the input beam and (b) the output beam.

For (b), $k = 52.34$ and $e_{RF} = 1.91 \times 10^{-2}$ for $\Delta = 1 \times 10^{-3}$.

**SMS HARDWARE**

The SMS consists of an achromatic, anisochronous magnetic chicane and a pair of linac accelerating sections. Chicane achromaticity is ensured by requiring all magnetic pole faces to be normal to the undeflected trajectory; the accelerating sections are assumed to be identical to those used in the linac proper. Figure 6 illustrates the dependence of the required energy gain in the SMS, $e_{RF}$, and the desired dispersion constant, $k$, on the length of the microbunches for the cases of ripple suppression and energy compression.

The magnitude of $e_{RF}$ is determined by the amount of RF power fed into the accelerating sections, the shunt impedance and attenuation parameter of the sections, and the beam current, should beam loading in these sections become appreciable. As shown in Figure 6(a), the required value of $e_{RF}$ can become quite large for the case of ripple suppression at the longer microbunch lengths. It can be shown by expanding the SIN term in Eq. (4) to first order, however, that for a fixed value of $e_{RF}$ and $k$, the width of the SMS output beam spectrum is given as $\Delta E_o$.

$$\Delta E_o = E_o(\theta_2, t) - E_o(\theta_1, t) = e_{RF}(\theta_1 - \theta_2)$$

(6)
Fig. 6. Dependence of $e_{RF}$ and $k$, (a) and (b) respectively, on the length of the microbunches, $|\theta_1 - \theta_2|$, for the cases of ripple suppression (RS) and energy compression (EC).

where $|\theta_1 - \theta_2|$ is the length of the microbunches.

Equation (6) indicates that for a fixed value of $e_{RF}/E_0$, any value of $\Delta E$ may be achieved through suitable variation of $|\theta_1 - \theta_2|$, thus alleviating the need for arbitrarily large values of $e_{RF}$.

The dispersion constant, $k$, is the $R_{56}$ element of the TRANSPORT $[R]^n$ matrix of the magnetic chicane. For an $\alpha-2\alpha-\alpha$ bend angle geometry, $k$ is given as

$$k = \frac{4\pi}{\lambda} \left[ L (\tan^2(\alpha) + (\rho_1 + \rho_2)\tan[\alpha-\alpha]) \right]$$

where $\lambda$ is the wavelength of the SMS RF, $L$ is the separation between pole faces of the $\alpha-2\alpha$ magnets as measured along the beam trajectory, $\alpha$ is the bump angle, and $\rho_1$ and $\rho_2$ are the bend radii of the $\alpha$ and $2\alpha$ bends, respectively.

CONCLUSIONS

By effectively smoothing and narrowing the spectra of beams generated by a pulsed linac for injection into a PSSR, the duty factor of current extracted from the ring and the efficiency of the extraction procedure are both increased. Standard magnets and beam acceleration components as well as modest levels of RF power required in the design of the SMS attest to the feasibility and economy of the system. With regard to the NEAL project, accurate estimates of the capabilities of the SMS will allow specification of constraints on: the electron bunch structure generated in the linac injector; the phase stability of the linac RF; and the energy admittance of the PSSR; needed for the detailed design of a Linac-Pulse Stretcher Storage Ring accelerator system.

REFERENCES

LONGITUDINAL BEAM OPTIMIZATION OF THE ARGONNE SUPERCONDUCTING HEAVY-Ion LINEAR ACCELERATOR

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Summary

The various aspects of optimizing the accelerator system in longitudinal phase space are discussed. There are three major components which must be properly adjusted: 1) the buncher system, which must produce a beam bunch of approximately 100 ps FWHM at the entrance to the linac, 2) the linac, which must accelerate the ions while maintaining an undistorted phase ellipse, and 3) the rebuncher/debuncher, which must be optimized to produce either a time focus on target or an improved energy resolution. Optimization of the buncher system and the linac is automatic and under computer control. Rebuncher optimization is only partially computer controlled at this time.

Introduction

In the past 3 years, the Argonne Superconducting Linac Heavy-Ion Booster has accelerated 17 different isotopes for nuclear and atomic physics experiments. Because of varying needs of beam current and maximum energy, the total number of ion types, including charge state combinations, rises to over 25. The diversity of beams makes it imperative that efficient techniques be developed for tuning the accelerator system.

Another requirement of the tuned accelerator system is fast and easy energy variability. The linac functions as a user-operated accelerator to a large degree, and many experimental programs call for frequent changes in the linac output energy. In order for this to occur efficiently, the tuneup of the accelerator must provide the system with information concerning the precise field levels and phase angles of each resonator. Once this data is stored in the computer's data base, the settings necessary for a particular energy are calculated and the linac is automatically configured to the new requirements.

The beam optimization procedures developed depend heavily on the linac control computer described in a companion article presented at this conference. The beam sensing devices used consists of an array of profile monitors, faraday cups, surface-barrier detector scattering systems, and room-temperature helix resonators used as phase detectors. These devices are strategically placed along the beam line as indicated in Figure 1 of the accompanying article.

Fig. 1. Effects of the three bunching elements on the Initial D.C. beam. Typically 70% of the D.C. beam is injected into the linac in approximately 100-ps wide pulses.

Tuning the linac proceeds in a sequential fashion, starting with the bunching system and proceeding through the linac, one resonator at a time. Finally the rebuncher/debuncher is tuned, if needed, to achieve optimal conditions at the experimental station.
Bunching

The bunching system for the superconducting linac consists of three elements. First a pre-tandem room-temperature buncher operating at 48.5 MHz with a sawtooth-like waveform bunches 70% of the D.C. beam into 1 ns wide pulses at the terminal of the tandem. The sawtooth waveform is produced by adding three harmonics to the fundamental frequency. The relative amplitudes and phases are locked to the fundamental, so that only the fundamental amplitude need be changed for different ion species or injection energies. This amplitude is calculated by the computer and set manually by the operator. No manual tuning has been necessary for optimum performance after the relative phases and amplitudes of the harmonics are adjusted once.

The second element of the bunching system is a vertically sweeping electrostatic sinusoidal chopper. The chopper removes the tails of the bunched beam from the pre-tandem buncher. The criteria for proper tuning of the chopper is that the transmission function be approximately 1.0 ns wide and that the pulse be centered in the transmission window. The later requirement translates into maximum beam transmitted as a function of chopper phase angle.

The chopper is under direct computer control. The chopper amplitude and phase are calculated and set automatically by the computer. The calculated amplitudes require no further adjustment, but the calculated phases can occasionally be improved by manual adjustment. The phase error is generally less than five degrees and often zero. This manual fine-tuning will be computerized in the near future when the computer will have direct control of Faraday cups and can read the output from a new electrometer recently obtained.

The last element of the bunching system is the superconducting buncher. This unit is a single low-beta (.062c) split-ring resonator which is operated at a phase angle of 90° in order to produce a time waist at the first linac resonator. The time waist must have a width of approximately 100 ps in order for the longitudinal phase ellipse to be transmitted through the linac without distortion.

The beam pulse time resolution can be observed at the entrance to the linac with a scattering foil and surface-barrier detector located at that point. The amplitude can then be varied for minimum observed time width and the phase adjusted for no energy gain from the buncher. A more common technique employed is to observe the time width and the energy gain using a surface barrier detector system located at the linac exit. The field required to form a time waist at that point is scaled in order to achieve a time waist at the linac entrance. Adjustments to this value are made to produce the desired minimum in the energy width curve for the first resonator. The results of numerous measurements in this manner provided the calibration data needed to compute directly the amplitude of the superconducting buncher. The calculated phase angle is manually adjusted to achieve zero energy gain. Operating the superconducting buncher with zero energy gain serves as a useful reference for reproducing previous tuneups. In general, the phase angle requires manual optimization in order to obtain zero energy gain. The error is generally only a few degrees but this can produce significant phase shifts because of the drift space to the first resonator. The final correction to the phase angle for the superconducting buncher is currently being added to the computer routines.

The use of the computer for setting the bunching system parameters has reduced to about one minute the time required to set the bunching system. The bunching system functions in an essentially trouble-free mode and requires no additional adjustments during a run. The action of the bunching system on a beam is shown in Figure 1. A significant benefit to calculating and setting the bunching system prior to other tuning is that the chopper serves as a time-of-flight filter which, along with the analyzing magnet, unambiguously determine the ion and charge state combination being accelerated. For certain ions such as nickel, the location of the second stripper foil in front of the analyzing magnet can result in two charge-state combinations that have nearly identical magnetic rigidity at the analyzing magnet. If the tandem control system locks on the wrong ion species, it is immediately obvious since the chopper will not transmit the incorrect species. This has proved useful to the tandem operators on many occasions.

Tuning the Linac

Tuning the linac resonators consists of determining the resonator phase setting which produces maximum energy gain, setting the phase angle to a value which produces a phase-focusing condition, and determining the energy gain of the beam from the resonator being tuned. The amplitude is predetermined, based on the operating history of each resonator. This procedure is performed for each resonator in the linac in a sequential manner, beginning with the first resonator in the linac.

Two detection systems may be used for tuning the linac. The first system consists of a silicon surface barrier detector which detects particles elastically scattered by a gold foil in a forward direction. The second system is a time-of-flight system which employs a room-temperature helix 1/2 resonator as a beam pulse detector.

The surface-barrier detector system has the advantage that both timing and energy information are independently available. Pulse width information is also available which allows some inferences to be made concerning the shape of the longitudinal phase ellipse. But the surface-barrier detector also has significant
disadvantages. These include: calibration difficulties, detector deterioration, pulse-height defect for heavy ions, and (probably most important) a high degree of susceptibility to beam steering in the linac because of the collimation required in the detector system.

The helix resonator phase detector has the advantage that its response is largely independent of beam current, thereby allowing the tuning of beams with low intensity. Beams of 0.1 - 1.0 nA are detectable with the helix resonator. Also because of the large acceptance of the resonator, the detection system is not so sensitive to beam steering effects in the linac. The disadvantages of the resonator is that information concerning the beam phase ellipse is sacrificed. During routine tuning, we find that phase ellipse information is not critical. Therefore this loss of information is not very serious.

The procedure followed for tuning a resonator is the same for both detection systems. The steps involved are:

1) Measure the energy into the resonator.
2) Determine the approximate peak in the acceleration curve.
3) Measure the energy gain as a function of phase angle in the vicinity of the peak.
4) Fit these results in order to determine the phase setting which produces the maximum energy gain.
5) Set the resonator phase to the desired value.
6) Store results of scan and proceed to the next resonator.

Fig. 2. Energy gain (AU) and full width at half maximum (width) as measured using a surface-barrier-detector scattering system for one resonator during a linac tuneup.

Although the word "energy" is used above, the prescription is the same for the helix phase detector. Here a phase change (flight time change) is measured which can be converted immediately into an energy gain.

The tuning procedure is completely under computer control. All that is normally required is to maintain sufficient beam current at the diagnostics area. An example of the results of a resonator scan using the surface-barrier-detector system is shown in Figure 2.

The tuning time of the whole linac generally requires 1.5 to 2 hours, and the best time observed is 30 minutes. The helix phase detection system is still undergoing development and certain straightforward improvements should reduce the tuning time with that system by at least 30%.

The linac tuning procedures are performed at the maximum operating field levels. Once performed at the maximum energy, any intermediate energy is obtained by a simple request at the linac control console.

Rebuncher/Debuncher Tuning

The rebuncher/debuncher is a single high-beta (105 c) split-ring resonator. Its tuning relies on the detector system in use by the experimentalist. The linac control system can accept the data and scan the rebuncher in a manner similar to the tuning of resonators in the linac to determine the phase setting to produce zero energy gain and the bunching condition. The amplitude and phase angle are then manually adjusted to produce the optimum conditions. Future plans call for automating this procedure in order to improve the tuning speed and make the system more compatible to quick energy changes.

Results of Tuning Procedure

The primary result of the linac tuning process is to provide an efficiently accelerated beam without distortion of the phase ellipse. The litmus test of the success of the procedure and the overall operation of the accelerator system is the quality of the delivered beam at the experimental station. Experiments now scheduled at the linac are designed to be most sensitive to, and to make use of, the good timing potentially available from the linac.

The results of various timing tests using the rebuncher in the bunching mode are tabulated in Table 1. These tests indicate that bunch widths of <120 ps are readily obtainable. The results obtained in the 34S tests are significantly worse than in the other tests and reflect the poor timing observed from the pretandem buncher. For sulfur the bunch width from the pretandem buncher is usually <1.1 ns but in this case even the rather large width of 1.3 ns could be obtained only by reducing the source aperture to the relatively small value of 1/8" diameter. Interestingly there was no other indication of a problem in the system. Within four days the source failed and had to be repaired. It has been found that beam-bunch timing is a sensitive measure of system operation, albeit a hard to interpret one.
Table 1. Results of timing resolution tests with the superconducting linac system.

<table>
<thead>
<tr>
<th>Ion Configuration</th>
<th>System*</th>
<th>Tandem energy(keV)</th>
<th>Linac buncher timing (ns)</th>
<th>Measured timing resolution on target (psec)</th>
<th>Beam timing resolution (corrected) (psec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12C5+</td>
<td>A</td>
<td>510</td>
<td>110.3</td>
<td>.62</td>
<td>119</td>
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<tr>
<td>16O6+,8+</td>
<td>A</td>
<td>56.0</td>
<td>108.7</td>
<td>1.0</td>
<td>105</td>
</tr>
<tr>
<td>28Si8+,13+</td>
<td>B</td>
<td>75.5</td>
<td>229.0</td>
<td>1.1</td>
<td>118</td>
</tr>
<tr>
<td>34S8+,13+</td>
<td>A</td>
<td>76.5</td>
<td>163.0</td>
<td>1.3</td>
<td>210</td>
</tr>
</tbody>
</table>

*Refer to Figure 1, Ref. 1: (A) D cryostat located in B position. Measurements made in 65" chamber. (B) B cryostat removed, 4 m drift distance between A and C cryostat. Measurement made in 18" chamber.

The other timing results are in fair agreement with ray tracing calculations based on the assumption that the linac is injected with a vertical phase ellipse of 100 ps width and total area of 40 keV-ns in longitudinal phase space. If the timing resolution observed is at the phase space limit, then the time resolution will be determined by the initial phase space area of the beam and also the relative distances between the linac exit, the rebuncher, and the experimental chamber. We plan to continue this investigation by looking at the effects of various phase-space area-changing components in the tandem injection system such as stripper foils and energy defining slits. We will combine these measurements with direct measurements of the beam-energy width from energy-loss straggling in the stripper foils that make use of the pulsed-beam structure using time-of-flight techniques.

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References

1. J. Aron et al., "Status of the Argonne Superconducting-Linac Heavy Ion Booster", these proceedings.
A MODULAR SYSTEM FOR THE CONTROL OF COMPLEX ACCELERATORS USING PORTABLE SOFTWARE

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Summary

When designing the Mainz Microtron control system, care was taken to achieve an expandable system with long-lived application software. A multi-processor system was built from the beginning.

The software is split into modules, according to function and position in hierarchy, which are distributed over the computers. The decoupling which results from modularity eases software development and maintainance. RATFOR was chosen as implementation language.

With a message system for communication between the modules, several aims were reached at once: (i) symbolic addressing of the accelerator components throughout the software layers, (ii) transparent access to I/O devices (CAMAC) at remote computers, (iii) multitasking in FORTRAN (and RATFOR) programs, (iv) a separating layer for adaptation to different operating systems - essential points for software portability.

The system is in operation since April 1979 for the control of MAMI stage I.

Introduction

The Mainz Microtron 1,2 (MAMI) is a three-stage cw electron accelerator which is constructed step-by-step, starting rather small and expanding in the course of several years. Due to the large number of return paths (20 in stage I), many components have to be controlled. MAMI is fully computer controlled, as was decided at an early design state.

stage

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
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<tbody>
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<td></td>
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<td>dipoles</td>
<td>5</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>lenses</td>
<td>14</td>
<td>12</td>
<td>280</td>
</tr>
<tr>
<td>steering</td>
<td>92</td>
<td>210</td>
<td>300</td>
</tr>
</tbody>
</table>

Tab.1 Number of main elements per accelerator stage (including interface beamlines)

The computer control system must be able to expand with the growing control requirements. The computing and I/O capacity will grow - so the number of computers involved will increase, and there should be no limitation to a specific computer type because hardware architecture will probably change during accelerator construction. Thus we will end up with an inhomogeneous multi-processor system.

For the process peripherals, CAMAC was chosen as a long-term standard system.

Long-lived software is difficult to achieve in an expanding, inhomogeneous hardware environment. The software must be distributed, and probably re-distributed, over the computers. Thus it must be split in modules. The modules must be portable among the computers with their different operating systems. Distributed modules need a way to communicate with each other. Portability poses restrictions to the form of communication.

The above features are the subject of this paper. The tools developed to make accelerator operation, adding of new accelerator components, and program development comfortable are described elsewhere 6,7. The same is true for details of the electronics 8.

Present Hardware Configuration

The present system is based on two HP1000 minicomputers which are loosely coupled, point to point, via the I/O system. This capacity will be sufficient to operate stages I and II.

The process peripherals - operator desk and accelerator components - are interfaced via CAMAC branch and single crate systems.

![Fig. 1 Present hardware configuration](image)

Operator Desk

The operator desk is equipped in the standard way with two touch panels, four incremental knobs for quasi-analog input, a color TV, a trackball, and six analog displays. In addition to this unit, a portable mini operator desk is available, consisting of a terminal with four incremental knobs and touch-screen.

V24 line.

Accelerator Instrumentation

The accelerator components are served via seven kinds of CAMAC modules (in order of importance):

- 256-word memory (8 bit) with DAC and analog multiplexer. - Used for the big number of steering coils 3-4.
- 16-bit output module with 4-bit status input and 2 pulse outputs (two channels/slot) - Used for the magnet power supplies.
16-channel scanning ADC (12 bit). - Used for voltages and currents of power supplies, beam currents on collimators and faraday cups, etc.

- Fast 12-channel, 12-bit ADC plus special trigger generator. - Used to digitize the position, phase, and intensity signals from RF monitors.
- 16-bit input module (two channels/slot). - Used for NMR, precision DVM, etc.
- 16-bit pulse module (two channels/slot). - Used to change polarity of dipoles, etc.
- 2-channel pulse train unit. - Used for stepper motors (RF phase shifters etc.).

**Software**

Software modularity is a demand in a multiprocessor system, and it is necessary for clarity and maintainability of the entire software system. Establishing the right form of communication between the modules is the major step towards portability, as by this means the modules may be freely distributed over the computers.

A prerequisite for portability is to use a higher-level programming language which is, and will be in the future, available on most computer systems.

A further critical point with respect to portability is the software interface to the I/O system. This problem is solved (i) by the programming language, (ii) by making the I/O devices globally available from all computers, and (iii) by creating enough layers in the software hierarchy.

**Software Modules**

From the functional point of view, most of the modules are arranged in four layers of hierarchy. Few, e.g. the data base management, do not fit into this scheme. Starting from the lowest (omitting the CAMAC drivers etc.), the four layers are:

- The "service routines" (SRs). These are the only modules which have knowledge about the special hardware operations (i.e., a series of CAMAC functions) necessary for one logical function (e.g., change a magnet current), and the only modules which access CAMAC directly by I/O requests (exception: see OP below). There is one SR for each kind of equipment (e.g. one for all magnet power supplies). CAMAC addresses and all other data are held in the database, such that the SRs are somewhat re-entrant. - The SR layer enables all the higher-level modules to access CAMAC in a strictly hardware-independent way.
- The "handlers" and the simple automatic control loops. The handlers mediate, on operator's request, the connection between op-desk equipment and accelerator components. For this purpose they communicate with the appropriate SRs. The simple control loops connect accelerator component SRs (e.g., NMR with magnet power supply to control the magnetic field).
- The high-level automatic control loops and the setup/shutdown module. They perform tasks like "optimize injection to stage 1" or "reproduce state of machine from database". This layer is split into sub-levels.
- The operator process (OP) constitutes the highest layer in the system. All operator actions are initiated via the touch panels which are private devices of the OP.

From the operating system's viewpoint (presently HP RTE-IV), module = task = program (or process).

**Fig. 2** Schematic picture of the software modules, distributed over both computers. Communication is shown as the central axis. Hierarchy is not exhibited here because in principle every module can communicate with any other.

**Fig. 3** Software modules involved when the operator changes a magnet current. Meaning of the sequence numbers:

1. Interrupt from touch panel (TP). OP initiates connection.
2. Handler HINTM gives actual current as starting value to SR KNOB which assigns a knob.
3. Whenever the knob is turned, new data are routed to SR INTM and passed on to power supply and database. (n-1) Interrupt from TP indicates end of action. (n) HINTM cancels connection, KNOB turns off knob.
Communication

In order to achieve modular and portable software, a message system for inter-process communication has been implemented. Messages are exchanged via two requests, SEND and RECEIVE. Properties of the message system are:

- Communication has the same form when being local in one computer as well as between several computers - necessary for portability.
- A functional addressing scheme is used. I.e., sender and receiver are not identified by program and computer name, but by a 10-byte mnemonic for the object (e.g., a magnet) to be acted upon.
- It is a packet-switching system (128-byte packets) with simple line protocol.
- It has store-and-forward capability, such that computers which are not directly connected can communicate through intermediate stations.
- Operating system tasks, in particular the CAMAC drivers, can take part in the communication. By this means interrupts are distributed as messages, even to remote computers.
- Messages are used as the vehicle for I/O requests to devices on remote computers. So the devices are made globally available.
- Although being part of the operating system, the message system is written in RATFOR. So it can be adapted to other computer systems.

Mnemonic addresses have the following structure which is suited to name the accelerator components.

\[ \text{name} = \text{ZONE-GROUP [-NUMBER]} \]

E.g. INT2-QUAD-1 for the 1st quadrupole of the 2nd interface beamline, OPER-KNOB for the knobs of the operator desk. ZONE and GROUP are each one to four characters long, NUMBER (optional) is a 16-bit number. These names are used throughout the software layers. They also serve for addressing the individual database records associated with each accelerator component. The names are mapped to target computer and program by the message system using globally-defined configuration tables.

SEND and RECEIVE requests have parameters as follows (less important ones omitted):

\[ \text{SEND} \quad (\text{receivername}, \text{sendername}, \ldots, \text{messagelength}, \text{message}) \]

\[ \text{RECEIVE} \quad (\text{waitcode}, \text{receivername}, \text{sendername}, \ldots, \text{messagelength}, \text{message}) \]

The names are mnemonics as defined above. In the receive case, a maximum wait time may be specified. The sendername may be set to "any" if it is not desired to wait for messages from a specific sender. By this means, a module can be ready and waiting for several tasks at the same time (e.g., CAMAC interrupt response and normal requests from other modules). So some multitasking is established in the modules, just by branching according to sender and contents of the received message.

SEND and RECEIVE are primitives of the communication. If handshaking is desired in the module-to-module protocol, one uses a series of SEND/RECEIVE.

Language

RATFOR, a preprocessor to standard FORTRAN, is used\(^5\). The advantages in the present application are:

- It has a macro preprocessor. So the language can be easily adapted to the problem. This is especially useful for CAMAC I/O requests, where the operating system dependence can be confined to the macro definitions. E.g., we write

\[ \text{CH(C,N,A,F, data)} \]

for a CAMAC write request.
- It is available on all systems which know FORTRAN. The preprocessor is written in RATFOR and it thus portable itself.

Current work

Preparation for connecting the components of stage II is finished.

An interactive beam optics simulation program is installed in the MAMI computers. It will be available at the operator desk (with touch panel and knobs) during MAMI operation.

The message system developed for MAMI is currently modified for implementation in a HP 3000 (central computer of the institute), a third HP 1000 and (soon) a PE 3220 (experiment computers). We are then free to shift some modules to the much faster PE 3220.

Conclusion

The control requirements of a complex accelerator whose construction takes several years lead to a growing, inhomogeneous multiprocessor system. Nevertheless, a clear and long-lived software system can be achieved. Besides choosing a higher-level programming language, the software interfaces from a process to the I/O system and to the other processes must be carefully designed. RATFOR in combination with a message system for interprocess communication were found to work well and to meet the above requirements.

References

1. H.Herminghaus et al., Nuclear Instruments & Meth. 138 (1976) 1
3. H.J.Kreidel, Internal Report Institut für Kernphysik, KPH 16/81, Mainz, 1981
4. W.Heyne, Internal Report Institut für Kernphysik KPH 20/81, Mainz, 1981
8. K.Merle and G.Stephan, Internal Reports, Institut für Kernphysik
The Distributed Control System for the
Fermilab 200 MeV Linac*

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Summary

A new MC68000-based distributed control system is currently being assembled and installed for use on the Fermilab 200 MeV Linac. Sixteen local Secondary stations are interconnected by a 1-MHz, fiber optic, serial (SDLC Loop) communications link to a Primary station. This Primary station interfaces to the Host computer and collects data from the Secondary stations on behalf of either the Host or other Secondaries. This system features synchronous 15-Hz response, extensive integral local control capability and provision for display and control of remote parameters from any Secondary console.

Introduction

The preliminary design of the new distributed control system for the Fermilab 200 MeV Linac has been described in Ref. 1. Although much of the system remains the same, the processor type has been upgraded from an 8-bit MC6809 to a 16-bit MC68000. This paper describes the hardware and software implementation of the system along with some measured performance characteristics and the present status of the project.

General Description

The new Linac control system is a distributed network of sixteen Multibus-based local Secondary stations linked to a Primary station using a SDLC Loop protocol. Each Secondary station contains an MC68000 processor card, the I/O interface cards to read and control all the equipment in a local area of the accelerator, and a small keyboard/video console to allow operator interface to the local station and the network. The Primary station controls the communication on the Loop, collecting data from the network and returning it to the requestor. The requestor may be either a Secondary or the Host computer that supports a console in the Main Control Room. Two MC68000 processors are used in the Primary station; one drives the SDLC link and the other interfaces with the Host computer.

To operate as a stand-alone control system each Secondary must maintain its own portion of the distributed data base that includes device names, analog settings and calibration constants, and digital control and reading characteristics. This data base resides in non-volatile core memory at each Secondary and can be modified locally or downloaded from the network. To participate in network activity the stand-alone Secondary is simply inserted into the communications loop. Programs for Secondary stations are stored in PROM memory so that a Secondary will recover from a power outage in an operating state independent of the communication link.

The systems described here all operate synchronously with the Linac 15-Hz repetition rate. Each Secondary acquires all its data each cycle and scans the data for out-of-tolerance values or improper status conditions. New alarm messages that result from this monitor scan are returned to the Primary during the alarms poll. From any Secondary console an operator can simultaneously display and control a selection of parameters from the local and several remote Secondaries. Careful attention has been given to preserving the fast response and interactive "feel" of the system. Data are returned to the requestors at 15-Hz and settings are sent to the appropriate Secondary at 15-Hz so that the effects of an adjustment can be noticed on the next cycle. The 1 MHz SDLC link and its supporting software drivers easily support more than 100 messages each fifteenth of a second.

Hardware

Secondary stations are complete stand-alone local control systems that include the computer, I/O and a small console. The following is a brief description of the hardware components.

Each station contains an Intel ICS80 Multibus chassis that houses the processor card, a 32K byte core memory card, the communication card, and binary and analog I/O cards. The processor card is a Fermilab design because no MC68000-based Multibus board was commercially available until recently. The card contains one MC68000 processor, two serial RS232 ports, four bytes of parallel I/O, a three channel timer and eight pairs of byte-wide memory sockets for RAM and ROM.

Commercially available Multibus-compatible D-A converters are used where 12-bit bipolar D-A control is needed. External 16-channel unipolar 10-bit D-A chassis are used to control the 171 drift tube quadrupole power supplies.

Nearly all Linac analog signals are pulsed, so a modular 16-channel sample-and-hold/A-D chassis was designed. In a typical station four

*Operated by the Universities Research Association, Inc. under contract with the U.S. Department of Energy.

†Multibus is a trademark of the Intel Corp.
of these chassis are daisy-chain connected to a binary I/O card in the Multibus chassis by a single 50-pin ribbon cable.

All the binary I/O requirements for this system are met using a single binary I/O card design. This card provides nine bytes of data organized as three groups of three bytes. Each group interfaces to a 50-pin card edge ribbon cable connector. Individual bytes can be input or output; output bytes can be read back, so they appear as memory to the processor. The pinout of the card edge connector is compatible with Opto22 style isolated I/O modules used to replace some of the relay-based controls of the RF systems. The characteristics of each bit are controlled by the software. This allows a bit to be do or pulsed, active high or low, and short (≤20 µs) or long (≤x66 ms) pulse. Short pulsed outputs are used for stepping motor controllers; long pulses may operate large contactors.

A communications card interfaces the computer with both the console and the SDLC link. A 16 line by 32 character video RAM display generator is included on this card to drive the 5" CRT on the local console. This provides a much faster interface for supporting page-style updating displays (equivalent to a 640K baud terminal). A serial interface outputs two bytes of data to the console to control the lighted pushbuttons. Data input from the console are two bytes of switch status, one byte of data from the ASCII encoded keyboard and one byte from an up-down counter connected to the console shaft encoder knob.

A Motorola MC6851 LSI controller performs much of the protocol logic needed to receive and transmit messages on the SDLC loop. Link data are read into and transmitted out from the 32K core memory board under DMA control. Because the Multibus may not be immediately available to the DMA controller, a 16-byte FIFO is used, in both the transmit and receive channels, to provide about 125 µs of temporary storage. A 26-pin card edge connector interfaces the communication card with the link repeater chassis.

A fiber optic light link interconnects Secondary and Primary stations. A separately powered link repeater chassis is used so the computer can be powered-down without interfering with other activity on the link. As a result of using a fiber optic link to interconnect the Secondaries, the two stations for the pre-accelerator high voltage domes can be the same as all other Secondaries. Control of the ion source equipment can be accomplished from any Secondary console.

Selected Data Scheme

Central to the design of the new Linac Control System software is the plan devised to provide lists of selected data items to many requestors at 15-Hz. Such a request must be sent ahead of the time the data is needed in order to prime the system to deliver the list of requested data efficiently. It is clear that using loop communications could cause the Primary to become a bottleneck to efficient message transfer since every request must pass through that system. To alleviate this problem the Primary, without taking time to analyze each item requested, broadcasts the request to all Secondaries. During that same cycle, each Secondary scans the entire request, noting those items which belong to its own system, and builds an index list of relative pointer values into the answer list which will ultimately be returned by the Primary to the requestor. The following cycle the Primary polls for index lists for each newly-created list and then polls for answer lists for all active lists to be polled according to each list request's update frequency. The index lists are saved and used by the Primary to place the final answer list in the original request order. The answer list is then delivered to the requestor, whether it be the Host, the Primary Console or a Secondary.

Secondary Software

Secondary station software is divided into two kinds of modules - interrupt routines and tasks as shown in Figure 1a. Interrupt routines are scheduled by the hardware priority interrupt system to support SDLC communications (highest priority), serial console communications at 4800 baud, stepping motor pulsing at 150-Hz and Linac data acquisition at 15-Hz. Eight tasks are sequenced by a simple non-preemptive round-robin multitasking scheduler. Each task has a separate data region for its stack and local variables which may be shared by as many as eight subtasks which are priority scheduled by the task itself.

Interrupt Routines

The SDLC Driver interrupt routine operates at the highest priority level to receive messages from the Primary into the input queue under DMA control. If the message is a poll message the driver sends the response frame immediately. Poll messages are requests for answer lists, index lists, commands to request new data lists or control devices, alarms and a diagnostic test. Usually poll messages are broadcast to all Secondaries. The responses from each Secondary are sent to the Primary in physical link order according to SDLC loop protocol. If the message is not a poll message then the Link Command Task is triggered to process it further.

The Timer interrupt routine initiates serial console communication by sending control commands to update the console switch lights. The response data triggers the console link interrupt. Another timer channel is used to generate 150-Hz interrupts used to send pulses to any active stepping motors.

The 15-Hz routine acquires all the analog and binary data in that Secondary. The exact parameters of the data acquisition are specified in a Data Access Table to facilitate making device changes and to help make it possible for all the Secondaries to have the same software. Five tasks are triggered as indicated in Figure 1a. The
15-Hz routine executes in 3 ms for a system which has 64 analog channels and 24 bytes of binary status.

Tasks

The eight tasks used in one Secondary are: Link Command, Alarms, Console, Application Program, Small Memory Dump, Date & Time, Update active data requests, and Diagnostics.

The Link Command Task is triggered by the SDLC interrupt driver upon receipt of a non-poll message. Link commands from the Primary include requests for repetitive data lists or for device control on behalf of either the Host computer or another Secondary. Most other messages are answer lists to a Secondary's active data requests.

The Alarms Task scans all active analog channels and binary status bits each cycle for changes in alarm conditions. The time to scan 128 analog channels and 192 binary status bits is 4.2 ms with 40 active channels and 40 active bits.

The Console Task processes keyboard input characters, cursor activity, knob counter accumulation, switches and lights logic, display page selection, and page title changes. The console switch lights are under software control so that only switches which are used by a given page will light up when pressed.

The Small Memory Dump Task, when active, is used to display eight bytes of local Secondary memory on the bottom display line as a diagnostic aid. Applications programs do not use the bottom display line, keeping it free for system use.

The Application Program Task simply provides a task environment for the application program which is currently active. Application programs are written in PASCAL, compiled, linked, downloaded from the Motorola EXORmacs development system and programmed into PROMs. At present there are four application programs. The Parameter Page program displays an arbitrary list of up to 14 analog channels from any set of Secondaries in the network. Console switches select readings, settings, nominals, tolerances, channel numbers, or settings upon entry to page, to be displayed in engineering, volts, or hex units. Analog control may be effected with keyboard entry or by raise/lower switches or knob control with 15-Hz updating. Optional analog-associated digital status and control may also be supported for each channel. Normal updating displays averages of readings on beam pulses over the last 13 cycles. These characteristic features have evolved over 12 years of experience with Fermilab accelerator control systems. In fact, the Secondary console switch options were designed around the requirements of the Parameter Page. The Analog and Binary Descriptor Pages allow one to display, list, or change any Secondary's data base. The Memory Dump Page is a diagnostic tool which displays 64 bytes of memory organized as eight lines of four words. Each line may separately refer to any eight contiguous bytes of data anywhere in the network. The display is in hexadecimal or volts units and updated at 15-Hz.

The Date and Time Task keeps track of the time of day by counting 15-Hz triggers and updates the display on the top line each minute. The Update Task is triggered each cycle after local data has been read to update answers for all active Primary data request lists. The Diagnostics Task optionally displays local alarm messages on the bottom display line.

Primary Software

Primary Link Driver software is also divided into interrupt routines and tasks as in Figure 1b. Interrupt routines support SDLC loop communications and provide for scheduling poll activity for specific portions of the 15-Hz cycle. Five tasks are sequenced by the same multitasking scheduler as used in the Secondaries.

Interrupt Routines

The SDLC Link interrupt routine is used for loop communications. Messages from the Loop Xmit Queue are sent around the loop. Responses received from poll messages are collected under DMA control into the Loop Receive Queue, and the Loop Receive Task is triggered.

The Timer chip on the CPU board is used to schedule loop communications within each 66 ms cycle. The 15-Hz interrupt occurs about 1 ms after Linac beam time and establishes a reference for Timer chip scheduling. The Timer interrupt triggers the Cycle Task whose subtasks queue the appropriate poll messages for the Loop Xmit Task. Current times used are:
Poll indexes for new lists 10 ms
Poll answers for active lists 15 ms
Diagnostic Test poll 36 ms
Poll for commands 41 ms
Poll for alarms 51 ms

The Primary Console CPU resides in the same Multibus crate as the Primary Link Driver and is the link to the Host computer. If a command is sent from the Host to the Primary Console, it queues it to the Primary Link Driver which merely triggers the Host Receive Task. The Primary Console system may also queue commands in the same way.

Tasks

The five tasks used in the Primary are the Host Receive Task, Loop Xmit Task, Loop Receive Task, Cycle Task, and the Diagnostic Task.

The Host Receive Task removes messages from the Host Command Queue and the Primary Console Command Queue. It recognizes only two types of messages - requests for new data lists and setting commands. This underscores the simplicity of the Host interface as these messages merely represent read and write access to accelerator data. Requests for new data lists will, on succeeding cycles, result in answer lists being sent to the Host. Setting commands are simply passed on to the Secondary addressed by the command.

The Loop Receive Task processes all responses received due to Primary polls of the Secondaries, including index lists, answer lists, commands, alarms and test poll responses. Index lists are saved in the memory block which supports that data list. Answer lists are arranged in proper sequence using the previously saved index lists and then delivered to the requestor. Commands are requests for data lists or setting commands on behalf of a Secondary. They will be queued for the Loop Xmit Task. Alarm messages are queued to send to the Host via the Primary Console. An attention interrupt alerts that CPU to examine the Host Response Queue. The test poll responses are used to determine if all Secondaries are able to communicate on the loop.

Present Status

The Primary to Host connection must await the completion of the new central control computer changeover. However, we are starting Secondary stations and interconnecting them to the Primary on the SDLC link. We presently have all nine Linac systems, the 750 KeV beam line and the presaccelerator ground station operating. We plan to have the Host computer working with the new Linac system before the analog and binary I/O connections are made to the Linac hardware.

As a test of the communications software we called up Memory Dump Pages on 10 Secondaries each of which requested data lists of eight bytes of memory from eight other stations. The time required for the Primary to poll for the 10 answer lists, arrange them into the correct order, and deliver the results to the 10 requesting Secondaries (a total of 100 messages) was 36 ms.

Discussion

In summary, the system described here promises to provide reliable responsive control for the Linac. SDLC, because it is an intercomputer link standard, supported by available LSI circuits, easily handles the high speed variable length memory to memory data transfers required. The choice of MC68000 microprocessor has been viewed by some as overkill for a Secondary station. It does not increase the cost, so the real question is "Why not use the MC68000?" It has been our experience that considerable time and effort is saved by using a more capable processor. Traditional problems of processor speed, limited address space and error detection and recovery are alleviated by the inherent design of the processor itself.

The software development has been done using a Motorola EXORmaos multi-user development system. The system has been reliable and efficient to use with its screen editing facilities and hard disk. Application programs written in PASCAL are more readable and easier to debug and maintain than we have experienced before.

Modularizing the design so that a Secondary connects to all data in a geographic area rather than by function was obvious in this case since the old Linac control system was organized by area. Nevertheless, a new system design could profit from the same approach in that stand-alone operation can support an entire local area of the accelerator, and analog signals are all close to the digitizer and the microcomputer.

Acknowledgements

We would like to acknowledge the continued support of this project by the Accelerator Division Heads Russ Huson and Rich Orr and the Controls Group Leaders Mike Gormley and Dixon Bogert. We want to recognize the contributions of Bob Florian, Al Forni, Al Jones, and Jay Ticku by way of their enthusiastic efforts in the design, fabrication, checkout and installation of the hardware components of this system.

References

Summary

The problem of obtaining the electrode shapes to produce a conically converging proton beam that has constant current density over each spherical surface of convergence is treated in spherical coordinates. A cone is taken from the Langmuir and Blodgett solution for the region within, and at the edge of, the conically converging beam. A solution for the LaPlace equation, required for the region outside the beam, is in terms of a power series in r and the Legendre polynomials of \(\cos \theta\)

\[ V(r,\theta) = A_n P_n r^n . \]

The Langmuir and Blodgett potentials required at the edge of the beam are fitted by a power series in r,

\[ V(r) = \sum a_n r^n . \]

At the beam edge the two solutions are matched by making \(A_n P_n = a_n\).

Introduction

A mathematical method has been used to obtain the shapes of electrodes required to produce a conical spherically converging beam that has a uniform current density over each spherical surface of convergence. This is generally referred to as Pierce flow.

The theory for converging flow between concentric spheres was determined by Langmuir and Blodgett. The potentials required as a function of radius, those required along the edge of the beam, can be determined from Table I of the reference.

The problem is treated in spherical coordinates. A solution for the LaPlace equation, required for the region outside the beam, is known. The variables are separable and the solution is in terms of a power series in r and the Legendre polynomials of \(\cos \theta\)

\[ V_\phi, r = A_0 P_0 r^0 + A_1 P_1 r^1 + A_2 P_2 r^2 + A_3 P_3 r^3 + A_4 P_4 r^4 + \ldots . \]

where,

\[ P_0 = 1, \ P_1 = \cos \phi, \ P_2 = 3/2 \cos^2 \phi - 1/2 , \]

\[ P_3 = 5/2 \cos^3 \phi - 3/2 \cos \phi , \]

\[ P_4 = 7/4 \times 5/2 \cos^4 \phi - 5/4 \cos^2 \phi + 3/4 \times 1/2 . \]

Each term of the series is a solution of the differential equation. In addition, any sum of such solutions is also a solution. Consequently, a truncated series is a valid solution.

Five terms of \(V_r = \sum_{n=0}^{n=4} a_n r^n\) were found to provide a good fit to the table of potentials given by Langmuir and Blodgett for converging flow between concentric spheres (see Table I). Any larger number of terms is also allowable.

Following their procedure the equations are reduced to dimensionless form by using \(r = \frac{r}{R_0}\) and \(V = \frac{V}{V_0}\) volts/cm\(\times v_{\text{max}}\) volts \(V_{\text{max}}\).

The values of \(r\) for the case in which the diameter of the beam is reduced to half its initial value are such that \(r < 1\) so \(r^n\) decreases as \(r\) decreases and \(n\) increases.

In the first try, the coefficients \(a_n\), of

\[ V = \sum_{n=0}^{n=4} a_n r^n \]

were chosen to fit the reference table at five places. Subsequently, the coefficients were chosen by a least squares fit (see final paragraph, page 3) to all the values given in the table.

The coefficients of the two series

\[ V = \sum_{n=0}^{n=4} a_n r^n \]

for the region within, and at the edge of, the beam and

\[ V = \sum_{n=0}^{n=4} A_n P_n r^n \]

for the region outside the beam are matched at the edge of the beam; that is,

\[ a_n r^n = A_n P_n r^n \]

or \(A_n = a_n/P_n\) beam edge.

Note that \(P_n\) is a function of \(\phi\), and the match is made for \(\phi\) corresponding to the angle between the axis of the beam and the conical beam edge.

Table I gives the Langmuir and Blodgett values for \(V\) as a function of \(r\), and those obtained by the least-squares fit to the power series

\[ V = \sum_{n=0}^{n=4} a_n r^n . \]

*Work supported by the US Department of Energy.
Table I

LEAST SQUARES FIT

\[
V = \frac{V_{\text{volts}}}{V_0} V_{\text{max}}
\]

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<th>(r = \frac{R_{cm}}{R_0\text{cm}})</th>
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The coefficients are:

6.5530  -23.52025  34.91341  -25.22779  7.27889

Differences between the two values for \(V\) as a function of \(r\) are given also. Most of these differences are a few parts in ten thousand, so the fit is adequate for our purpose.

The idealized electrode shapes are those of the corresponding equipotential surfaces.

The example given below is that used in the first design for the PIGMI injector.\(^2\) This is for a 50-mA uniform proton beam from an idealized spherical plasma surface. The beam is accelerated to 250 000 eV and converges spherically from an 8- to 4-mm diam. The point of convergence would be 9.354 cm from the plasma surface. The 4-mm-diam exit aperture at -250 kV is 4.677 cm from the above mentioned center of convergence. The extraction electrode, at -50 000 V with respect to the plasma surface, is at 7.38 cm from the same center. The half-angle of the beam, from the axis to the edge, is 2.398°. The above numbers are also shown in Table II. A zero emittance beam is considered for the purpose of the calculation.

The shapes for the equipotential lines, those on which the shape of the column electrodes are based, are shown in Fig. 1. Table III gives numerical values for the shape of the electrode meeting the plasma surface from which the beam is
The angle between the axis of the beam and the beam edge is 2.398°. The proton beam current is 50 mA; \( R_0 = 9.354 \text{ cm} \). \( v_{\text{max}} = 250 \text{ kV} \).

Reference.


Modulator Reliability and Bandwidth Improvement: Replacing Tetrodes with MOSFETs

A.R. Donaldson

Summary

Three types of power MOS field effect transistors were studied with the intent of replacing a parallel pair of vacuum tube tetrodes in a linear modulator. The tetrodes have the shortest lifetimes of any other tubes in the system. The FETs offer definite performance advantages when compared to bipolar transistors and definite cost advantages when compared to vacuum tubes. Replacement of the tetrodes does however require careful consideration of voltage, current and to a lesser extent bandwidth capability in order to enhance overall modulator reliability without compromising present performance.

Introduction

The Fermilab linac modulators are 10 MW peak power linear systems which consist of three cascaded amplifiers. The output stage is composed of three parallel switch tubes (ITT 1123). The switch tubes are driven by two paralleled triodes (ML6544) and the tetrodes are controlled with two paralleled tetrodes (4CX600J). The switch tubes have logged up to 80,000 hours of operation and average life has been approximately 70,000 hours. The tetrodes average lifetimes have bordered on 24,000 hours. The tetrode lifetimes rarely exceed 8,000 hours and average about 6,000 hours. As there are two and it is time consuming to determine the weak or faulty unit both are generally replaced which reduces operating life to about 3,000 hours between either scheduled and/or unscheduled repairs. Diagnostic circuitry which could pinpoint specific tetrode failures has been contemplated but never commissioned because of the required complexity, volume limitations and location of the stage at high voltage (a bootstrapped pulse amplifier) within the the modulator. Downtime repair personnel can enter the modulator and replace the tetrodes easily since they are compact, air cooled and socketed, and because of past poor confidence, they are always suspect.

Modulator circuit analysis and operation have revealed that the tetrodes are responsible for a system small signal bandwidth limitation at 300 kHz. Beam loading compensation is accomplished with a feedforward signal derived from a beam current toroid which with appropriate scaling offers load cancellation. However, the pulsed load cannot be quickly or completely transient cancelled because of the 300 kHz bandwidth limitation, furthermore bandwidth decreases with tetrode age.

Solid state replacement of the tetrode would be an obvious strategy for enhanced reliability. The first consideration is high voltage as the triode stage must be driven into positive bias which requires a typical 800V swing (where 0.5A<2A) to generate a 30 kV modulator output pulse. For a 300 kHz bandwidth the necessary charging current is

\[ i_0 = C_L \frac{dV}{dt} \]

where: \( C_L \) is the sum of deck to deck, triode input and stray capacitance \( dV \) is the necessary triode grid pulse \( dt \) is the 10% to 90% rise time

\[ i_0 = \frac{(680 \, \mu F)(800V)/(1.2 \, \mu s)}{45A} \]

To maintain optimum linearity the maximum current drive should be five to ten times greater, i.e., the source impedance should be 0.2 to 0.1 of the load impedance. The drive impedance is dependent on the dynamic plate resistance \( R_p \) of the tube and the load resistance \( R_L \). Decreasing the \( R_L \) in an effort to improve the bandwidth would probably decrease reliability and the tubes are in parallel to maintain a low \( R_L \). For a 600 kHz bandwidth the charging current must be doubled. Then for linearity insurance the drive current should be 5A to 10A. This necessitates either four or five tubes in parallel or a semiconductor device with a low turn-off impedance. The turn-off time is controlled by the load capacitance and \( R_L \), a smaller \( R_L \) will decrease turn-off time.

The recent introduction of power MOS field effect transistors and their supposed superiority for fast power handling compared with bipolar transistors initiated this tetrode replacement analysis. The MOSFETs do exhibit some definite advantages, i.e., wider bandwidths because turn-off is not controlled by microsecond-like storage times, negative instead of positive thermal coefficient for comparable properly heatsinked devices, no secondary breakdown voltage effect and supposedly higher input impedance. The major disadvantage of power MOSFETs is high cost coupled with long lead times when compared to bipolar transistors, but these disadvantages are minor when compared to the cost, $470 per vacuum tube.

Table I lists the MOSFETs that were purportedly available and consequently acquired except for one. The table compares the published specifications and the test data between devices. The BVDS and \( I_D \) were the primary selection criteria. The \( I_D \) was measured with the FET in either a common source circuit or the bootstrap configuration with various resistive loads. The \( I_D \) ratings are published values and are more than adequate when the 0.006 modulation duty factor is considered. Furthermore, the modulator has adequate space and forced-air
cooling which will ensure conservative heat sink design. The \( R_{DS(on)} \) value is of minimal use for linear application as it describes the saturated switch resistance of the FET. The tetrode, however, exhibits an \( r \) which is two to five times larger than the FET dynamic \( R_{DS} \).

The table also provides actual threshold data, gain, capacitance and rise time data for two circuit setups. The input capacitance (\( C_{in} \)) and reverse transfer capacitance (\( C_{rss} \)) coupled with the gain offer a prediction of the possible rise times.

The devices were tested in the order they arrived. The Tokin device has the rather limited maximum operating voltage of 800V, but the triode stage only requires 700V to 800V of drive. Two I.R. FETs were connected in series with an appropriate resistive divider for a combined 1 kV maximum operation. The I.R. unit is in fact representative of U.S. involvement in the power FET market; all of the U.S. FETs have a 450V or 500V maximum limit. The 1 kV Siemens unit has been on order for the past seven months but recently an 800V device with reduced current capability became available and was tested.

The tetrode driver had to be redesigned to drive the FETs since they all exhibit input capacitances of 9 to 25 times that of the parallel tetrodes. It became obvious that the power FETs needed fast and low source impedance drivers. In spite of the high input impedance claim, it is only high during d.c. conditions and not the transient because of the high input capacitance. Fig. 1 illustrates the linear amplifier developed for comparison testing of the Tokin FET and tetrode. Both devices require a cutoff bias and then a positive voltage swing to near zero volts for linear operation.

The Tokin FETs exhibited an unfortunate and non-semiconductor-like performance variation with regard to speed and cutoff bias. The literature describing the development of the Tokin devices does not offer any reason for the variations. The bias problem can be accommodated with the driver circuit as the cutoff bias can vary from -40V to -75V. The speed is dependent upon the driver swing but not absolutely as once fast device required a 40V pulse while another needed a 55V pulse and both had 200 ns rise times. The medium speed devices had 400 ns rise times and required 45V pulses for 700V non-saturated outputs (\( V_{DD}=800V \)). One Tokin FET the slowest, had a 600 ns rise time. All rise times quoted are for linear operation with a load capacitance of 680 pf and \( R_s=330\Omega \) and faster times are possibly if the gate is driven positive to realize switch or saturated operation. The respective large signal bandwidths using \[ BW = 0.35c \tau_{(10-90)} \] are 1.75 MHz, 875 kHz, and 580 kHz. This three to one ratio could be reduced if the Tokin device were enclosed in a feedback circuit.

The Tokin FET has a bandwidth advantage dependent upon selection, a much higher current capability, but the output pulse is limited to 800V peak at saturation or less for linear operation. One Tokin device has been operated successfully for 600 hours with a \( V_{DS}=900V \) but considering the variation between devices it is not likely that this is a reliable operating value. The FET has a power dissipation rating of 300W at 25°C; tetrode drive requirements indicate the operating power dissipation is 3W to 5W for a .006 duty factor which implies very conservative application of the device.

The circuit of Fig. 2 illustrates the technique attempted for a series connection of lower voltage FETs. The voltages across the FETs are equalized with the high voltage divider and the FET at high voltage must be driven from an isolated source. The pulse transformer is an effective driver except that modulation duration is 330 \( \mu \)s to 400 \( \mu \)s and while the EGT rating of the transformer was large enough to permit full power operation the droop was unacceptable. Transformers with higher primary inductances are unfortunately slower. The inability to locate a commercial transformer with a fast rise time and large \( L_\pi \) meant that a linear light coupled isolator should be considered if the circuit complexity did not compromise reliability, but this approach has been temporarily sidetracked.

The third power FET tested was the 800V Siemens device. The Siemens FET like the I.R. FET is an enhancement mode device. Turn-on can be accomplished with an 5 to 10V pulse referenced at zero. The gain of the device is consequently large. The circuit of Fig. 3 shows the Siemens unit and FET buffer driven by a fast operational amplifier. The Siemens FET would provide the most compact package for tetrode substitution the floating box would only require a ±15V power supply for a reduction in stray capacitance, and hence better bandwidth for equal or less charging current capability. The question of reliability however is postponed until the higher voltage and current unit becomes available for testing.

**Remarks**

Refer to Table 1 for operating data comparisons. The common cathode/source amplifier data is not as pertinent to FET selection as the bootstrap amplifier data but was easier to obtain, allowed grid and gate monitoring without h.v. isolation and offered an idea of the Miller effect capacitance. When the load capacitance can be minimized the bootstrap amplifier offers a definite bandwidth advantage.

The Tokin FET has the lowest gain and the element determining rise time is the \( C_{rss} \).

The Siemens FET has the highest gain and hence, bandwidth is limited with the common source amplifier. The Siemens device was connected with a fast operational amplifier in a feedback bootstrap arrangement and with a 500V output pulse exhibited a 50 ns rise time but the circuit was unstable for a 700V output. Open loop circuit performance was evaluated and is presented in Table 1 offering a comparison with the other devices which were also evaluated open loop.
Until the 1 kV Siemens unit becomes available for evaluation the Tokin device although of limited h.v. utility and bandwidth is the tetrode replacement selection. It has operated successfully in the modulator and has more than adequate current and power handling capability. The triode stage does require a gain increase but this was easily accomplished and while triode lifetime may decrease slightly; the overall system reliability should be significantly improved.

Acknowledgement

The investigation was accomplished with the cooperation of Lester Wahl. He also made contributions to driver circuit design and operated the test modulator.

References

3. J. Nishizawa et al., High Power Static Induction Transistors, Late paper, 1978IEDM.

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Power MOSFETs

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FIG. 1. Tetrode bootstrap amplifier with MOSFET replacement.

FIG. 2 Series FET circuit.

FIG. 3. Amplifier with the BUZ-80.
Abstract

The new main RF amplifiers for the SuperHILAC are designed for high reliability, short repair-time, and low cost. Innovative use of copper-plated aluminum components cuts fabrication time, weight, and materials costs. The use of a simple, cylindrically loaded, $\lambda/2$ anode resonator is cost-effective and allows quick access to the tube when replacement is required. A high gain, neutralized, grounded cathode configuration simplifies the drive requirements. The EIMAC X2170 (8973) was chosen for proven reliability and low cost.

Introduction—Background

The SuperHILAC main RF amplifiers were originally designed around the RCA 6949 super power shielded gridtriode. This tube is very well mannered and easily achieves a stable gain of 18 to 20 db delivering the required 500-700 kW with 10-15 kW drive. The water-cooled beam former makes this tube extremely rugged and well-suited to driving "dirty" accelerator sparking type loads. However, in recent years, the RCA 6949 has become unavailable for tube replacement at any reasonable cost. Knowing that we would soon run out of the RCA 6949's, we soon run out of suitable replacement tubes prompted us to begin design studies for a replacement amplifier.

Design Specifications

1. The new design should use a tube of domestic manufacture and of reasonable cost, one that hopefully will remain in production for the remaining life of the SuperHILAC.
2. The new amplifier cart must be mechanically and electrically compatible with the existing systems as they will be used interchangeably for several years while we use up our supply of RCA 6949's.
3. The new design must provide increased reliability and maintainability over the existing system.

The EIMAC X2170/8973

The X2170 is the only serious contender in the power/frequency/price class. Although the X2170 is very cost-effective and exhibits very high gain, it has several very serious disadvantages when socketed for linear accelerator service, the first of which is its fragility. Since the X2170 is not a shielded grid design, it is therefore extremely prone to destruction from high-energy anode-to-screen grid arcing common in this service. At the SuperHILAC we have installed fast-acting crowbars to protect the tube from the stored RF energy in the main resonators as well as fast-modulator disconnects in the B+ line.

SuperHILAC amplifier with 4CW25K driver.

The SuperHILAC Amplifier Design

The requirement for compatibility between the new and old amplifier types puts some very severe limitations on the amplifier design. The most serious is the requirement that the new amplifier be driven to full output from the existing drive chain. (In the case of the prestripper, this is about 15-20 kW maximum per tube.) This requires a stable gain of about 17 db, thus precluding the possibility of running the stage in grounded grid configuration.

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Nuclear Science Division, U.S. Dept. of Energy under Contract No. W-7405-ENG-48.
To meet these objectives, we have designed the amplifier as a conventional grounded cathode stage with Jk/2 grid and anode sections. The anode resonator consists of a cylindrically-loaded coax with the blocking capacitor placed in the output transmission line. With this design, the voltages on all parts of the structure are low, the resonator is inexpensive and easy to fabricate, and the blocker is an off-the-shelf standard commercial unit.

The screen bypass capacitor is a multilayer kapton-insulated subassembly, capacity about 65 nF. The neutralizing network penetrates the screen capacitor at six places. Spark gaps are mounted on the top surface to protect the insulation in the event of an anode/screen arc.

By far the most challenging task facing our group was the design of the grid resonator/neutralizer system. The input capacity is high, currents are high, and space is at a premium. As a cost-saving measure, we elected to use the shortened radial line that has proved so effective on the 6949 amplifier. This saved considerable space directly below the socket, and placed the 180° point directly under the edge of the screen flange. This made it very easy to merely penetrate the screen capacitor with six neutralizing tabs coupled to the lower end of the active anode by a corona ring. This produces a simple neutralizing system free of any parasitic modes near the operating frequency. Since the grid input impedance of this tube varies widely with level and tune, it is imperative to use heavy resistive swamping on the grid. In our case, this amounted to 20 kW worth of nichrome-on-alumina water-cooled resistors mounted radially around the grid contact ring. This gives a grid-to-ground resistance of ~12 ohm and a gain of ~18 db.
Reliability

With the RCA 6949, the most serious problem is high-current joint failure at the junction of tube and resonator. This invariably results in total destruction of the 6949 tube.

In the X2170 cavity, all high current joints are massively bolted and are additionally water- or air-cooled.

Maintainability

The X2170 cavity/amplifier is designed so that the tube or the entire cart may be changed in a fraction of the time required to change the RCA 6949. The main improvement is making the anode transmission time a quick disconnect unit and designing the X2170 resonator system so that the tube is installed into a socket rather than having the resonators built up around the tube.

Conclusion

The X2170 and its cavity have proven that they can provide the required power output and ease of maintenance. Considerable work remains to be done to fully stabilize the amplifier at partial drive levels and eliminate the parasitic oscillations at 500 and 959 MHz.

References

THE rf MODULATOR DESIGN AND PHASE AMPLITUDE CONTROL FOR
A HIGH-POWER FREE-ELECTRON-LASER LINAC

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SUMMARY

The continued interest for building tunable lasers using an electron accelerator as the source of primary energy has resulted in the design of a new accelerator. Earlier work by other members of the Los Alamos team has demonstrated that this design does work in an amplifier mode. The accelerator is to be upgraded for use in an oscillator experiment and the new rf power amplifier system must meet some of the very stringent demands for power and stability placed on the electron beam for the free-electron laser (FEL) interaction to be observed. These demands are particularly stringent because the electron beam energy ultimately will be circulated back through the accelerator so that the electron beam energy not used in the FEL interaction is not wasted. These considerations have to some measure been incorporated into the design of the second FEL system at Los Alamos and are discussed in this paper.

INTRODUCTION

The primary needs of this accelerator are to provide the "make-up" power that must be replaced during the intrapulse interval to get the power back to the operating level required for satisfactory FEL interaction. The basic schematic for one of the possible accelerator configurations is shown in Fig. 1. System requirements call for a 100-μs pulse length and more than 7 MW peak power for some of the experiments. These are already severe requirements that exceed rated performance of existing klystrons. Additional performance criteria arise from the unique demands caused by the FEL interaction experiment. These demands relate particularly to the stability requirements of the phase and amplitude controls needed for the experiment. These stability requirements can be categorized as long-term stability (days), short-term stability (seconds), and phase stability (submicrosecond). These requirements must be met to have synchronization in the FEL interaction region. The output electron-beam energy must be held constant from pulse to pulse to have the correct electron momentum for resonance (and energy extraction) with the laser field. The condition for this resonance is given by the expression (in mks units)

\[ \gamma_T^2 = \frac{\lambda_w}{\lambda_L} \left( 1 + \frac{e^2 \gamma_w^2}{2 \alpha_m \alpha_c} \right) \]

where \( \lambda_w \) is the wiggler period, \( \lambda_L \) the laser wavelength, \( e \) the electron charge, \( B \) the rms magnetic induction of the wiggler, \( m \) the electron rest mass, and \( c \) the velocity of light. The term in parentheses represents a correction (generally of the order of unity) for the change in path length caused by the electron excursions in large magnetic fields. The allowable detuning of the laser from the resonance condition, the gain bandwidth of the FEL amplifier, is given by the approximate expression

\[ \Delta \lambda \sim \frac{1}{\lambda} \frac{\Delta \lambda}{2N} \]

where \( N \) is the number of magnet periods along the length of the wiggler.

The requirement on rf amplitude stability then becomes related to the frequency-gain characteristic of the particular wiggler used in the experiment. For example, the initial system has effectively 20 magnetic periods, so that from Eq. (2) the allowable frequency change is approximately

\[ \Delta f / f = - \Delta \lambda / \lambda = - \frac{1}{2N} = -2 \frac{1}{2} \% \]

so that

\[ \Delta \gamma_T / \gamma_T = - \frac{1}{2} \frac{\Delta \lambda}{\lambda} = 1 \frac{1}{4} \% \]

Long-term and short-term frequency stability of the rf is important in the experiment to avoid constant retuning of the optical cavity length. The frequency changes of the accelerator are
caused by thermal drifts and by aging. The optical cavity length is to be held to five parts in $10^3$. These changes can result in a phase shift of $8.2 \times 10^{-2}$ radians/pass that accumulates during the 100-us accelerator pulse length. To maintain less change in the accelerator, then

$$\Delta f / f < 2.0 \times 10^{-4}$$

Retuning the accelerator center frequency may be a convenient way to optimize (over small ranges) the optical cavity.

The laser cavity also is a resonant structure that sets requirements on the phase stability during shorter intervals. To allow the laser resonance to adjust, the phase of the electron-beam bunches entering the laser cavity should not change too rapidly. The response time is set by the laser cavity Q, which is greater than 50. During this interval, the frequency of the accelerator should not change enough that the photon packet and the electron bunch fail to overlap within 1-1/2 of phase, so that

$$\Delta f / f < 5.5 \times 10^{-4}$$

in a period of a few microseconds.

Another phase-stability requirement in a cyclic device is to have the electrons re-enter the accelerator at the proper phase (180° out, with respect to acceleration) to give up their energy to the accelerating structure. This requirement is also dependent on the accelerator emittance and longitudinal velocity spread, the beam bending magnets, and the amount of beam fluctuation introduced by the FEL interaction region. For this FEL with 100-MeV electrons, a 60-m-path length, and an allowable phase shift of about 5°, the allowable single-pass frequency shift is

$$\Delta f / f = 5.3 \times 10^{-5}$$

in a period of 200 ns.

Another constraint on the phase stability is that the electron micropulse packets must be properly spaced within the FEL interaction region. The typical figure for FEL design is that the intrapulse jitter be such that the phasing between the optical pulse and the electron pulse be synchronized within ten per cent of their width. For the present case, this means that the phase shift is limited to 2°, so that

$$\Delta f / f < 5.5 \times 10^{-4}$$

in a period of 50 ns.

Other rf Constraints

Aside from the normal personnel and equipment safety requirements, other constraints on the rf system include:

1. operation of one klystron to drive three separate accelerating rf cavities with independent phasing and amplitude control for each; and

2. the rf amplifiers need to be continuously variable in output power and pulse length to allow different experimental configurations.

The rf Modulator Design

The basic electrical schematic for the modulator has been previously described and is shown in Fig. 2. The system includes single-point grounding at the modulator tank and substantial rf shielding around the capacitor bank. The large capacitor tank (8.75 μF) was needed to minimize voltage droop during the pulse. This system, at full power, results in 1500-V droop during the pulse. This results in a phase shift of the rf pulse caused by the klystron with a beam path length, $l$, of

$$\Delta \phi = \omega \Delta t = \frac{\omega}{C} \left( \frac{1}{\beta^2} - 1 \right) = 0.22 \text{ radian, or about 12°,}$$

so that $\Delta f / f = 1.7 \times 10^{-6}$ in 100 μs.

Also, the long pulse length puts additional stress on the switch tube: fortunately, the standard LAMPF triode proved to be satisfactory for this application.

The rf Power Distribution System

The requirement to feed three tanks from one klystron actually was beneficial. This allowed for much less complex rf phase control because each tank was locked to a single driver, and slow phase control could be employed between the tanks. The rf distribution system shown in Fig. 3 has been assembled and has an insertion loss of less than a decibel (without the isolator). A similar distribution system has been demonstrated at X-band. The use of low phase versus temperature cable and some thermal control was necessitated by the long cable runs.

The rf Phase Control

The requirements for phase stability described above resulted in design of rf controls at the state-of-the-art. The rf source chosen for this system has long-term stability of three parts per
million, and minimized phase noise; these are accomplished by choosing the crystal frequency to be as high as possible and using low noise electronics. The phase spectral density (frequency domain) and Allan Variance (time domain) for two oscillators are now being characterized. In evaluating the performance of the rf source, as compared to the system requirements, the effect of the acceleration cavity also must be considered. This is a side-coupled, standing-wave structure with an anticipated loaded Q of 6500. The effective Q is anticipated to be very similar because of little rf overdrive available. This means that the cavity will not allow for frequency changes in time scale less than

$$\Delta t = \frac{1}{\Delta f} = \frac{Q}{f} = \frac{6.5 \times 10^3}{1.3 \times 10^9} = 5 \mu s$$.

This greatly simplifies the source design because both the rf source and the accelerating cavity are narrow band pass, high Q elements that do not allow fast frequency changes. Power provided to the tanks at the wrong frequency is dissipated in the isolators, circulators, and external loads designed into the system as shown in Fig. 3.

**The rf Amplitude Control**

The need for the very long pulse length in this experiment requires active amplitude control. The droop in the capacitor bank voltage results in a corresponding droop in the accelerating fields. This is accomplished with absorptive active attenuators that respond to the rf power droop during the pulse. The complete rf drive system is shown in Fig. 4.

**Acknowledgments**

It is with great pleasure that the authors acknowledge the help of Charles Brau, Robert Jameson, and Tom Boyd in translating the experimental program requirements into terms useful for rf design. The helpful conversations with Charles Brau, Robert Jameson, and William Stein have certainly made this a more useful design. The assistance of Ralph Garcia and Dave Keffler in making some of the rf tests and measurements is gratefully acknowledged, as is the earlier rf amplitude and phase control efforts of the designers of the Los Alamos Meson Facility.

**References**


Summary

Although the SUPERFISH program is used for calculating the design parameters of an RFQ structure with complex vanes, an analytical solution for electrical properties of an RFQ with simple vanes provides insight into the parametric behavior of these more complicated resonators.

The fields in an inclined plane wave guide with proper boundary conditions match those in one quadrant of an RFQ. The principle of duality is used to exploit the solutions to a radial transmission line in solving the field equations.

Calculated are the frequency equation, frequency sensitivity factors \( S \), electric field \( E \), magnetic field \( H \), stored energy \( U \), power dissipation \( P \), and quality factor \( Q \).

Simple Vanes

For this derivation, simple vanes are vanes whose sides form one straight line from vane tip to vane base, Fig. 1.

![Fig. 1a, b: Examples of Simple Vanes](image)

Principle of Duality

A structure which describes the fields in one resonator of an RFQ is an inclined plane wave guide. The fields in this structure are the duals of those in a radial transmission line. Therefore, all of the well-known equations for radial lines can be used for the inclined plane wave guide with the substitutions shown in Fig. 2.

![Inclined Plane vs Radial Line](image)

Solving for the constants \( A \) and \( B \) gives for the field equations:

\[
E_\phi = n \frac{G_1(\kappa r)}{G_0(\kappa r)} \left[ A \ e^{j\phi(\kappa r)} - B \ e^{-j\phi(\kappa r)} \right]
\]

\[
H_z = \frac{G_1(\kappa r)}{G_0(\kappa r)} \left[ A \ e^{j\phi(\kappa r)} + B \ e^{-j\phi(\kappa r)} \right]
\]

where

\[
\kappa = \sqrt{\mu \epsilon}, \quad n = 2\pi/\lambda
\]

\[
G_0(\kappa r) = \sqrt{J_0^2(\kappa r) + N_0^2(\kappa r)},
\]

\[
G_1(\kappa r) = \sqrt{J_1^2(\kappa r) + N_1^2(\kappa r)},
\]

\[
\phi(\kappa r) = \tan^{-1}\left[ J_0(\kappa r)/J_1(\kappa r) \right],
\]

\[
\psi(\kappa r) = \tan^{-1}\left[ J_1(\kappa r)/-N_1(\kappa r) \right].
\]

A and \( B \) are constants to be determined. The time varying part of the equations is not shown, and the end effects of the RFQ resonator are not taken into account.

Referring to Fig. 3, the boundary conditions are:

\[
E_\phi = E_i \text{ at } r = r_i,
\]

\[
E_\phi = 0 \text{ at } r = r_L.
\]

![Fig. 3: One RFQ Resonator](image)

Because the vanes create a highly foreshortened structure, the small argument approximations for the Bessel functions apply. Using these gives for the field equations:

\[
E_\phi = \frac{G_1(\kappa r_i)}{G_1(\kappa r_i)} \sin(\psi - \psi_L),
\]

\[
H_z = \frac{E_i}{jn} \frac{G_0}{G_1} \cos(\phi - \psi_L),
\]

where \( G_1 = G_1(\kappa r_i), \psi_i = \psi(\kappa r_i), \delta_1 = G_1(\kappa r_i), \) etc.; \( J = j - 1 \).
At resonance, \( H_z \) can also be written as:

\[
H_z = (E_f/\Omega_n) \frac{1 + (kr_L^4)(\gamma + \ln(kr/2))/2}{kr_L^4[1 - (r_L/r_i)^2]/2}.
\]

Other Parameters

The stored energy in a resonant structure can be expressed as:

\[
U = \frac{e}{2} \int \left| E \right|^2 \, dv = \frac{e}{2} \int_{r_i}^{R} \left| E_\phi \right|^2 L_0 \phi_0 \, r \, dr,
\]

giving for one resonator:

\[
U = \frac{e E_f^2 L_0 \phi_0}{2r_i^2 [1 - (r_L/r_i)^2]} \left[ (r_L^4 - r_i^4)/4 - r_i^2(r_L^2 - r_i^2) \right.
\]
\[
+ \left. r_i^4 \ln(r_L/r_i) \right];
\]

\[
U_{TOTAL} = 4U.
\]

The power dissipated in an RFQ resonator is composed of two parts, that lost in the vane walls, and that lost in the cylindrical surface. The two parts are given approximately by:

\[
P = 2 R_s/2 \int_{S} \left| J_r \right|^2 \, dS + R_s/2 \int_{S} \left| J_r \right|^2 L_0 \phi_0 r \, L
\]

where

\[
R_s = 1/\sigma, \sigma = \text{conductivity}, \delta = \text{skin depth},
\]
\[J_r = H_2(kr) = \text{current per unit width}.
\]

At resonance,

\[
-\left[ \gamma + \ln(kr_i/2) \right] = 2/(kr_L)^2
\]

(see frequency equation below), and \( P \) can be written as:

\[
P = \frac{R_s E_f^2 L_0}{2\pi} \frac{[1 - (r_L/r_i)^2]^2}{(kr_L)^2} \times
\]

\[
\left\{ \frac{\left[ \gamma + \ln(kr_i/2) \right]^2}{1 - \gamma + \ln(kr_i/2)} \phi_0 r_L
\]
\[
+ \frac{kr_i^4}{2} \left[ r_L - 2r_i + r_L \ln(r_L/r_i) - 1 \right]^2 \right\}.
\]

The Frequency Equation

The field shapes in an RFQ are greatly distorted from the TE210 mode in a conventional cylindrical resonator. This results in a resonant frequency on the order of four times lower than the classical TE210 mode.

The input wave admittance, Fig. 2, for an inclined wave guide is given by:

\[
Y_{i} = \frac{H_z}{E_\phi} = Y_{0} \cos(\psi_i - \psi_L) + j Y_{0L} \sin(\psi_i - \psi_L),
\]

Given that the structure, Fig. 3, is resonant, we have:

\[
Y_{L} = \omega, \text{ boundary condition,}
\]
\[
Y_{i} > 0, \text{ resonant condition,}
\]

therefore

\[
\psi_i - \psi_L = \pi/2
\]

and \( \tan(-\psi_i) = \cot \psi_L \), giving for the frequency equation:

\[
N_0(kr_1)/J_0(kr_1) = N_1(kr_1)/J_1(kr_1).
\]

Using small argument approximations for the Bessel functions gives for the frequency equation:

\[
-\ln \frac{kr_1}{2} = \gamma + \frac{2}{(kr_L)^2}
\]

where \( \gamma = 0.5772\ldots \) = Euler's constant.

One immediate result is the fact that the resonant frequency does not depend on the angle of inclination of the two planes.

Two examples:

1. RFQ model for Bevatron linac preinjector.
   (For cross section, see Fig. 1b.)

\[
r_i = 0.145 \text{ cm} \quad \text{Resonant Frequency} \quad \text{SUPERFISH} = 372 \text{ MHz}
\]
\[
r_L = 8.5 \text{ cm} \quad \text{Calculation} \quad = 370.6 \text{ MHz}
\]

\[P_{TOTAL} = 4P.\]

The quality factor (Q) for the resonator is defined as:

\[
Q = \omega U/P.
\]

Substituting for \( U \) and \( P \) gives:

\[
Q = \frac{\epsilon}{4k_s} \frac{\phi_0 k_n^2 n^2}{\left[ (r_L^4 - r_i^4)/4 - r_i^2(r_L^2 - r_i^2) \right.}
\]
\[
+ \left. r_i^4 \ln(r_L/r_i) \right]^2 \phi_0 r_L
\]
\[
+ \frac{(kr_i^4)}{2} \left[ r_L - 2r_i + r_L \ln(r,L/r_i) - 1 \right]^2 \right\}.\]
2. RFQ cold model I for the Numatron Project.²
(For cross section, see Fig. 1a.)

\[ r_i = 1.0 \text{ cm} \]
\[ r_L = 9.5 \text{ cm} \]

Resonant Frequency
SUPERFISH = 453.9 MHz
Calculation = 452.9 MHz

A quick look-up graph for RFQ resonant frequency vs. dimension is given in Fig. 5 for ranges of common interest.

![Graph of Freq vs. r_L](image)

**Fig. 5: RFQ Frequency vs. r_L**

**Sensitivity Factors**

The variation in resonator frequency due to dimensional errors can be found by taking differentials of the frequency equation. The sensitivity factors for errors in input and output radius are shown below and plotted in Figs. 6 and 7 for typical radii.

![Graph of Sensitivity Factor vs. r_L](image)

**Fig. 6: Sensitivity Factor for r_i**

![Graph of Sensitivity Factor vs. r_i](image)

**Fig. 7: Sensitivity Factor for r_L**

\[ S_i = \frac{df}{f} \left| \frac{dr_i}{r_i} \right| = \frac{4}{(kr_i)^2 - 1} \]
\[ r_i = \text{const.} \]

\[ S_L = \frac{df}{f} \left| \frac{dr_L}{r_L} \right| = -\frac{4}{(kr_L)^2} \frac{1}{4/(kr_L)^2 - 1} \]
\[ r_L = \text{const.} \]

Example:
\[ f = 200 \text{ MHz}, r_i = 0.31 \text{ cm}, r_L = 15.8 \text{ cm}, Q = 4000 \]
\[ df = 50 \text{ KHz} \quad \text{one-half power bandwidth} \]

from figure 6,
\[ dr_i = \frac{r_i}{S_i} \times \frac{df}{f} = 6 \times 10^{-4} \text{ cm} \]

from figure 7,
\[ dr_L = \frac{r_L}{S_L} \times \frac{df}{f} = 3.5 \times 10^{-3} \text{ cm} \]

This demonstrates the extreme frequency sensitivity due to dimensional changes.

The sensitivity factor, \( S_\phi \), for vane tilt errors can be written in terms of the other factors as:

\[ S_\phi = \frac{df}{f} \frac{d\phi}{\phi} = -S_L \frac{1}{2} \cot^2 \theta \]

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References

Measurement of Model Inter-digital H Type Linac

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Introduction

It is known that the inter-digital H type linac (IH linac) will have high shunt impedance per unit length ($Z_s$) for the acceleration of low velocity particles.\(^1\)\(^-\)\(^3\) IH linac is therefore suitable for heavy ion acceleration, and $Z_s$ as high as 120 MR/m has been realized in the post accelerator of the Tandem Van de Graaf accelerator in Munich.\(^4\) This extremely high $Z_s$, however, is due to low capacitance between the drift tubes which are not mounted with focusing element and are very small. The $Z_s$ depends on the capacitance per unit length, $C$, as $C^{-3}$.\(^1\) In case of IH linac which directly accelerates the particle from usual Cockcroft-Walton injector, the $Z_s$ will be considerably lower than the one in Munich linac due to large capacitance between closely aligned drift tubes with focusing element. $Z_s$ also depends on particle velocity to be accelerated, $\beta = \frac{v}{c}$, as $\beta^{-2}$,\(^1\) and it is interesting in what velocity region the IH linac has the advantage over Alvarez linac. When $\beta$ is assigned, $Z_s$ is regulated by tank component dimensions such as waveguide ridge, drift tube, drift tube stem and so on. This will be examined by model tank experiment more efficiently than by the computational means because the electromagnetic field in the tank is not symmetric and is so much complicated. We are performing the rf measurement on a 1/6 scale model tank following the study on a simplified 1/8 scale model.\(^5\) The aim of series of measurements are a) to obtain the dependence of the shunt impedance on the tank structure, b) to know the resonance characteristics for the various tank structure, which is necessary for equivalent circuit analysis, and c) to study the electric field distribution along the tank axis and to clarify the effect of the tank end structure on the field pattern.

Model Tank

The model tank in the present work is shown in Fig. 1 and 2. It has been prepared by reducing to a scale of one-sixth of the natural tank which will have a diameter of 2.4 m and will be operated by an rf of 25 MHz. The dimensions of the tank component which will affect the shunt impedance can be modified stepwise. These parameters are shown in Table 1.

| Tank diameter (D) | 400 mm |
| Ridge length (L) | 800 ~ 960 mm |
| Ridge width (W) | 800 mm |
| Aperture** (d) | 30, 50, 60 mm |
| Drift tube diameter | 18.7, 26.7, 30, 33.3 mm |
| Stem diameter | 6, 8, 10 mm |
| Gap to cell length ratio ($g/L_c$) | 1/3 |

*) Electric tank length is adjusted by sliding the end plates.
**) Ridge to ridge distance.

Table 1. Parameters of model tank.

Resonance Characteristics

In Fig. 3, resonant frequency of fundamental mode $TE_{111}$ is plotted against $\beta$. The resonant frequency is given by $1/2\pi\sqrt{L/C}$, $L$ and $C$ being inductance and capacitance of the tank, respectively, and it increases as the drift tube spacing become distant, i.e., $\beta$ become large due to the decrease of the capacitance. In the tank for actual acceleration, therefore, the local resonance frequency varies according to the curves in Fig.3
as the structure of the tank changes along the longitudinal direction. Fig.3 inversely indicates the amount of frequency difference to be adjusted when one needs constant resonant frequency along the entire tank length. The frequency difference is 4\(\pm 13\)\% for 1\% change in \(\beta\). It is also seen in Fig.3 that the resonant frequency increases when ridge to ridge distance is decreased in the \(\beta\) region above 4\% and vice versa around 3\%. This means that the growth of the capacitance is overcompensated by the fall of inductance due to the reduction of the effective cross section of the tank in the \(\beta\) region above 4\%.

Fig.4 and 5 are dispersion curves. As seen in the figures, the group velocity of the electromagnetic wave is definitely positive, periodic nature of the waveguide being not apparent in dispersion characteristics. One can determine the equivalent circuit parameters by using the accurately measured frequencies up to fourth harmonics. Analysis is now in progress.

Field Distribution

The electric field distribution was measured by the perturbing ball method with 5.6 \(\phi\times30\) mm and 3 \(\phi\times30\) mm cylinder of acrylic acid resin as a perturbator.

Fig.6 shows the field distribution of typical constant velocity type tank of \(\beta = 4\%\). In case of \(L = 880\) mm i.e. ends of the ridge being shorted, the electric field strength is sinusoidal along the axis, as shown in Fig.6. This resonant mode is TE111. In case of \(L = 880\) and 960 mm, that is, for the resonator tank longer than the ridge, and having end spaces, the field distribution is fairly flat as shown in Fig.6. More flat field distribution is possible by using the capacitive tuners of brass plate (40 mm \(\times\) 10 mm \(\times\) 2 mm) as shown in Fig.1. Introduction of the capacitive tuner, however, results in 30\% reduction of Q-value. Therefore, two inductive tuners for tank end and eight inductive tuners for the ridge end are now being manufactured. We expect that the field distribution can be controlled by the inductive tuners without deterioration of shunt impedance.

The gap-voltage distribution of the acceleration type tank was measured for various resonator lengths as shown in Fig.7. In case of \(L = 800\) mm, the gap voltage distribution can be calculated by using the dispersion curves of constant velocity type tank (Fig.3) with the same dimensions. The calculated values agree with the measured values very well as shown in Fig.7. Therefore, the field distribution of acceleration type tank which are shorted at the end of ridge, can be calculated by the dispersion curves for the constant velocity type model.
If Gtp Voltaga Distribution
o( Ace. Typ. I .-.**)

Fig. 7 Gap voltage distribution along the axis (acceleration type model).

Shunt Impedance

Shunt impedance is obtained by measuring a Q-value and a resonant frequency shift $\Delta f/f_0$ due to a dielectric perturbaor and by using the following equation,

$$Z_s = Q_0 \frac{\Delta f}{f_0} \frac{L_c}{L_t} \alpha \frac{1.14}{r^2(r+1)} \times 10^4 \text{ [m]}$$

where $Q_0$ is unloaded Q-value of the tank, $L_c$ is tank length, $L_t$ is total cell length, $\alpha$ is gap to cell length ratio $g/L_c$, $r$ is the radius of the dielectric rod spanned over entire tank through beam bore and $\epsilon$ is a dielectric constant of the rod.

The results are shown in Fig. 8 and 9. The indicated shunt impedance is for model tank which is made of brass, and the value for the actual tank is $\sqrt{Q_0/Q_{0b}} \cdot n$ times the one for the model, where $Q_0$, $Q_{0b}$ and $n$ are the conductivity of the copper and of the brass, and the scaling factor, respectively. It is seen from Fig. 8 that $Z_s$ varies with $\beta$ as nearly $\beta^{-1.4}$.

In both figures, the effect of the tank end space on $Z_s$ is clear. Since the ridge length is kept to be 800 mm, the model tank with $L = 800$ mm has no space at tank ends, whereas $L = 960$ mm means that 20% of the tank is free cylindrical waveguide at its ends. The shunt impedance is remarkably higher for the model with the end space than for the one without the end space. It is supposed that the power loss increases unless the space for the longitudinal H field to turn at the tank ends is prepared. Shunt impedance for the tank with $L = 880$ mm, which is not shown in the figure, almost coincides with the one with $L = 960$ mm. This means that the preparation of end space causes the extension of the tank length, but the improvement of the field strength contributes for $Z_s$ to be nearly constant.

Thus the structure of the tank end is of great importance for improving the shunt impedance as well as for controlling the field distribution along the axis as described in the preceding section. An empty waveguide at the tank ends is the most simple example.

Fig. 9 shows the dependence of $Z_s$ on a ridge to ridge distance. A larger distance is better as far as $Z_s$ is concerned. This result has great significance and should be discussed further. On the other hand, a larger ridge to ridge distance results in a higher resonant frequency at a higher $\beta$ as shown in Fig. 3. If one wants to keep the resonant frequency of the tank at a given value under condition of the reasonable tank diameter, one has to use a ridge for the tank. We might conclude tentatively that the ridge dimension is determined from compromising the reasonable tank diameter and a shunt impedance at a given frequency.

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References

AN RFQ LINAC FOR HEAVY ION ACCELERATION

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Summary

An rf characteristic has been studied on an RFQ model cavity with two kinds of vanes, straight and modulated. The measured resonant frequency is 296.0 MHz for the TE210 mode and well agrees with the calculated value 296.5 MHz by SUPERFISH for the straight vane. The measured one is 293.5 MHz for the modulated vane which has the same cross section as the straight vane at its quadrupole symmetry plane. The measured electric field in the acceleration bore agrees with the calculated one within the statistical error. A sufficient mode separation and uniform field distribution have been obtained with a single loop coupler which matches the cavity to the feeder line.

On the basis of the modelling study, a lithium ion test linac 'LITL' has been designed and is in course of construction. It is designed to accelerate heavy ions of 5 keV/u with charge to mass ratio, q/M of 1+7 to the final energy of 138 keV/u in the vane length of 1.22 m. The operating frequency is 100 MHz and the rf power is fed with a single loop coupler. The maximum intervane voltage is 62 kV, which corresponds to 1.8 times the Kilpatrick's limit.

Introduction

The NUMATRON is a high energy heavy ion accelerator proposed at INS.1) It consists of injector linacs and two synchrotrons which accelerate heavy ions including uranium to 1-2 GeV/u. The injector linacs are required to accelerate heavy ions from several keV to 10 MeV/u. An RFQ linac is preferable at the lowest energy stage of the injector owing to its buncher function and applicability to high intensity beams in a low B region.2,3) On application of an RFQ linac to heavy ions the following subjects remain to be studied on the structure and rf power feed.

In order to get sufficient focusing force for particles with low charge to mass ratio q/M, it should be operated at a low frequency, for example, 25 MHz for U⁵⁺. This frequency results in a cavity diameter of 2.5 m. Then the first problem is how to mount the vanes to such a large tank with a close tolerance and good electric contact. The second is how to tune the cavity to get the required resonant frequency and field distribution. The required rf power is inversely proportional to (q/M)² and the beam loading much differs with ion species. The rf power in a wide dynamic range should be fed to the cavity with a variable input impedance. A loop coupling is desirable because it needs no outer chamber and is flexible to the change of the input impedance. It is the third problem how to make a uniform field and get a sufficient mode separation with a single loop coupler.

To study these subjects, a modelling study has been done on a low power model. In parallel with the modelling study, a beam dynamics study has been done. On the basis of these works, a test linac has been designed and is in course of construction. In this paper the results of the modelling study and the design of the test linac are described.

Modelling Study

Model Cavity

The cavity was manufactured with close tolerance in order to study the effect of the mechanical errors on the field distribution. The vanes are attached to the tank in the ways of setting and electric contact which are applicable to an actual acceleration cavity, though the cavity dimension is much smaller than an actual one. The tank is 258 mm in inner diameter and made of aluminum alloy. The vane is 35 mm thick, 960 mm long and has gaps of 20 mm to the end walls, and is made of copper. The straight vanes were attached to the tank and then replaced by the modulated vanes. The modulated vane has a constant cell length of 30 mm and a characteristic radius of 14.3 mm. The modulation factor m is 2. The minimum aperture radius is 10 mm. The cell length and aperture are exaggerated for the convenience of the filed measurement in the bore. The vane tip is approximated to a circular arc. The straight vane has the same geometry as the modulated vane at the quadrupole symmetry plane. The vane tips were machined with an NC milling machine. The vanes are contacted to the tank with copper braids which have elastic cords inside. The final error of the vane setting is within 0.1 mm. Opposed to the vane ends eight end tuners are mounted on the end walls. The side wall has 36 holes for the rf coupling and field measurement.

Field Distribution

The cavity has been tuned by means of the end tuners so that the magnetic field distribution might be uniform longitudinally and azimuthally in the four chambers. The field distribution has been measured by the perturbation method. Before the tuning the nonuniformity of the field amounted to ± 25% in spite of the close tolerance. After the tuning nonuniformities within ± 2% have been obtained for the both sets of the vanes.
The electric field distribution on the axis has been measured by using an aluminum perturbing ball 6 mm in diameter. The result agrees with the calculated one (Fig.2). The electric field distribution around the vane tips is similar to that of the magnetic field in the chambers. In the case of an acceleration cavity whose bore is so small as to make the field measurement difficult, the electric field in the bore will be estimated by means of the magnetic field measurement.

**Mode Separation**

Figure 3 shows the resonant frequencies for the various modes in the cavity with the straight vane, which is tuned so as to give a uniform field for the TE210 mode. The resonant frequency for the TE210 mode is 296.0 MHz and well agrees with the calculated value 296.5 MHz by SUPERFISH. The ones for the TE110 modes are 294.0 and 293.2 MHz, respectively, and considerably higher than the SUPERFISH value 285.7 MHz. For the modulated vane the resonant frequencies are 293.5 MHz for the TE210, 289.6 and 288.7 MHz for the TE110 modes. In the case of the TE110 modes, the magnetic flux is dominant in a pair of opposing chambers and faint in the other pair. TE110 mode has two resonant frequencies corresponding to the choice of the pair. When plates have been placed in the zero potential surfaces for the TE210 mode, the mode separation has been bigger two times with little effect on the field distribution around the vane ends.

![Fig.2. Electric field distribution on the axis.](image)

![Fig.3. Resonant frequencies for various modes of the cavity with the straight vane.](image)

The Q Value and rf Coupling

The loaded Q values have been obtained from the decay time constant of the stored energy in the cavity for various rotation angles of the input coupling loop. The pulsed rf power is fed to the cavity through a circulator and the reflected power from the cavity is dissipated in a 50 Ω resistor. The unloaded Q value has been obtained from the decay time constant with an infinitesimal coupling. For the straight vane, Q is 3400, which is 44 % of the calculated value. With an effective loop area of 23 cm² the loaded Q value is half of Q, and the cavity has been matched to the feeder line, which has been assured by the use of a network analyzer. This loop area agrees with a calculated value by an equivalent circuit analysis.7

The magnetic field was stronger in the chamber with the loop and weaker in the opposing chamber, whereas a slight re-tuning has brought a uniform field with the strong coupling.

![Fig.4. Loaded Q value vs. A_1 Cos^6.](image)

An RFQ Lithium Ion Test Linac 'LITL'

**Beam Dynamics Study**

An RFQ test linac has been designed in order to study the following subjects: rf power feed to the cavity with beam loading, sparking limit, cavity cooling and comparison of the characteristics of the accelerated beam with the PARMTEQ results. Considering the ion sources and related power supplies available at INS, the input beam parameters have been chosen as follows: q/M = 1.1/7 (H^+, vN), the injection voltage V_i = 5 keV/u, and the normalized emittance ε_n = 0.3 π mm-mrad. The maximum surface field strength of 20.5 kV/mm has been adopted, which corresponds to 1.8 times the Kilpatrick's criterion at the operating frequency of 100 MHz. Under these conditions the optimum vane parameters have been searched.

Details of the design procedure and the vane shape of the radial matching section are described in the separate papers.5,6 The PARMTEQ parameters and result of the beam dynamics simulation are shown in Figs.6,7. In 132 cells including 12 cells of the radial matching section, the particles are accelerated from 5 to 138 keV/u. The characteristic aperture radius has a constant value r_0 = 4.1 mm except at the radial matching section. The modulation factor m is varied 1 to 2.2. The minimum aperture radius is 2.5 mm. The intervane voltage is 61.8 kV for q/M = 1/7. The transmission is 97 % for the injected dc beam with a normalized emittance ε_n = 0.6 π mm-mrad when the space charge effect is...
negligible. This value becomes 85 % for a 5 mA beam of q/M = 1/7.

Acceleration Cavity

The cavity cross section at the quadrupole symmetry plane has been determined with SUPERFISH so that the resonant frequency is 100 MHz for the TE210 mode. The geometry has a calculated resonant frequency of 97.6 MHz for the TE110 mode. The tank is 360 mm in inner diameter, 1.4 m long and made of copper plated mild steel. The vane has a length of 1223 mm and gaps of 5 mm to the end walls, and is made of OFHC. Each end space for the magnetic return path has an area nearly equal to one eighth of the cavity cross section. The central part of the both end walls are protruded to the vane ends to keep the narrow gaps. The tank and vane are electrically contacted with silver coated stainless steel tubes. The vane is approximated to a circular arc which has a radius equal to the radius of curvature of the theoretical shape at the vane top. With the vane shape, higher vane voltage is applicable due to the wider intervane distance and a practically quadrupole field is obtained in the acceleration bore. The cavity is evacuated with turbomolecular pumps, operated at a vacuum pressure below 1.10^-7 Torr. The tank and vanes have cooling passes which suppress the elongation of the vane length by temperature rise below 100 μm on cw operation at full power.

The rf power is supplied with a master oscillator and power amplifier system. A tetrode tube Eimac 4CW25000 supplies a cw rf power of 25 kW. The intervane voltage of 62 kV requires 14 kW with the calculated Q value of 18000. At that time the peak current on the cavity wall is 15.2 A/cm.

The modelling study has shown that a sufficient mode separation and uniform field can be obtained with a single loop coupler. The beam dynamics study has given a vane design which has a satisfactory acceptance and an average acceleration rate of 0.8 MV/m over the full length. On the basis of these work, a test linac 'LITL' and an rf power system are now in course of construction. Measurements on the following subjects will be made and compared with the PARMTEQ results:(1) Dependences of the transmission on the vane voltage, the intensity, emittance and input energy of the input beam:(2) Emittance, energy spread and time structure of the output beam.

Acknowledgement

The authors would like to thank Toshiba Electric Corporation Tsurumi Works for their continuous interest and manufacturing of the cavities. The SUPERFISH calculation has been performed with FACOM 180 II AD at INS.

References

4) T. Nakanishi et al., INS Report, INS-NUMA-30, to be published.
5) N. Tokuda and S. Yamada, contributed to the Conference.
6) S. Yamada, contributed to the Conference.

Fig.5. Magnetic field distribution in the cavity matched to the feeder line.

Fig.6. The PARMTEQ parameters for LITL.

Fig.7. Transmission vs. input beam intensity(q/M=1/7).

Fig.8. Cavity structure of LITL.
EXPERIMENTAL RFQ AS INJECTOR TO THE CERN LINAC I*  
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Summary
Since the successful development and testing of a radio-frequency quadrupole (RFQ) prototype at Los Alamos, the use of RFQs as injectors to the CERN linacs is being envisaged. As a pilot project, a 202.56-MHz RFQ for Linac I (Old Linac) is being built in close collaboration between Los Alamos and CERN. We intend to complete this project in about 15 months, a time scale imposed by other CERN programs. The CERN RFQ is based on the Los Alamos proven design approach, but will have to meet requirements of the existing CERN environment. The design characteristics of this accelerator are described, and some conclusions based on model work at CERN are given.

Introduction
The successful proof-of-principle test of an RFQ at Los Alamos,1-3 announced at the 1980 International Accelerator Conference,4 was the trigger for launching a collaboration between CERN and Los Alamos on this project. The aim of this joint development effort is to design and build an RFQ as a preaccelerator for CERN's Linac I, where it has to fulfill the stringent requirements generally imposed on an injector. We hope that this project can be taken as a model for an RFQ that can later replace the 750-kV Cockcroft-Walton and the low-energy beam transport on Linac II. In general, it would serve to refine and to further test the validity of the design techniques, and would provide the CERN staff with insight that could be useful for future potential applications for the RFQ.

Description of The Project
The schematic layout of the CERN RFQ project is shown in Fig. 1. A low voltage, 50 kV, has been chosen for the low-energy beam transport to simplify the high-voltage installation. Two solenoids suffice to focus a rotationally symmetrical beam into the rotationally symmetric transverse RFQ acceptance.

The high-voltage beam transport is at 520 keV, the injection energy of the CERN Linac I. The construction of the first Alvarez tank (separate vacuum vessel around the actual rf structure, and no quadrupole in the first half-drift-tube) is an inconvenient arrangement for the RFQ, which normally should be brought within a distance of a few centimeters of the rf structure. This being impossible, a 520-keV transport line, comprising three quadrupoles and a buncher (or "matching cavity"), had to be designed.

The rf power is fed directly into one of the RFQ's intervane spaces. Movable bulk tuners in all four quadrants insure the tuning. The vane modulation has been computed and they are being machined at Los Alamos.

*Work supported by the US Department of Energy and by CERN, Geneva, Switzerland.
No steering elements are included in the setup. The RFQ and the 520-keV beam transport will be aligned on the Alvarez tank. The steering will be achieved by mechanical adjustment of the source and the 50-keV transport before mounting them on the RFQ.

The CERN RFQ has to be installed on an existing Alvarez linear accelerator; hence, some constraints are put on the choice of parameters. The RFQ should be designed for a 202.56-MHz frequency, a 520-keV output energy, and an ~100-mA beam intensity. Furthermore, the RFQ should give a high capture efficiency, a limited emittance growth, and reliable operation. The design, proposed by Los Alamos, follows the usual concept of dividing the RFQ in sections; because of the relatively low final energy, the last (accelerating) section has been omitted, so that only the radial matching section, the shaper, and the gentle buncher remain.

Precautions must be taken with respect to maximum electric fields in the RFQ. To compute the enhancement of the electric field caused by vane modulation, a special computer program has been developed capable of treating three-dimensional field problems. With the condition that $E_{\text{max}} < 1.75$ times the Kilpatrick limit (~25.7 MV/m), the parameters given in Table I have been established for the CERN RFQ.

Beam Transport and Matching

Preinjector and 50-keV Transport: A CERN duoplasmation ion source, slightly modified, is used with a 50-kV dc accelerating column. The three-electrode column also provides some focusing and screening against backstreaming electrons.

Because the beam is rotationally symmetrical at the column output, and should be so at the RFQ input, quadrupole lenses were found to be inconvenient for this region. The high beam intensity also made the use of electrostatic lenses impractical; finally, solenoids were chosen. The high fields compelled one to treat iron saturation, in addition to aberration problems. A compromise design resulted in a pulsed solenoid with laminated-iron return yoke; the central field on axis approaches 1 T, the effective length being ~10 cm. Figure 2 shows the beam evolution from the ion source to the RFQ.

The 520-keV Transport: Three quadrupoles and a matching cavity are necessary to bring an acceptable beam into the Alvarez. In the Alvarez, the first four quadrupoles complete the transverse matching, so that the beam is matched into the linac's transverse acceptance from the fifth cell onwards (see Fig. 3). Longitudinally, we cannot avoid a slight mismatch; this mismatch probably will not be too harmful. Furthermore, the relatively large distances between the tanks of the Linac I constitute other unavoidable sources of longitudinal mismatch. For the moment, some beam losses will be tolerated in Tank 1, because the required gradients for the first and third quadrupoles (73 and 60 T/m, respectively) are out of reach of the present magnets.

The rf Aspects

Two models have been built for the experimental study of the tuning process: a rough approximately half-scale mock-up, and a one-to-one model of high precision and rigidity (Fig. 4A). Tests have been done on the latter, with a single unmodulated vane isolated by a roof-shaped shield at the symmetry planes of the quadrupole mode (Fig. 4B).

![Fig. 2. Beam envelopes for 50-keV beam transport.](image)

### Table I

<table>
<thead>
<tr>
<th>CERN RFQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>W (MeV)</td>
</tr>
<tr>
<td>$E_s$ (MV/m)</td>
</tr>
<tr>
<td>$r_0$ (mm)</td>
</tr>
<tr>
<td>$\phi_s$ (deg)</td>
</tr>
</tbody>
</table>

PARMETEQ RESULTS

<table>
<thead>
<tr>
<th>Ion: proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency: 202.56 MHz</td>
</tr>
<tr>
<td>Input current: 100 mA</td>
</tr>
<tr>
<td>Output current: 89 mA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input (90°): 0.068</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output (90°): 0.20</td>
</tr>
<tr>
<td>Input (rms): 0.017</td>
</tr>
<tr>
<td>Output (rms): 0.043</td>
</tr>
</tbody>
</table>

$a$ The emittances are normalized values and are to be multiplied by $\pi$ to obtain the ellipse area in cm-mrad units.

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Let $\phi_1, \phi_2,$ and $\phi_m$ represent the axial magnetic flux (or interchangeably, a transverse electric field quantity) at Ends 1, 2, and in the center of the vane section. If the relative loading of the two end cells is modified so that the overall resonant frequency remains constant, the linear tilt ($\phi_1/\phi_2$) can be set to any arbitrary value; however, the nonlinear term $[2\phi_m/(\phi_1 + \phi_2)-1]$—that is, the relative field deviation from linearity in the middle—remains essentially unchanged. Repeating the test at different frequencies, and with different end-cell geometries, leads to curves such as Fig. 5: the nonlinear term is zero only at a particular frequency, which depends slightly on the shape of the end cell. Operating above this frequency leads to increasingly convex longitudinal field distributions; operating below this frequency leads to increasingly concave shapes.

This behavior can be interpreted as the combined action of two effects.

- A solely vane-dependent part determines a unique frequency for the zero of the nonlinear term, and its slope, in this region. This frequency is the cutoff, or zero-order frequency of the vane geometry and may be calculated by codes such as "SUPERFISH." The slope reflects the structure's reaction to detuning and associated reactive-power transfer.
- A higher mode part accounts for differences in the field pattern of the intervane space and the end pieces. The higher modes, created at the ends, tend to reinforce, or to cancel, the already existing nonlinearity and cause the observed frequency spread for vanishing nonlinearities around the unique cutoff frequency.

The RFQ will be tuned as follows.

- The end cells are permanently tuned by movable or exchangeable inserts in a cutout at the base of the vane ends. The distance of the cavity endplate from the vane tips is 10 to 15 mm; at that distance, the influence on the tuning is minimal.
- In the vane region, each quadrant contains two bulk tuners (a total of 8) that are adjustable during operation. Two rows of five diagnostic holes per quadrant, vacuum sealed by glass tubes, will permit continuous monitoring.

The rf power will be fed directly, by a single loop, into one quadrant; however, additional flanges are provided to feed each quadrant, if necessary. Despite its many attractive features, the rf manifold has not been included in the design; the relatively large outer diameter of the cavity did not permit a sufficiently wide manifold to be added, without danger of running into circumferential mode problems.

**Mechanical Engineering and Vacuum**

The RFQ cavity and vanes are made of mild steel, electrolytically copper plated. The vanes supported at three points inside the cavity, so that they can be aligned without introducing deformations in either the cavity wall or in the vanes.

The whole assembly, from preinjector to the matching cavity, is mounted on a common underframe; this frame is supported at three points by low-rate flexible springs to remove a large portion of the bending moment from the existing Alvarez tank or on which the RFQ structure must be rigidly fixed.
Cavity-vane connections, both electrical and thermal, are made by using flexible copper strips that are welded after vane assembly, before final alignment and initial rf tuning. The whole structure is water cooled through tubes glued to both main flanges of the cavity.

The nominal pressure throughout the system is 10⁻⁷ torr. The preinjector is equipped with two turbomolecular pumps of 500 λ/s, the cavity with three ion pumps of 500 λ/s, and one turbomolecular pump for roughing. Aluminum seals are used on all joints except on the preinjector, where rubber seals are used.

Status and Outlook

The parameters have been frozen; some components have been ordered, and a few have been delivered. Beam measurements are expected to begin later this year: first using only the ion source and the 50-kV extraction, and later with the solenoids in place. We plan to have the beam measurements at the 520-keV level finished by May 1982, so that the beam can be obtained from Linac I by July 1982.

Because it may turn out that alpha beams are requested from Linac I for ISR operation, it is imperative to allow for quick disassembly of the RFQ and for reinstallation of the Cockcroft-Walton. Later requests for alpha beams, or other light ions, may require another RFQ injector with a quick changeover facility for different particles.

References


A 750 KEV RFQ LINAC FOR THE AGS POLARIZED PROTON PROGRAM

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Summary

A radio-frequency quadrupole (RFQ) linac has been chosen for use as the preaccelerator for the polarized H⁺ beam at the BNL AGS. The low injection energy of 20 keV eliminates the need for installing the bulky and complex polarized ion source within a large high-voltage dome. A preliminary design, BNL 4, has been completed which accelerates 1 mA of polarized H⁺ from 20 keV to 750 keV with 98% transmission efficiency. It uses the four-vane structure with modulated vane tips developed at LANL as the linac cavity. It has an average aperture radius, \( r_0 \), of 0.47 cm and nominal normalized acceptance of 0.27 cm-mr. The structure has a vane length of 1.248 m and requires only 45 kW of rf excitation power. It has been conservatively designed to operate with a maximum surface electric field strength of 22.4 MV/m (1.52 times the Kilpatrick limit).

Design Parameters

TABLE I - AGS RFQ Design

<table>
<thead>
<tr>
<th>Frequency</th>
<th>201.25 MHz</th>
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<tbody>
<tr>
<td>Ion</td>
<td>H⁺</td>
</tr>
<tr>
<td>Number of Cells</td>
<td>137</td>
</tr>
<tr>
<td>Length</td>
<td>124.8 cm</td>
</tr>
<tr>
<td>Vane Voltage</td>
<td>55 kV</td>
</tr>
<tr>
<td>Peak Surface Field</td>
<td>22.4 MV/m</td>
</tr>
<tr>
<td>Initial Radius, ( r_0 )</td>
<td>0.47 cm</td>
</tr>
<tr>
<td>Final Radius, ( a_F )</td>
<td>0.29 cm</td>
</tr>
<tr>
<td>Initial Mod., ( m_1 )</td>
<td>1.00</td>
</tr>
<tr>
<td>Final Mod., ( m_f )</td>
<td>2.06</td>
</tr>
<tr>
<td>Initial ( \phi_s )</td>
<td>-90°</td>
</tr>
<tr>
<td>Final ( \phi_e )</td>
<td>-30°</td>
</tr>
<tr>
<td>Estimated Peak rf Power</td>
<td>45 kW</td>
</tr>
<tr>
<td>Nominal Acceptance</td>
<td>0.27 ( \pi ) cm-mr</td>
</tr>
<tr>
<td>Initial Energy</td>
<td>20 keV</td>
</tr>
<tr>
<td>Final Energy</td>
<td>750 keV</td>
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</table>

TABLE II - PARMTEQ SIMULATIONS RESULTS

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_i )</td>
<td>( I_o )</td>
</tr>
<tr>
<td>( W_i )</td>
<td>( W_o )</td>
</tr>
<tr>
<td>( \epsilon_n ) (100%)</td>
<td>( \epsilon_n ) (100%)</td>
</tr>
<tr>
<td>( \epsilon_n ) (90%)</td>
<td>( \epsilon_n ) (90%)</td>
</tr>
<tr>
<td>( \epsilon_n ) (rms)</td>
<td>( \epsilon_n ) (rms)</td>
</tr>
</tbody>
</table>

\( \epsilon_n \) is the normalized emittance in cm-mr. Transmission is 98% for a 750 kV transducer to ground, thereby enormously easing the installation, operation, and maintenance of the system.

Introduction

The four-vane RFQ linac\(^2,3\) is a structure which has four-pole symmetry and produces focusing, bunching, and acceleration of charged particle beams by the use of radio frequency electric fields only. No internal static magnetic or electric quadrupoles are required in the structure proper, as is the case with a conventional rf linac. The four-pole symmetry of the device produces a strong electric quadrupole field in the vicinity of the beam aperture which can be used to focus and confine low beta charged particle beams. Because the beam focusing is performed by the rf electric field, it is possible to produce strong focusing forces in the low beta region where conventional quadrupole magnets are not feasible. In fact, it is the strongest known low beta focusing structure.\(^4\) By modulating the pole pieces, a longitudinal component of the electric field is produced which is used to bunch and accelerate the beam. Proper design of the radial matching, shaping, bunching, and accelerating sections results in a linac capable of accelerating particles of low injection energy to moderately high output energy levels with greater than 90% capture efficiency.\(^4\)

An RFQ has been selected as the preaccelerator for the BNL polarized beam facility because it enormously eases the development, operation, and maintenance of the polarized ion source. The complex and bulky equipment associated with the ion source can be placed at beam line floor level and therefore is easily accessible for adjustment and maintenance. The controls and diagnostics can be hard-wired to the control station without the need for a 750 kV transducer to ground, thereby enormously easing the installation, operation, and maintenance of the system.

Design Parameters

The preliminary parameters of the AGS RFQ design, BNL 4, are listed in Tables I and II. A package of auxiliary programs and PARMTEQ developed at LANL were used to design the linac and study its beam dynamics. The RFQ has an average \( r_0 \) of 0.47 cm and a nominal acceptance of 0.27 \( \pi \) cm-mr (normalized). There is only a modest emittance growth from 100% of the particles of 0.06 \( \pi \) to 0.10 \( \pi \) cm-mr normalized for 1 mA beam current input. The transmission efficiency is 98%. The modulated vanes are 1.248 m long. The RFQ was designed with a inter-vane voltage of 65 kV which produces a peak surface electric field strength of 22.4 MV/m (a conservative level of only 1.52 times the Kilpatrick limit). Only 45 kW of rf power are required to excite the structure.

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* Work supported by U. S. Department of Energy.
Mechanical Design

The preliminary mechanical design for the AGS RFQ is shown in Fig. 1. It consists of an outer manifold and the symmetrical four-vane RFQ assembly. The outer manifold is a resonant half-wavelength RF cavity and is tuned using the movable end shorting plates. It also serves as the vacuum manifold for high-speed uniform vacuum pumping. The eight slots cut into the inner cylinder wall function both as vacuum pumping holes and RF coupling slots to the RFQ. There are five large access ports on the outer cylinder of the manifold. Two of the central ports are used for vacuum pumping while the off-center port is used for the RF power input feed loop.

The vanes are to be made of solid copper reinforced with a bolted and pinned steel support plate in the vane base. The base also contains a water cooling channel for temperature control. The vanes are easily removed for repair or replacement. Their electrical contact is provided by thin copper membranes which are electron-beam welded to the vanes. The other side of the membrane is brazed to a steel frame. A crushed gold wire is used to provide the electrical contact between the frame and the RFQ cylinder. The membrane also electrically hides the steel support plate and positioning mechanism of the vane from the RF field. The vanes are aligned by means of a set of support bolts around a pivot point at each end. The vane tip modulations will be machined on a three-axis numerically-controlled mill.

The other major parts of the RFQ will be made of mild steel and electroplated with 254 μm of copper. We have developed, during this past year, an electroplating procedure with an industrial vendor using brightening and leveling agents which produces a bright, high-conductivity copper deposit on large internal or external surfaces with apertures. It displays good adhesion under heat and vacuum. An initial strike of cyanide copper is followed by a 254 μm deposit of acid copper. The resulting deposit is very uniform. Typically, the procedure levels the surface finish from 1.27 μm to 0.25 μm. The copper deposit has an electrical conductivity greater than 90% of pure copper.

RF Design

The RFQ structure will be excited in the 'mode by the use of a manifold cavity (developed at LANL). The manifold cavity is formed by placing a larger metallic cylinder around the RFQ linac cavity. This forms a rigid coaxial line with the outside cylinder of the RFQ, and can be made to resonate at the RFQ frequency by placing shorts n/2 apart. In our case, the shorts will be A/2 apart. Energy is coupled into the RFQ from the manifold by cutting eight slots in the outside cylinder of the RFQ.

Three steps are planned to tune the structure to frequency and set the proper field level. First, small, adjustable protruding cylinders are placed at the ends forming a capacitor between pole tip and end wall. Adjusting the gaps of these “buttons” allows frequency tuning, field leveling, and also provides the proper terminating impedance for the vanes. Second, adjustable slug end tuners, either placed on the end plates near the vane base or on the vane base itself, will allow further adjustment of cavity frequency and field level. They will be adjusted until the end buttons are in their nominal range. Third, small adjustable tuners in the cylindrical wall of the RFQ will provide fine tuning adjustment. The fine tuners will allow some decoupling of the mechanical alignment requirements from the requirement to balance the vane voltages.

Vacuum

The vacuum pumping will be provided by a 1000 L/sec cryopump and a 250 L/sec ion pump. With the impedances of the eight RF coupling slots and pumping between the vanes, the effective speed at the beam position is 390 μsec. This will give a base pressure of 4 x 10^{-8} Torr under ideal conditions with only the gas load from the 10 m² of non-OFHC copper. Under normal operating conditions, it will probably be an order of magnitude worse. This will still be excellent for high voltage standoff, and will strip less than 0.1% of the beam.

Schedule

The RFQ preaccelerator is scheduled for installation at the AGS in early 1983. The low-energy transport line to provide matching into the 200 MeV linac has a preliminary design using existing elements. Two low-voltage fundamental frequency bunchers are required to maintain the bunch structure in the transport line.

It is expected that the AGS operation with polarized protons will start by mid-1993.

References

Fig. 1 A 20-750 keV RFQ Linac Preaccelerator for the Polarized H⁻ Beam at the AGS.
A 30-kV proton injector designed for matching a 31-mA proton beam into the radio-frequency quadrupole (RFQ) section of the PIGMI accelerator has been constructed and tested. This injector uses a small efficient duoplasmatron ion source and a single-gap extraction system for creating a convergent ion beam, and a three-element unipotential einzel lens for focusing the ion beam into the RFQ. A description of this prototype injector is presented, along with the experimental data obtained during the testing of this system.

Introduction

Under the PIGMI (Pion Generator for Medical Irradiations) program at the Los Alamos National Laboratory, the major technologies for constructing a compact linear accelerator for pion therapy have been identified and developed, and the configuration of this accelerator has been described. The PIGMI accelerator begins with a small proton injector, followed by an RFQ linac.

The RFQ linac dramatically simplifies the low-energy end of the accelerator. It can accept a 30-keV proton beam from the injector and accelerate it to 2.5 MeV in 1.8 m, at which point the beam is easily injected into the conventional drift-tube linac. In addition, the RFQ also provides >90% capture of the 31-mA proton beam, as well as radial focusing. Thus, the RFQ has eliminated the need for a large high-voltage Cockcroft-Walton power supply, a complex multicavity buncher system, an extensive low-energy beam-transport system, and associated control instrumentation.

The 30-keV injection energy was chosen to minimize the length of the RFQ with the optimum capture efficiency, while allowing reliable operation of the single-gap high-brightness extraction system. Injector operation at 30 kV dramatically simplifies the design and makes the system small while increasing the reliability. In addition, this low injection energy for the RFQ allows electrostatic focusing of the ions because it is more effective than magnetic focusing at this energy. Thus, an einzel lens can be used to match the 30-keV proton beam from the injector into the RFQ.

In the PIGMI experimental program, a prototype of this compact 30-kV injector has been constructed and tested. This injector contains a small, efficient duoplasmatron ion source, a single-gap extraction system, an einzel lens, and diagnostics equipment enclosed in a small re-entrant vacuum chamber that attaches directly to the vacuum housing of the RFQ. A self-contained equipment cabinet contains the electronics, power supplies, and other systems to operate the ion source, extraction system, vacuum system, and einzel lens.

*Work supported by the US Department of Energy and by the National Cancer Institute, Division of Research Resources and Centers, Department of Health, Education, and Welfare.
The iron plasma-expansion cup in this duoplasmatron uses a boron nitride insulator along the straight side of the cup. This self-biasing electrode, suggested by Bacon, for this geometry, increases the proton fraction in the extracted ion beam to 90% or more, compared to the 70% this geometry yields without the insulator.

**Extraction System and Vacuum Housing**

The cutaway view of the injector in Fig. 1 also shows the arrangement of the 30-kV extraction gap and high-voltage isolation of the ion source within the re-entrant vacuum housing. The high-voltage isolation is maintained by a single glass insulator held between two 0-ring surfaces by permali bolts. The radial alignment of the ion source is maintained by precision-machined lips on each surface. The outside of the insulator and the permali bolts are enclosed in a pressurized Lucite dust cover (1 atm psig of nitrogen gas) to ensure against breakdown across the insulator caused by dust or moisture.

As seen in Fig. 1, the ions are extracted from the duoplasmatron by a single gap 30-kV extraction system. The focus electrode and extractor electrode in this system were designed with the ion extraction code SNOW to give a small convergent beam of 31 mA at 30 kV, with a 1.5-cm extraction gap. To prevent electrons (generated in the residual gas by the ion beam) from backstreaming through the extraction gap to the ion source, a magnetic dipole field is maintained just beyond the extraction electrode by small permanent magnets.

A turbomolecular pump located near the ion source efficiently pumps the gas load in the extraction gap. The gas in the transport system is pumped directly by the RFQ vacuum system, because the injector housing is bolted directly to the accelerator. This arrangement, coupled with the small apertures between the various regions, will allow differential pumping and a large pressure difference between the ion source and accelerator.

**Beam Transport and Diagnostics**

As previously mentioned, the low energy of the proton beam and the close coupling of the injector and RFQ allow the ions to be focused into the RFQ with an electrostatic lens. A three-element unipotential lens was designed, along with the extraction system, to accomplish this task. The calculated beam optics for the final design of this system, with a 31-mA proton beam, is shown in Fig. 2.

As seen in Fig. 2, a drift space of ~4.5 cm exists between the back of the extractor electrode and the first electrode of the einzel lens. This space has been used for insertion of beam-diagnostic equipment. A biased beam stop and a multiwire beam harp can be individually inserted to measure the extracted ion current or beam profile. In addition, a small window-frame steering magnet can be inserted to magnetically steer the extracted ion beam through the einzel lens and into the RFQ. This steering can be used to compensate for small misalignments in the system.

**Equipment Cabinet**

The equipment cabinet, shown in Fig. 3 with the injector mounted, is a self-contained system for operating the injector. The entire high-voltage region of the injector has been enclosed in an interlocked, grounded cabinet (76 in. high by 24 in. wide by 41 in. deep). As seen in Fig. 3, the front half of the cabinet contains, from the bottom up, the turbomolecular pump power supplies; the high-voltage power supply; the ion source power supplies located at high voltage; an oscilloscope for monitoring the arc pulse; the einzel-lens control and meter; the pulsing and timing controls and the interlock system; and the ionization gauge controller. The rear portion of the cabinet contains the high-voltage isolation transformer (rated for 3 kVA at 50 kV), the hydrogen gas bottle, regulator and gas distribution system, the ac distribution panel, the high-voltage crowbar system, the einzel-lens power supply, and the closed-loop cooling system for the ion source. An interlocked Lucite rear door gives easy access to the high-voltage region in the cabinet, and thus to the back of the ion source and the associated power supplies. This makes routine maintenance and troubleshooting of the system very easy and rapid. Also, the transparent door allows inspection of the system during operation. In addition, the panels on both sides of the cabinet can be removed and the high-voltage region is visible during operation through interlocked Lucite panels within the cabinet.

Although all of the power supplies for operating the ion source are located at high voltage, the manual control for the power supplies, as well as the stepping motors for computer control, are located at ground potential with insulated shafts to the control Variacs. All meters for the power supplies are located at high voltage, but are visible through glass windows on the front panel of the cabinet. The oscilloscope and current transformer used to monitor the arc pulse are at ground potential, with the current lead from the arc pulser to the ion source isolated through the current transformer. The timing pulse for the transistor arc pulser and power supply is supplied.

---

Fig. 2. Calculated ion-beam optics for the 30-kV injector, including the einzel lens.
The prototype 30-kV injector system has been assembled and successfully tested. The assembled system was tested as shown in Fig. 3, but with several additional diagnostics beam boxes, one which had a 120-l/s turbomolecular pump attached to it. For these tests the typical operating parameters were

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc voltage</td>
<td>120 V</td>
</tr>
<tr>
<td>Arc current</td>
<td>15 to 20 A</td>
</tr>
<tr>
<td>Arc magnet current</td>
<td>0.9 A</td>
</tr>
<tr>
<td>Filament current</td>
<td>30 A</td>
</tr>
<tr>
<td>Hydrogen gas flow</td>
<td>1.0 atm cc/min</td>
</tr>
<tr>
<td>Arc chamber pressure</td>
<td>180 microns</td>
</tr>
<tr>
<td>Column pressure</td>
<td>6 x 10^{-6} torr</td>
</tr>
<tr>
<td>Einzel lens voltage</td>
<td>0 to 32 kV</td>
</tr>
</tbody>
</table>

The injector was operated at 60 Hz, with a 75-μs pulse width; it produced a 25-mA ion beam with a 31-kV extraction voltage. The extracted current increased to 30 mA at 33 kV, indicating that the extraction gap must be shortened to obtain the required 31 mA of protons at 30 keV.

During testing of the injector, an emittance measuring station was positioned with the slits at the same position as the RFQ entrance would be during accelerator operation. Emittance scans made at 31 keV, with an extracted beam current of 25 mA, gave a normalized emittance of 0.039 cm-mrad for 96% of the beam. This is in excellent agreement with the normalized emittance of 0.037 cm-mrad measured for this source, with a 25-mA beam at 112 keV, on the LAMPF ion-source test stand. Measurements on the test stand also showed that the proton fraction in the beam was ~90%, and that the ion source could operate stably at a 6% duty factor.

The emittance measurements at 31 keV were made using the einzel lens; therefore, these measurements include the aberrations of the lens, a possible explanation for the small difference in the two measurements described above. However, these emittance measurements also showed that the einzel lens could be adjusted to produce a converging beam with the proper match for the RFQ, as shown in Fig. 4, where the acceptance of the RFQ, the experimental phase space of a 25-mA beam, and the calculated phase space for a 31-mA beam are overlaid on the same plot.

During magnetic field measurements it was found that the flux leakage into the plasma expansion cup of the new duoplasmatron was almost double the value measured on the larger version of this source. This is probably from saturation caused by using a thinner and smaller iron anode housing; this is also suspected as the cause of the larger emittance from this ion source (~0.04 cm-mrad) relative to the emittance of the larger version of the ion source (~0.03 cm-mrad). However, small changes in the anode aperture mounting arrangement could reduce the flux leakage and increase the brightness of this injector, if necessary for accelerator operation.


Fig. 4. Overlay of calculated (dots) and measured (vertical lined area) ion-beam phase space with the calculated acceptance (ellipse) for the RFQ.

Acknowledgments

The authors wish to thank Lloyd Wilkerson and the drafting staff of AT-1, for their contribution to the design of the injector; Sally Stevens, for her assistance in the design calculations; and Raymond DePaula and Felix Martinez for their assistance in the construction of this prototype.

References


The electric field potential function in an RFQ radial matcher has been formulated, adopting the lowest order potential function expanded in a Fourier-Bessel series. The focusing strength varies sinusoidally with the distance along the beam axis. The overlap between the time-dependent RFQ acceptance and the injected beam phase space area has been calculated. The overlap more than 90% can be attained with a several cell long radial matcher, and it is found that the length must be chosen accurately at (integer) × βλ.

Introduction

The radial matcher at the entrance of an RFQ linac plays an important role to attain a high capture efficiency, especially in a machine, of which the acceptance is not large enough. As the ellipse parameters of the RFQ acceptance change with the rf phase, it is necessary to match the time-independent injected beam emittance ellipse through a radial matcher. In the radial matcher the beam is focused and de-focused alternately along the beam axis, where the focusing strength increases from zero to its final value.

In spite of the significance of the radial matcher, the electric field distribution in it has never been formulated. We have derived the electric potential function imposing a ground plane and line on the cavity end wall and the beam axis, respectively, and adopting the lowest order potential function expanded in a Fourier-Bessel series. The resultant focusing strength increases sinusoidally with the distance along the beam axis, which is appreciably different from the linearly increasing one proposed by LASL.1

In this paper we describe the derivation of the potential function and the performance of the new radial matcher, i.e. the capability of achieving a good overlap between the phase space areas to be matched.

Formulation of the Potential

The potential of the electric field in a four conductor quadrupole cavity is generally expanded in a Fourier-Bessel series.

\[ U(r,z,\psi,t) = \sum_{n=1}^{\infty} F_n(r,\psi) \sin nkz \]

where

\[ F_n(r,\psi) = \sum_{m=0}^{\infty} A_{nm} r^m (nkr) \sin m\psi , \]

\[ k = \pi/L , \]

and \( r \) and \( z \) are defined as in Fig. 1. The length, \( L \), is half of the periodic length. To determine the coefficients we impose boundary conditions: The potential vanishes on the beam axis and the cavity end wall,

\[ U(r=0) = 0 , \]

\[ U(z=0) = 0 . \]

From the condition of Eq. (6), the potential must be an odd function with respect to \( z \), so \( F_0(r,\psi) \) vanishes. As the potential is quadrupole symmetric, only the term of \( m = 1 \) in Eq. (3) is taken. Then the potential is

\[ U(r,z,\psi) = \sum_{n=1}^{\infty} A_n I_1(nkr) \sin nkz \cos 2\psi . \]

This potential satisfies the condition of Eq. (5). Taking the lowest order potential, \( n = 1 \), we have

\[ U(r,z,\psi) = \sum_{n=1}^{\infty} A_n I_1(nkr) \sin nkz \cos 2\psi . \]

To obtain a smooth connection of the radial matcher and the modulated vane, the z-component of the electric field must be vanishing at the end of the radial matcher, \( z = z' \). So the periodic length \( L \) should be equal to \( 2z' \), and

\[ k = \pi/2z' . \]

The electric field components are derived as

\[ E_r = \frac{V}{2} k \frac{I_1(kr) - (2/kr)I_2(kr)}{I_2(ka)} \sin nkz \cos 2\psi , \]

\[ E_z = \frac{V}{2} k \frac{I_2(ka)}{I_2(ka)} \cos nkz \cos 2\psi , \]

\[ E_\psi = \frac{V}{2} k \frac{I_2(ka)}{I_2(ka)} \sin nkz \sin 2\psi , \]

The focusing strength is obtained from the coefficient of the linear term of \( E_r \),

\[ B(z) = \frac{1}{8} \frac{k^2a^2}{I_2(ka)} B_0 \sin nkz , \]

\[ = B_0 \sin nkz , \]

The vane shape of the radial matcher is given by equipotential surface obtained from Eq. (8):
\begin{align*}
\frac{I_2(kr)}{I_2(ka)} & \sin kz \cos 2\varphi = 1, \\
0 & \leq z \leq \ell.
\end{align*}

Figure 2 shows the vane shape and electric field lines in the x-z plane calculated for LITL (Lithium Ion Test Linac)\(^2\); $$\ell = 5.876$$ cm (12 cells), $$a = 0.041$$ cm. Practically the vane is chopped at $$r = 0.4$$ cm, so that the electric field in a beam passing region ($$r \leq 0.25$$ cm) might not change so much. The gap distance between the end wall and the vane should be determined also considering the electric surface field and the convenience of attaching end tuners.

![Electric field lines in the radial matcher.](image)

**Fig. 2.** Electric field lines in the radial matcher.

**Beam Dynamics Study of the Radial Matcher**

With the sinusoidally increasing focusing strength, the overlap between the input beam phase space area and the RFQ acceptance has been calculated. It has been found that the length of the radial matcher effects on the overlap significantly.

The ellipse parameters of the RFQ acceptance are first calculated for various phases in the modulated vane, where the focusing strength is constant: $$B_0 = 5$$ according to the LITL design. Figure 3 shows such obtained ellipses, corresponding to phases 90° apart. The normalized emittance is 0.6 \(\times\) mm\(\text{mrad}\) ($$\beta = 0.00326$$). The parameters of the phase spaces, at the input of the radial matcher, to be matched with the above acceptances at the output are calculated by use of a matrix. This is derived from the product of transfer matrices of segments, into which a cell is divided. Phase space ellipses with such parameters are shown in Figs. 4 (a) and (b) for two cases of 11 and 12 cell long radial matchers, respectively. As two cells comprise one focusing unit, it is expected that a good overlap among the ellipses is attained with a radial matcher of even-number cell length. This is graphically shown in the figures. For the case of 12 cells it is possible to draw an ellipse over the phase space ones to attain an overlap with ten more than 90%. The time-independent phase space of the input beam must be shaped to the ellipse. With 11 cells the overlap reduces to 50%.

Figure 5 shows the dependence of the overlap on the length of the radial matcher. Sharp peaks appear at every even-number cell length. This means that the length of the radial matcher must be accurately set at (integer) \(\times\) $$\beta_0$$. In the figure are plotted transmissions through RFQ structures, of which the modulated vane part is same as that of LITL. The computer code PARMTEQ is used in the calculation. The transmissions agree well with overlaps. Generally, however, the overlap is not always equal to the transmission, as it depends on the whole RFQ structure.

![Phase space ellipses at the input of the matcher. They are matched with the RFQ acceptance ellipses through a radial matcher of 12 cells (a) or 11 cells (b).](image)

**Fig. 4.** Phase space ellipses at the input of the matcher. They are matched with the RFQ acceptance ellipses through a radial matcher of 12 cells (a) or 11 cells (b).

![Dependence of the overlap, between the input beam phase space area and the RFQ acceptance, on the length of the radial matcher (solid line). Circles denote transmissions.](image)

**Fig. 5.** Dependence of the overlap, between the input beam phase space area and the RFQ acceptance, on the length of the radial matcher (solid line). Circles denote transmissions.

Figure 6 shows the reduction of transmission due to space charge effect for two extreme cases; an 11 cell long radial matcher and a 12 cell long one. With 11 cells the plateau extends to a higher current than with 12 cells. This pattern agrees qualitatively with the experimental result of POP at LASL.\(^2\)

From the above considerations, a radial matcher part of an RFQ linac should be designed so that its length can be regulated to correct the slight change of the length due to the effect on a hole for beam entrance and the chop of the vane.

**Conclusion**

The potential of the electric field in the radi-
al matcher of an RFQ has been formulated. The derived focusing strength increases sinusoidally from zero to its final value with the distance along the beam axis. The length of the radial matcher is measured from the end wall of the rf cavity, but not from the truncation point of the vane. From the viewpoint of beam dynamics, the length must be accurately \( n \times \lambda \) (\( n \) : integer). The overlap between the time-independent injected beam phase space area and the time-dependent RFQ acceptance has been calculated, and a high value more than 90% has been attained.

![Graph](image)

Fig. 6. Space charge effect on the transmission for two cases of radial matchers with 11 and 12 cells.

Acknowledgment

The authors express their sincere thanks to J. Staples and R. Gough at LBL for their encouragement and discussions during the work.

References

2) N. Ueda et al., An RFQ Linac for Heavy Ion Acceleration, contributed to the Conference.
BUNCHER SECTION OPTIMIZATION OF HEAVY ION RFQ LINACS

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Tanashi, Tokyo 188, Japan

Summary

Some extensions in designing and optimizing a low-intensity heavy-ion RFQ linac are developed. Linacs with transmissions of more than 90% which are somewhat shorter than those using the LASL prescription have been obtained. The design equations and some examples of applications of this design procedure are described.

Introduction

The structure design of RFQ linacs for high-intensity beams has been extensively studied by LASL. According to the proposed design procedure, the overall RFQ linac is divided into four sections: radial matching, shaping, gentle bunching, and accelerating sections. The main role of the gentle buncher is to complete the beam bunching during several periods of longitudinal phase oscillations. Either the Kapchinskij and Lazarev method or the generalized method is used for the section to minimize both of particle loss and transverse emittance growth.

The gentle buncher, however, requires a number of unit cells and the linac tends to have a low shunt impedance. For heavy-ion RFQ linacs, where the space charge force is not so important, more efficient particle acceleration can be achieved without increasing particle loss and emittance growth.

In this paper, some extensions in design procedure for a low-intensity RFQ linac are described. The basic equations and notations are essentially same as those in reference 2). The discussions will be limited to the cases where constant values of the focusing strength, B, and intervane voltage, V, are assumed throughout the linac.

Design of Transient Sections

In this procedure, the gentle buncher is divided into two sections: prebunching and bunching sections. Another section, booster, is introduced as a buffer between buncher and accelerator sections.

In the prebuncher, a fast beam compression is accomplished within about a half period of the longitudinal phase oscillations. The synchronous phase angle varies from -88° at the entrance to -60° at the exit of the section. The buncher section is designed so that the accelerating field is as high as possible without serious increase in transverse beam size during the gentle bunching process. The transverse acceptance is determined by the boosting section where the accelerating field goes to its maximum value. The transition energy between each stage will be determined by considering the transverse emittance growth, input and output energies, and capture efficiency. The design procedure of each stage will be discussed in the following subsections.

Prebuncher

According to a static approximation, the longitudinal acceptance is an area of separatrix. The area is almost proportional to the separatrix parameter, S, defined by

\[ S = \sqrt{|A|} \beta^2 \gamma^2 g(\phi_B) \]  

where \( \beta \) is the synchronous velocity in unit of light velocity, and \( \gamma = \sqrt{1 - \beta^2} \). The symbols \( A \) and \( \phi_B \) represent the rf-defocusing parameter and the synchronous phase angle. The function \( g(\phi_B) \) is given by

\[ g(\phi_B) = (\phi / 2\pi) \sqrt{1 - \phi_B \cot \phi_B} \]  

where \( \phi \) is an angular length of the separatrix.

An increase of the parameter S is important in forming the good beam bunch especially under an influence of strong space-charge force. For a low-intensity linac, however, it is found that constant S gives faster beam bunching with sufficiently high transmission. In the following discussions, the constant value of S is assumed through the prebuncher and buncher sections.

If the value of A is kept constant during the bunching process as suggested by Kapchinskij and Lazarev, a change in \( \phi_B \) must be very slow since the velocity increase is slow at large \( \phi_B \). In the prebuncher, A is assumed to increase with \( \phi_B \) in the following form:

\[ A = A_B - (A_B - A_{\pm}) \left( \frac{\beta - B_{\pm}}{\beta_1 - B_{\pm}} \right)^{n} \]  

\( (n = 1, 2, 3, \ldots) \)  

where \( A_{\pm} \) and \( A_B \) are the initial and final values of A in this section. The symbols \( B_1 \) and \( B_{\pm} \) are the corresponding synchronous velocities.

Applying a nonrelativistic approximation, the required number of unit cells in the prebuncher is

\[ N_c = \frac{2\pi}{|A_B|} \int_1^{R_B} \left[ \tan \phi_B \right] |f(\xi)| \frac{d\xi}{\xi} \]  

where

\[ f(\xi) = 1 - (1 - R_A) \left( \frac{\xi - R_A}{1 - R_B} \right)^n \]  

\[ R_A = \frac{A_1}{A_B} \]  

\[ R_B = \frac{B_2}{B_1} \]  

\[ \xi = \frac{\beta}{\beta_1} \]  

The number of small angle longitudinal oscillations in this section is given by

\[ N_{\text{po}} = \frac{1}{2 / |A_B|} \int_1^{R_B} \left[ \tan \phi_B \right] f^{1/2}(\xi) \frac{d\xi}{\xi} \]  

Buncher

In order to prevent the beam envelope being too large, the value of \( |A_B| \) should not be so large. The
The constant value of \( \Delta_b \) in the buncher section ensures the maximum accelerating field with the minimum growing up of the transverse beam envelope. The value of \( S \) is also kept constant to maintain the longitudinal acceptance. This section is quite similar to the gentle buncher proposed by LASL.

The numbers of unit cells and longitudinal oscillations in this section are

\[
N_c = \frac{n}{|\Delta_b|} F(\phi_f, \phi_2) \tag{6}
\]

and

\[
N_{po} = \frac{1}{8\sqrt{|\Delta_b|}} F(\phi_f, \phi_2) \tag{7}
\]

where

\[
F(\phi_f, \phi_2) = \int_{\phi_2}^{\phi_f} |\tan\phi| \frac{g'(')}{g(\phi)} d\phi
\]

and

\[
g'(\phi) = \frac{d}{d\phi} g(\phi)
\]

The symbols \( \phi_2 \) and \( \phi_f \) are the synchronous phase angles at the input and output ends of this section.

**Booster**

If the estimated beam envelope is smaller than the radius parameter, \( a \), at the end of the buncher, the accelerating field can be raised by decreasing the \( \Delta_b \). This process is done in the booster. The section has constant \( \phi_f \) and \( \Delta_b \), which should be same as \( \phi_2 \) and \( \Delta_b \), respectively.

The minimum value of the radius parameter can be estimated by the following equation:

\[
a_{\text{min}} = f_e \left( \varepsilon_n \lambda / \pi \right) B_{\text{max}}(B, \Delta_b) \tag{8}
\]

where \( f_e \) is the safety factor (\( f_e > 1 \)), and \( \varepsilon_n / \pi \) and \( B_{\text{max}} \) are the normalized beam emittance and the maximum value of the normalized beta-function, respectively. The symbol \( \lambda \) is the free space wave length of the rf-wave.

**Operating Conditions**

The numbers of unit cells required by the pre-buncher and buncher sections are strongly dependent on \( \Delta_b \). Therefore the values of parameters \( B \) and \( \Delta_b \) should be carefully chosen in order to improve the shunt impedance and transmission efficiency. The operating frequency, \( f_r \), and the maximum surface field on the vanetips, \( E_s \), also affect strongly on the length of the accelerator.

A simple procedure for choosing these parameters is to estimate the following parameter:

\[
\eta = \frac{\mu^2 \lambda}{\varepsilon_n / \pi} \tag{9}
\]

where

\[
\mu = \frac{q}{M e^2} \frac{E_s}{\kappa}
\]

\( q \); charge of the accelerated ions

\( M e^2 \); mass of the ions

\( \kappa \); surface field parameter determined by the geometrical arrangement of the vanetips (\( \kappa = 1.36 \)).

From eqs. (9), (18) and (19) in ref. 2, the radius parameter is represented by

\[
a = \frac{\sqrt{X}}{B} \mu \lambda \tag{11}
\]

where \( X \) is the focusing efficiency. Substituting eq. (11) into eq. (8), the following relation is easily obtained:

\[
nX \geq B^2 \beta_{\text{max}}(B, \Delta_b) \tag{12}
\]

At the high velocity limit, \( X \) is approximated by \( X = 2/(m^2 + 1) \), where \( m \) is the modulation parameter.

The function \( B^2 \beta_{\text{max}}(B, \Delta_b) \) is calculated numerically and shown in fig. 1. The eq. (13) and fig. 1 give a simple criterion in choosing the operating frequency and the upper limit of \( |\Delta_b| \). The value of constant \( B \) should be chosen at slightly larger value than the minimum points of the curve \( B^2 \beta_{\text{max}} \).

![Fig. 1. The function \( B^2 \beta_{\text{max}}(B, \Delta_b) \).](image)

**Design Examples of RFQ linac**

**Si\(^{5+}\) linac**

The basic requirements of the first example are as follows:

- Ion; Si\(^{5+}\) (\( q/\lambda = 0.179 \))
- \( f_r \); 200 MHz
- \( E_s \); 1.75 x (Kilpatrick's limit)
- \( \varepsilon_n \); 0.06\( \pi \) cm-mrad
- \( W_{\text{inj}} \); 8.9 keV/amu
- \( W_{\text{out}} \); 250 keV/amu

In the design calculations, the computer code PARMTEQ was used, and the input type parameter was chosen so that the input particles have an ideal phase space diagram as if they were through a perfect radial matching section. The program GENRFQ was coded and used to provide an input data table for PARMTEQ.

Figure 2 shows an example of calculated dependence of transmission of the linac on the number of small angle longitudinal phase oscillations in pre-buncher, \( N_{poop} \). In this calculation, the synchronous phase angle varies from -88° to -60° in the pre-buncher, and from -60° to -30° in the buncher.
Other parameters, for example, $B$ and $\Delta_b$ and the length of shaper are kept constant. The parameter $n$ in eq. (3) is chosen at 1. The maxima of the transmission appears at the defocusing points of longitudinal oscillations.

For a given value of $\Delta_b - 0.04$, it is found that the best solution exists around $B \approx 3.0$ and $N_{\text{pop}} \approx 0.5$. With similar discussions for different RFQ linacs, the optimized values of $B$ and $\Delta_b$ are obtained around the line $B \approx 2.2 + 20|\Delta_b|$ (13)

Fig. 2. The dependence of transmission on the number of longitudinal oscillations in the prebuncher.

$\text{Ne}^{5+}$ linac

The basic parameters for this example are

- Ion: $\text{Ne}^{5+}$ ($q/A = 0.25$)
- $f_B$: 200 MHz
- $E_0$: 1.95 x (Kilpatrick's limit)
- $\phi_0$: 0.05 cm-mrad
- $W_{\text{inj}}$: 12.5 keV/amu
- $W_{\text{out}}$: 1.0 MeV/amu

These parameters are chosen to be same as those for $q/A = 0.25$ linac described in ref. 4). The results of PARMTEQ calculations are summarized in the table together with those of LASL calculations. It is clear from this table that the length of the linac is shorter whereas the space charge limit is lower than the LASL design.

<table>
<thead>
<tr>
<th></th>
<th>LASL</th>
<th>INS</th>
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</thead>
<tbody>
<tr>
<td>Focusing strength</td>
<td>3.43</td>
<td>3.60</td>
</tr>
<tr>
<td>Synchronous phase (deg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at the entrance</td>
<td>-90</td>
<td>-90</td>
</tr>
<tr>
<td>at the exit</td>
<td>-26</td>
<td>-30</td>
</tr>
<tr>
<td>Modulation parameter</td>
<td></td>
<td></td>
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<tr>
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<td>1.00</td>
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<tr>
<td>maximum</td>
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<td>2.54</td>
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<td>Radius parameter (cm)</td>
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<tr>
<td>minimum</td>
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<td>0.19</td>
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<tr>
<td>Transmission (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at $I = 0$ mA</td>
<td>97</td>
<td>95</td>
</tr>
<tr>
<td>at $I = 10$ mA</td>
<td>90</td>
<td>79</td>
</tr>
<tr>
<td>Vane length (m)</td>
<td>4.23</td>
<td>3.33</td>
</tr>
</tbody>
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<th>References</th>
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| Conclusion |

The design procedure described here are effective in the design of accelerators for nuclear physics and medical applications where space-charge is not important. To improve the current limit of the linac, it is necessary to increase the parameter $S$ continuously in the prebuncher and buncher sections, which will increase the length of these sections.

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The author expresses his sincere gratitude to Drs. J. Staples and R. Gough for the encouragement, suggestions and helpful discussions during the work. He is indebted to Dr. N. Tokuda for valuable discussions. The author is grateful to Dr. H. Grunder and Prof. Y. Hirao for their continuous interest and encouragement.

<table>
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<th>Table</th>
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<tr>
<td>$\text{Ne}^{5+}$ RFQ linac design parameters.</td>
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<tr>
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<td>Synchronous phase (deg)</td>
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<td>at the exit</td>
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<td>Modulation parameter</td>
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<tr>
<td>maximum</td>
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<tr>
<td>Radius parameter (cm)</td>
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<tr>
<td>minimum</td>
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<tr>
<td>Transmission (%)</td>
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<tr>
<td>at $I = 0$ mA</td>
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<tr>
<td>at $I = 10$ mA</td>
</tr>
<tr>
<td>Vane length (m)</td>
</tr>
</tbody>
</table>

| Conclusion |

The design procedure described here are effective in the design of accelerators for nuclear physics and medical applications where space-charge is not important. To improve the current limit of the linac, it is necessary to increase the parameter $S$ continuously in the prebuncher and buncher sections, which will increase the length of these sections.

Acknowledgements

The author expresses his sincere gratitude to Drs. J. Staples and R. Gough for the encouragement, suggestions and helpful discussions during the work. He is indebted to Dr. N. Tokuda for valuable discussions. The author is grateful to Dr. H. Grunder and Prof. Y. Hirao for their continuous interest and encouragement.
HIGH-POWER KLYSTRONS...
A NEW BREATH, A SECOND YOUTH
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Introduction

Klystron amplifiers, created about 40 years ago, have not remained attached to a particular type of application but have been capable of being adapted to meet numerous and varied requirements. Important progress has been made in the radar field, thanks to pulsed multimegawatt klystrons, with instantaneous bandwidths exceeding 10% at the -1 dB points, and thanks to lower-power CW klystrons for Doppler radars, often of a technology allowing airborne use. In addition to their use in tropospheric-scatter microwave links in the field of telecommunications, klystrons deliver several kW CW to earth station uplink transmitters which operate all around the world at 6, 8, 14 and 18 GHz. But perhaps most important of all has been the wide-scale use of klystrons in particle accelerators.

It is in the last-mentioned field that major tube-development programs have been undertaken in recent years. The reason spring from the fact that klystrons are electron tubes in which the different functions are clearly separated: electron gun — amplification section — output circuit — and collector. Consequently, they are robust and capable of delivering large amounts of power. And it just so happens that a number of important accelerator projects will require high levels of injected CW RF power. For example, the LEP requires 16 MW in the first phase and 100 MW finally, at the relatively low frequency of 352 MHz. Other projects, such as the 136 MeV Linac at Harwell, U.K. (which will be used for nuclear physics research), necessitate high-power pulsed multimegawatt klystrons also being capable of high average power (for example, 25 MW/60 kW, at a frequency of 1.3 GHz).

In view of these new requirements, it is easy to understand the current efforts to first achieve the necessary high power levels and then — in view of the rising cost of electrical energy today — to achieve the highest possible efficiency.

There has also recently appeared a new application for high-power klystrons, the injection of RF power into plasmas confined in Tokamaks. It must be possible to effect this injection, which is one of the 'additional' plasma-heating methods under consideration, at several different frequencies, depending upon whether the ionic (several tens of MHz), electronic (100 GHz and above) or hybrid (several GHz) resonances are excited. It is the experiments at the last-mentioned frequencies that necessitate the use of high-power klystrons. In addition to the qualities already cited, these tubes must be able to operate with pulse lengths of several seconds, or even 10 to 20 seconds duration, and thus be capable of supporting the resultant thermal shocks.

Improving the Efficiency

Klystron efficiency depends upon the quality of the electron bunching at the input to the output cavity. The first-harmonic current component must be as large as possible, while the velocity dispersion around the average beam velocity is minimum. These two conditions are obtained by careful selection of the number of resonant cavities, their frequency, the length of the drift tubes between them, the dimensions of the interaction space, the beam diameter and the beam perveance.

Figure 1 illustrates the effects of the resonant cavities and drift tubes on the evolution of the current and the velocity dispersion along the tube axis. The output cavity is situated so that the beam induces the maximum current within it, and its impedance is chosen so that the voltage developed across its lips does not reflect a single electron during the period (see Figure 2).

The computational programs are usually of the “z-stepping” type and effected with the help of beam modeling by means of a series of rigid disks. This type of computation has demonstrated its effectiveness, for example in the TV 2002 S-band klystron (20 MW/20 kW), with computed and measured efficiencies at the output flange of 48% and 45 to 46%, respectively; and for the TH 2075, a 50-kW CW klystron operating at 2.45 GHz, with computed and measured efficiencies of 65% and 60% respectively. Of course, when the perveance decreases (2 μperv in the TV 2002 and 0.8 μperv in the TH 2075), the space-charge forces decrease and their disturbing effect on electron bunching is diminished. Consequently, the efficiency can be higher.
Nevertheless, it seems rather difficult to employ such z-stepping rigid-disk programs to fairly correctly compute structures and beams with tube efficiencies of 70%.

A first step toward greater precision is to shift to a time-stepping program, while remaining undimensional. But these programs do not benefit from the periodicity of the phenomena, and thus are much harder to use than the z-stepping type, which undoubtedly explains why they are little used. These programs, applied to the output cavity, allow one to obtain an indication of the klystron response to a varying load. Figure 3 gives an example of the Rieke diagram and one can distinguish the equi-efficiency curves and the number of reflected electrons. The appearance of the latter has been chosen to define the stable operating zone.

Certain reflected electrons are in fact electrons that oscillate once or more in the output cavity and then continue toward the collector. These so-called oscillating electrons provide the first sign of a coming drop-off in efficiency and an increase in the electron interception on the drift-tube lips.

A second step toward greater precision in predicting tube behavior is the r-z ballistic computation of the beam in the presence of RF fields, deduced from an earlier program, without omitting the effects of the beam-confining magnetic field. The kinetic efficiency is also computed. Figure 4 shows the evolution of the beam envelope during one period. It is seen that the ripple is perturbed after passage through the final cavities, and that the braking field in the output cavity has a convergent effect before the demodulated beam breaks up and produces strong current interception on the output lips.
A more compact form of the RF field has a beneficial influence on the efficiency. An analogous effect can be obtained by locally reducing the magnetic field, but the compromise between the reflection of electrons and the interception of electrons on the output drift-tube lips is then difficult to find — and difficult to realize, of course, technologically speaking.

To summarize, all of these computations show that efficiencies of 70% or higher are difficult to obtain with beams having a microperveance of 1 or 0.75, and that it is necessary to go down toward 0.6.

The best results already achieved by THOMSON-CSF (or anticipated, for the tubes in development) are summarized in the table:

<table>
<thead>
<tr>
<th>Tube no.</th>
<th>Frequency (GHz)</th>
<th>Pervance (μperv)</th>
<th>Output power</th>
<th>Efficiency (%)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV 2002</td>
<td>S-band</td>
<td>2</td>
<td>25 MW/25 kW</td>
<td>45 - 46</td>
<td>Accelerators</td>
</tr>
<tr>
<td>TH 2054</td>
<td>2.45</td>
<td>0.8</td>
<td>50 kW CW</td>
<td>60 - 64</td>
<td>Accelerators and μ wave heating</td>
</tr>
<tr>
<td>TH 2888</td>
<td>(modified)</td>
<td>1.3</td>
<td>1.5 MW/10 μs</td>
<td>62</td>
<td>Tokamaks</td>
</tr>
<tr>
<td>TGK.F1*</td>
<td>1.7</td>
<td>0.7</td>
<td>1 MW/10 s</td>
<td>85</td>
<td>Tokamaks</td>
</tr>
<tr>
<td>TH 2889*</td>
<td>0.352</td>
<td>0.7</td>
<td>1 MW 5W</td>
<td>70</td>
<td>Accelerators</td>
</tr>
</tbody>
</table>

† Development model
* Under development

Output Power

Klystrons are tubes which, by their nature, can deliver considerable amounts of output power. Nevertheless, a certain number of qualifying remarks should be made. The electron beam must be perfectly well confined, and must not be intercepted either by the drift tubes or by their thermally fragile lips within the resonant cavities. This is necessary not only to avoid lost efficiency, but also to prevent any undesirable out-gassing or even meltdown.

The electron beam is confined by a magnetic field whose strength, increasing along the tube axis, equals two to three times the Brillouin field. Experience has shown that the magnetic axis must be aligned with the mechanical axis to within three thousandths of a radian at each point. When the tube is horizontal, the sag that might appear must be cancelled by means of stiffeners or a rigid girder supporting the tube + electromagnet assembly.

The collector dissipates the residual kinetic energy remaining in the electron beam after the final interaction. Nevertheless, the collector must often be designed to dissipate the full applied power. Contrary to power grid tubes, such as triodes, the distribution of the power dissipated in the collector is not uniform and the power density is a maximum at the point of impact of the edge of the beam. Densities of 500 W/cm² at this point are dissipated without any risk and operation at up to 1000 to 1200 W/cm², as in the TH 558, is perfectly possible, thanks to Hypervapotron® cooling. The Hypervapotron technique, with narrow grooves on the collector's outer surface at right angles to the water flow direction, makes cooling possible without any danger of calefaction and with water-flow speeds not exceeding 2 m/s. In fact, up to 1500 W/cm² have been experimentally obtained.
This system also works very well with horizontal collectors. Recent experiments have shown no danger of an accumulation of bubbles near the upper part.

The problem is much more complex for the collectors of high-power pulsed klystrons (1 to 5 kW/cm² dissipation), with long pulses (1 to 20 seconds) that recur only every 2 to 5 minutes. Although the average-power densities are very low, as Figure 5 shows, it is necessary to cool them as effectively as in CW as soon as the pulses exceed several hundreds of ms duration. The limits are fixed by the temperature of the internal surface of the collector. The absolute limit is 400° to 500 °C, beyond which the copper collector could become irretrievably deformed. The operational limit is 250 °C, beyond which the copper crystals grow very fast, under the effects of repeated expansion and contraction, provoking a loss of cohesion and thus cracking.

The above remarks concerning the collector can be repeated for the drift tubes, and especially their lips in the cavities. The cavities themselves have rather low losses, and can be easily cooled. Nevertheless, certain orders of magnitude must be noted. The output cavity of a 1 MW CW klystron must dissipate 10 to 20 kW. The slightest RF defect of a tuning system (incorrect choice of material or non-appropriate metal or brazing) can therefore be very serious.

The cavities of klystrons designed for the 1st or 2nd harmonic are of simple form. It is nonetheless true that certain non-desirable modes, which can couple themselves to the beam, easily appear, and that these unwanted modes must be suppressed or shifted in frequency.

### Output Circuit and Window

The design of the output waveguide, a cumbersome but indispensable tube appendix, is extremely variable: above, below or through the pole piece, according to the desired form of the magnetic field while keeping a relatively simple technology. But the output window remains the most critical element of the tube. Although the dielectric losses are never very large, the temperature gradients can become unacceptable. For example, at 1 MW CW, 1 GHz, an externally cooled circular Al₂O₃ window shows a temperature difference between the periphery and the center of nearly 100 °C!

Under these conditions, either supplementary air cooling should be employed, a different window material (such as BeO) chosen (which is unfortunately dangerous to machine), or one has to be content with lower power levels, unless some alternate solution, such as two outputs, etc., can be found. In a pulsed regime, even with durations of up to several seconds, the problems are less severe.

In addition, the RF output windows are often the seat of single-surface multipactoring. This is combatted by means of a very fine metal film that is very delicate to lay. Multipactoring is triggered all the more easily when the window is immersed in the residual magnetic field of the electromagnet.

### Reflected Electrons - Unmatched Loads

Multipactor effects can occur in the resonant cavities and in particular, in the gaps, causing the absorption of power and the loss of gain, but they can be parried relatively simply by means of geometrical and material modifications. The problem posed by electrons reflected by the collector and the RF field of the output gap is unfortunately not so simple to resolve.

The electron reflected by the collector are refocused by the magnetic field, then reaccelerated and modulated by the RF output field. This reverse current, even if very small, propagates back to the input cavity and causes an oscillation that is superimposed on the amplified signal.

As for the electrons reflected by the output cavity, these are in fact electrons that oscillate in the RF field itself, according to the phase and amplitude of the latter. This signifies that the klystron cannot operate correctly for certain values of the load impedance, which is indicated by the Rieke diagram. The “forbidden” load-impedance zone is defined by too heavy an interception of beam electrons on the output lips or by spurious oscillations.
The practical problem is important, because it appears that the higher the efficiency, the lower the admissible all-phase VSWR is (1.4 : 1 on the TH 2054). When the load has a nearly constant phase, this load can be matched to the tube by an auxiliary circuit. In the other cases (industrial microwave heating, Tokamaks, etc.), to date one has been obliged to use ferrite circulators or be content with lower efficiency.

Means of Fabrication and Testing

The resolution of the problems mentioned above and mastery of the technology involved still are not sufficient to launch the development of such “superpower” klystrons. One must also have special facilities for manufacturing and testing, such as, for example, a double-vacuum oven 6 meters high and 2 meters in diameter, and a 100 kV/20 A power supply for the TH 2089 klystron (1 MW CW at 350 MHz).

Conclusion

Finally, it should be noted that during the coming years, considerable technological progress may make much-improved klystrons available, for example, by the addition of grids to their electron guns. “Shadow grid” electron guns exist already at 50 kV. Intercepting-grid guns will also soon be available for switching between the video and sync regimes in TV klystrons. Consequently, there is no longer any doubt that, despite the very high voltages and the large cathode diameter of these superpower tubes, the implementation of flexible and fast grid control will pose no major problem — neither for the grids nor for the modulator.

The total amplification coefficient could be on the order of 50. The grid-circuit capacitance is about 50 pF and the current intercepted is only several per cent of the total.

In conclusion, it is safe to say that development of the generation of superpower klystrons is off to an excellent start, which should allow the future users to envisage the design of extremely high-power RF generators with confidence.

Discussion

The TV 2002 tube can deliver 40-MW peak power, but we would have to use the laser gun, change the electromagnet, and perhaps use a thick window to extend the pulse length to 5 μs.

The TGK.F1 tube under development for pulse lengths of 10 to 20 s would also run satisfactorily in continuous-wave (cw) operations. The long-pulse operation is actually more difficult than cw because of the thermal shocks.
RF SOURCES FOR PARTICLE ACCELERATORS - A PROGRESS REPORT

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Introduction

The continuing need for efficient high-power RF sources for the particle accelerator and fusion reactor programs being sponsored worldwide has been and still is a strong influence on the R&D programs at EIMAC Varian. In the recent past, for example, in a cooperative program with LASL\(^1\), the EIMAC X2170 has generated over 1 MW CW power at 80 MHz.

This paper will describe very briefly two EIMAC sponsored developmental programs that attempt to go beyond current practice. One is a modular radial strip beam tube with an objective of several MW of CW power at frequencies up to 100 MHz. The basic advantages of a modular design will be discussed, and examples of modular tubes for low power and for fusion will be shown. The other is a gridded density modulated device which should be capable of a MW of CW power at 100 MHz, falling off to perhaps 100 KW CW at 1000 MHz, thereby bridging the gap between 100 and 300 MHz which has so far not been completely filled at high power levels by either conventional tubes or klystrons.

Multi-Megawatt Modular Tetrode Program

Figure 1 is a photo of the developmental X2224 modular tetrode with the anode removed. Eighteen modules, each consisting of a cathode, control grid and screen grid, are mounted on a water-cooled stem. The cathode is directly heated Thoriated Tungsten in strip form. The grids are made of pyrolytic graphite. The advantages of this type of construction for large power tubes is that the interelectrode spacings which determine the performance can be made much smaller than in a tube of conventional design. This results from the fact that the desired close spacings between active elements can be determined by suitable precision insulators located close to the active electrodes. Connections to a relatively non-precision stem are made with flexible straps.

In conventional tubes using monolithic grids and cathodes made of thin wire meshes or cages the interelectrode spacings must be increased in proportion to the overall size, or the variations in spacings over the structure will be unacceptable largely due to the fact that the interelectrode spacings are dependent upon the entire tube mount structure. Local overheating of grids and anode will inevitably occur. To prevent this the spacings must be increased and the performance especially the power gain of an RF amplifier will be reduced. On the other hand, a modular tetrode can be made indefinitely large without requiring an increase in spacings by simply adding more modules. This situation is pictured graphically in Figure 2 where the key parameter \( \frac{G_m}{A} \), or transconductance per unit area is plotted against overall tube size. Existing conventional tubes show transconductance per unit area varying inversely with size. The X2224 modular tetrode is seen to be superior, and a larger version would have the same transconductance per unit area. As future accelerators demand larger amounts of RF power, for example, several MW CW, from one tube, the modular approach would clearly be preferred.

precision obtained and will reduce the cost of manufacturing large power tubes compared to merely extending present technology.

At present the EIMAC X2224 is entering the test phase with the objective of about 1 MW CW output. The physical size of this tube is approximately the same as our new 300 KW Pyrolytic Graphite tetrode. Future development will concentrate on simplification and cost reduction of the modules themselves.

**Inductive Output Tube**

We have taken the IOT invented by A.V. Haeff and described by him in 1939\(^2\) and by Haeff and Nergaard in 1940\(^3\) to higher power levels and higher frequencies. Haeff's tube produced over 35 watts CW output at 500 MHz, a remarkable performance at the time. An early model of this glass envelope tube is shown in Figure 3.

![Figure 3 Experimental Haeff Tube](image)

Figure 4 is a schematic cross section of the inductive output amplifier as shown by Haeff and Nergaard in reference\(^3\). The electron beam is focused by a magnetic field and is density modulated at the input circuit RF frequency. RF power is extracted from the density modulated beam by a simple resonant output cavity.

![IOT Schematic](image)

![Figure 5](image)

**TABLE I - TEST DATA**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>771</td>
<td>820</td>
</tr>
<tr>
<td>CW Output (KW)</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Power Gain (dB)</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>52</td>
<td>55</td>
</tr>
<tr>
<td>Beam Voltage (KV)</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>Pulse Power Output (KW)</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>Pulse Power Gain (dB)</td>
<td>24</td>
<td>27</td>
</tr>
</tbody>
</table>

The data shown by no means represents the limits for this tube type. A Theoretical analysis indicates power vs. frequency from this first design, an improved version of Haeff's, to be as shown in Figures 6 and 7. Further improvements can be expected in the future.

The improvement in performance over the original Haeff tube, about 1000 times in power output, is due to the application of modern materials and microwave beam tube technology as well as certain proprietary improvements in design. It closely resembles the advances made in klystrons, (KW before World War II, MW after).

The fact that this interesting tube type lay dormant for 40 years is undoubtedly due to the tremendous emphasis on velocity-modulated tubes in the fifties and sixties. It is now possible to see how its ultimate performance compares with other tube types, or how it fits into the total picture. Being basically a gridded density-modulated tube, its power output is limited by the grid and its

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\(^2\)An UHF Power Amplifier of Novel Design by A.V. A.V. Haeff, Electronics, February 1939.

upper frequency is limited by electron transit time. The klystron is not limited by either, and its performance is accordingly more impressive. The attractiveness of the Inductive Output Tube lies in its much smaller length, so that at frequencies between 100 and 300 MHz it has manageable proportions where a klystron would be unwieldy, and its higher efficiency especially as a linear power amplifier in AM service. In this tube the beam current varies with drive level as in a classical tetrode. In a conventional klystron the beam current is invariant with drive level, making it very inefficient at low signal levels. Compared with conventional tetrodes, the IOT has more power gain, a simpler structure, an output circuit (cavity) all at d.c. ground potential, and a separate collector which can easily be made large enough to handle the waste beam power, as in the klystron. Other advantages include the possibility of operating the collector at a lower potential and the attainment of interesting bandwidths by optimizing cavity design.

Figure 8 is a projection of where the modular tetrode and the IOT may fit in the power versus frequency spectrum. Both devices have interesting possibilities in filling gaps in the frequency spectrum which have existed for a long time. More compact RF generators in the 100 MHz to 300 MHz region could simplify some of the constructional problems involved in large storage ring tunnels. More power per generator in the 100 MHz region and below will simplify RF equipment design in accelerators as well as fusion reactors. The potential features of these new tubes suggests that in today's world of increasing energy costs and tight money they should have a substantial place.

Discussion
The cathode grid arrangement described is not fully modular in the 800-MHz design, but it evolved from our earlier work on modular grids and cathodes.

Our present Inductive Output Tube (IOT) devices are not at high voltages yet. At 18 to 20 kV, we reach about 55% efficiency. If we can get up into the 100-kV region, we should approach 60 to 70%, which would be competitive with klystrons. The major advantage of the IOT is for AM linear applications, for example UHF TV, where the klystron is left way behind.

We think pyrolytic grids will eventually find their way into the 2170. We are working our way up from the smaller types. We are at 300 kW now, and have the facilities to grow the bigger cups; in a couple of years one could expect them in the 2170.

We are considering trying an IOT at lower frequency—500 MHz; it will have solenoid focusing.

On the question of higher peak powers at low duty factor, the chart shown indicated that 10 MW, 3 μs should be achievable at higher voltages, which we think we can reach. The input circuitry is complex, requiring isolation of the voltage and rf, but it is easier to handle than a tetrode's output circuit.
MECHANICAL DESIGN OF RFQ RESONATOR CAVITIES IN THE 400-MHz FREQUENCY RANGE*

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Summary

Many RFQ resonator-cavity design concepts have been proposed in the 400-MHz frequency range. Los Alamos has been evaluating RFQ resonator-cavity designs that provide acceptable combinations of necessary mechanical features, easy tunability and long-term stability. Four RFQ resonator test cavities have been fabricated to test rf joints between the RFQ vanes and the resonator cavity. Two of these joints (the C-seal and the rf clamp-joint) allow vane movement for tuning. These test data, and the design of the present generation of RFQ resonator cavities, are presented.

Introduction

The general configuration of the RFQ linac consists of four specially machined vanes mounted within a cavity. This cavity is both a mechanical support for the vanes and an rf resonant cavity. Experience with the all-copper 425-MHz RFQ POP linac (Fig. 1) has shown that the resonator cavity must be easily tunable and structurally stable to maintain the tuning. Seven desirable RFQ resonator cavity design criteria have been identified: (1) adequate structural stability, (2) low fabrication costs, (3) adequate cooling, (4) simple assembly techniques, (5) an acceptable cavity Q, (6) ease of tuning, and (7) long-term stability.

RFQ resonator-cavity design is an optimization process, trading off relative advantages and disadvantages between these criteria. The rf fields in an RFQ resonator cavity run axially between the vanes in the quadrant, circling the end of each vane to connect fields in the adjacent quadrants. The rf currents flow from vane to vane across the interior of the resonator cavity, as shown in Fig. 2. The rf requirements for frequencies in the 400-MHz range are:

- magnetic field equal in each quadrant to ±2%;
- longitudinal magnetic field distribution flattened to within ±5%; and
- frequency adjusted to the required frequency, corrected for the dielectric constant of air and the operating temperature of the cavity.

The basic tuning methods that may be used are:

- machining inserts and/or moving tuners at the ends of each vane (varies the capacitance between the vanes and the cavity, and adjusts the axial electric field distribution);
- radially moving the vanes (primarily adjusts the frequency);
- circumferentially rocking the vanes (primarily alters the field distribution between quadrants);
- adjusting quadrant tuning slugs (tunes the frequency, balances the quadrant fields, and adjusts the longitudinal field distribution); and
- mechanically deforming the resonator cavity (simultaneously changes all tuning parameters).

Surrounding the resonator cavity is the RFQ power manifold (shown in Fig. 3) that supplies and distributes rf power to the RFQ linac. The rf power in the manifold drives the RFQ through diagonal rf coupling slots; these are typically -1.6 cm wide, inclined at an angle of 30° to 45° from the orthogonal plane, and as long as possible to enhance the rf coupling. The cavity-wall thickness at the slot is relatively unimportant, provided that the slot width is at least equal to the wall thickness and less than -10% of the slot length. The exterior of the resonator cavity should be fairly smooth, free of protrusions, so that the power manifold rf fields are not unduly perturbed. The performance of the RFQ linacs increases dramatically with higher surface fields; therefore, the vacuum required within the RFQ resonator cavity should be well into the 10⁻⁷ torr range to suppress sparking. The interior of the RFQ resonator cavity is pumped through the rf coupling slots to the RFQ manifold.

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*Work supported by the US Department of Energy.
Schriber has developed a formula for the rf loss (manifested primarily as structure heating) per unit length for a four-vane RFQ linac. The rf current on the vane tip is relatively small, reaching a maximum (~9 kA/m, or 6 times the surface currents in a drift-tube linac) at the vane base and resonator cavity wall. Schriber concludes that thin vanes and small resonator cavity i.d. are desirable to reduce the rf losses.

RFQ Resonator Design Considerations

A prime function of the RFQ resonator cavity is to provide an rf current path from one vane to another. The exact shape of the quadrant is relatively unimportant, but it is desirable to approximate a cloverleaf cross section. The circular geometry with the vanes having flared bases is a compromise, and was selected for the first high-power test (the 425-MHz RFQ POP experiment); however, the soft-copper structure was insufficiently rigid, and there were unacceptable dimensional deviations from designed values. The cavity could not be tuned except by physical deformation. This procedure required a fair amount of "art", because movement of one structural component shifted all other components of the cavity. When the deformation force was removed, the resonator cavity would relax into yet another configuration. Tuning required approximately four weeks of intense work. Because most 400-MHz frequency range RFQ designs are 1.8 to 2.5 m long, and have an ~16-cm i.d. (insufficient for manual access to the cavity interior), assembly is complicated by the requirement that adjustments and other mechanical operations must be accomplished through external access holes. Vane-tip machining now is done easily and accurately with a one-piece steel vane that is copper plated by the leveling, bright-acid technique; this gives an excellent surface for rf currents, and the plating thickness can be adequately uniform in the tip region. As tuning experience has been acquired with RFQ linacs, it has become obvious that vane movement for tuning is essential to disconnect the rigid electric tolerance requirements from the mechanical tolerance requirements. A flexible vane-to-cavity rf joint allows the vane to be moved radially and rocked, but these joints are in the region of highest rf currents. Several methods have been proposed to make the vane-to-cylinder rf joint. An electron-beam weld is difficult because of the length of the cylinder and the small cross section. A laser weld cannot be done because copper is an efficient reflector of common laser wavelengths. A plasma-arc spray requires equipment too large to fit easily within the resonator cavity. A relatively low-temperature, vacuum, or hydrogen furnace braze procedure also is viable, but braze runs may upset the cavity tune. A copper-plate rf joint, using solution plating, would be difficult in such a complicated geometry, and brush plating would be difficult in the confined space of the quadrants. In either case, a gap between the vane and the cylinder might prevent the copper plate from forming the continuous surface necessary for a good rf joint.

An rf joint formed by using a compressed soft-metal wire or ring is a technique used in many accelerator applications. There are three problems with this approach for a simple vane-to-cylinder rf joint: (1) good rf contact requires large compression forces, (2) surface irregularities might cause a nonuniform rf contact, and (3) the radial position of the vanes cannot be easily altered. Recent Los Alamos efforts in 400-MHz-region RFQ resonator-cavity design have concentrated on the development of flexible rf joints between the vanes and the cylinder.

Flexible RFQ rf Joint Designs

Several types of flexible rf contacts have been proposed that are compatible with the restricted space in 400-MHz-size cavities. One flexible rf joint design concept under development for 400-MHz-size RFQ resonator cavities is the C-seal joint. A cross section of the C-seal RFQ is shown in Fig. 4. It is a simple cylindrical cavity with each vane held in place by two rows of screws. Inconel C-seals (commercially available in a variety of sizes), plated with 0.005-cm-thick copper, are captured in the vane groove, making contact with the vane and the RFQ with a nominal 20% squeeze. This results in an ~66.9 kg/cm contact force. In theory, as the C-seal is squeezed, the contact points are forced outward from the vane, causing a highly localized contact force at the point where the rf currents must pass. Because the C-seal is compact, the rf-coupling slots are not unduly shortened. The radius at the contact point lessens the probability that the copper-plated surfaces will be damaged. The small surface area for rf current flow implies that the potential for heat-caused changes in the contact force is lessened. The good contact force allows the C-seal to adjust to minor cavity surface irregularities; also, the C-seal concept is very simple and inexpensive.

The other flexible rf joint under development for 400-MHz-size RFQ resonator cavities is the rf clamp-joint, shown in Fig. 5. This rf joint is made by two compression bars that force two soft-copper contact strips into contact with the copper-plated edge of the steel resonator-cavity cylinder. The 0.08-cm-thick copper contact strips are furnace brazed to the mild steel vane. The compression force on the contact edge can be up to 357 kg/cm — the normal design force on a wire vacuum seal. Assembly of the resonator cavity begins by placing the vanes in a nominally correct mechanical position in the cavity. The cavity is then tuned by slight movements of the vanes, and the compression bolts are tightened until the cavity Q is satisfactory. Final minor vane movements and tuning
RFQ rf Joint Tests

Four test cavities of essentially the same 400-MHz geometry were used to evaluate RFQ rf joints. Each cavity was an ~26-cm-long, ~15-cm-diam cylinder in which four vanes were mounted. The vanes were foreshortened; therefore, the actual resonant frequency was ~800 MHz. All components were copper-plated steel. Cavity 1 had the vanes furnace brazed in place to provide a benchmark for the remaining tests. Cavity 2 was used to evaluate wire seals of various materials. Cavity 3 was used to test the C-seal rf joints, and Cavity 4 was used to evaluate the rf clamp-joint. The results of these tests are summarized in Table I. These tests indicate that a good mechanical joint is achievable. The gold-to-gold joints all have a Q of ~6400; most copper-to-copper joints have a Q of ~4600. It may be that the surface conditions at the contact point are more important than the contact method or force. These joint tests are continuing.

Table I
RFQ rf Joint Tests

<table>
<thead>
<tr>
<th>Cav. No.</th>
<th>Joint Type/Contact Material</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Brazed Cusil (72% Ag, 28% Cu)</td>
<td>6100 ± 305</td>
</tr>
<tr>
<td>2</td>
<td>Wire Gold wire/gold</td>
<td>6400 ± 320</td>
</tr>
<tr>
<td>3</td>
<td>Copper wire/gold</td>
<td>6400 ± 320</td>
</tr>
<tr>
<td>4</td>
<td>Copper wire/copper</td>
<td>4400 ± 220</td>
</tr>
<tr>
<td>5</td>
<td>Gold-plated copper wire/gold</td>
<td>6300 ± 315</td>
</tr>
<tr>
<td>6</td>
<td>C-seal Copper-plated Inconel/copper</td>
<td>6000 ± 300</td>
</tr>
<tr>
<td>7</td>
<td>Clamp Copper sheet/copper</td>
<td>4800 ± 240</td>
</tr>
</tbody>
</table>

Conclusions

The C-seal joint, using commercially available hardware, is the essence of simplicity, but it must make two rf contacts per joint, doubling the joint losses and the probability of an eventual contact failure. The positioning screws are under tension; relaxation of the screw threads will cause the vane position to change, altering the cavity tune. Also, the rf contact force is directly coupled to the vane position. The rf clamp-joint approach involves more machining than the C-seal; but the positive and vane-position-independent action of the rf clamp-joint may provide better long-term stability. For high duty-factor applications, the heat transfer with the rf clamp-joint copper strips may be an advantage over the copper-plated Inconel C-seals. Much has been learned about the tuning and technology of RFQ linacs. The search for a tunable design having long-term stability is still in progress, but the development of flexible mechanical rf joints promises to be an important technological advance in RFQ linac design.

Acknowledgments

The authors would like to acknowledge the aid of J. L. Johnson, R. F. DePaula, and R. D. Bramlett in the test-cavity fabrication, F. J. Humphrey for rf measurements, and J. L. Uher for the wire-seal rf joint experiments.

References

HIGH POWER, ON-AXIS COUPLED LINAC STRUCTURE

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Summary

A prototype linac structure with five accelerating cells and four on-axis coupling cells has been constructed and operated at 805 MHz with 100% duty factor. The structure is a favoured design for both a spallation breeder and a high power microtron. Magnetic coupling slots provide 10.4% first neighbour coupling, and two mechanical tuners cover the necessary frequency range for resonance control. Thermal detuning effects, controlled by independent radial and circumferential cooling circuits, are observed at power levels up to 100 kW/m with diagnostic probes in each cell. Results of experiments of beam blow-up mode excitation with current pulses in a thin conductor are reported.

Introduction

Structures optimized for use in linacs designed for fundamental research are not necessarily appropriate for high power applications. The large power dissipation and strong beam-cavity interactions can lead to unstable operation and loss of the beam. Such conditions are encountered when the accelerating structure is run in the cw mode and large currents are accelerated.

Operation of biperiodic structures at 100% duty factor has already been demonstrated\(^5\). Modified versions of the LAMPF side-coupled structure are presently operating at 0.7 MeV/m in the Electron Test Accelerator (ETA)\(^2\) and stable operation up to 50% beam loading has been achieved. Beam loading up to 80% has been achieved at a lower gradient\(^3\). A more attractive design based on work by Schriber et al.\(^4\) at S-band is possible when the coupling cells are placed on-axis. Simple assembly procedures and reduction in fabrication costs have already encouraged designers of electron storage rings to choose a coaxial design of single periodicity for cw operation. In these designs, the ingenuity and complexity of the segment cooling is motivated by a desire to decrease losses from the temperature-dependent variation in electrical conductivity\(^5\).

The main parameters to be optimized for high current application and consequent heavy continuous beam loading are the field tilt and the system stability. This favours high intercavity coupling and biperiodicity. The structure to be described\(^6\) has both and was built for tests at high field gradient. So far high power tests, limited only by the available power, have been done up to 105 kW/m at 804 MHz with energy gradients up to 1.8 MeV/m. High current operation in ETA is planned at a later time.

Design Description and Low Power Tests

A drawing of the copper, 930 mm long, $\varepsilon$=1 structure is shown in Fig. 1. There are five accelerating cells and the rf power is fed to the centre cell through an iris which is demountable for ease of machining during testing at low power. Mechanical tuners in the end cells are used to keep the structure on resonance. They provide a range of 2.2 MHz which exceeds the frequency shift occurring during start-up. Magnetic field probes are provided in each cell for control and diagnostic purposes. The tank rests on a vacuum manifold with ports on the second and fourth accelerating cells. There is sufficient conductance through the beam hole and coupling slots to provide a vacuum in the $10^{-5}$ Pa range in the other cells.

A 5 mm (dia.) dielectric bead gave a frequency shift of 10.1 kHz and with a measured unloaded Q of 22,600 the shunt impedance is 28.5 M$\Omega$/m. This is 35% less than that predicted by SUPERFISH\(^8\) and is an indication of the penalty for the various slots and apertures necessary in a prototype structure.

The effect of the tuners on the fields in a coupling cell is shown in Fig. 2. A frequency shift from the reference fully out position caused by one tuner must be balanced by a corresponding shift in the second tuner to reduce the coupling field. These observations are confirmed by the RLC-coupled loop model and indicate that even with the $\pi$/2-mode, a tuner located away from the structure centre can seriously imbalance the field distribution. The measurements also confirm that...
the tuned condition, i.e. minimum coupler field, is near the position of minimum penetration into the cavity.

It is hoped to investigate structure stability at very high field gradients, hence considerable care was taken with the cooling design. Radial and circumferential cooling are separate circuits, each with counter flow as shown in Fig. 3. Flow tests confirm the design with a total flow rate of 4.5 l/s for a pressure drop of 340 k Pa with both circuits operating simultaneously.

Beam Blow-up Mode Excitations

In high current applications, and particularly in circular machines where beam disturbances may be regenerative, the excitation of the TM_{110}-like modes (beam blow-up modes) by an off-axis beam is important. These excitations were studied by simulating the off-axis beam by short pulses of current in a thin conducting wire (0.127 mm dia.) displaced from the structure symmetry axis. Previous measurements have shown that the field distribution of the TM_{110}-like modes are not perturbed by this technique for small wire displacements, provided the electric field lines of the modes are not intercepted by the wire.

The coupling slots in the cells resolve the azimuthal degeneracy of the TM_{110}-like mode into two modes of neighbouring frequency. The two modes have orthogonal symmetry planes, each running through a set of coupling slots. The frequency of

With current pulses from an oscillator sweeping a frequency domain around the frequencies of the TM_{110}-like modes, the amplitudes of these modes in accelerating and in coupling cells are measured as a function of the wire's displacement from the structure symmetry axis. As shown in Fig. 4, a coupling cell is more sensitive to TM_{110}-like mode excitation than accelerating cells for a given wire displacement indicated by the steeper curve. Accelerating cells with tuners in the fully retracted position are less sensitive, suggesting that the electric field maximum is further displaced from the structure axis.

High Power Test Procedure

All four cooling circuits were instrumented with Resistance Temperature Devices (RTD's) and annular flow meters. RF power from the field probes was sent to individual crystal detectors. Thermocouples were used to measure the outer surface copper temperature only, as the radial cooling design precluded access near the beam aperture. An ionization chamber placed on-axis recorded the radiation level. All analog lines were read by a computer and were available for on-line analysis.

The tank was powered with a 100 kW cw klystron, Varian type VR-853M. A 3 dB isolator with a forward-to-backward ratio of fourteen was used to attenuate the reverse power. The field control loops described previously were used
in the tests except that the transmitted phase and not reverse power was the controlled variable for resonance control of the tuners. The water temperature, controlled by a task activated in the computer every ten seconds, keeps the electrically ganged tuners within range.

Several problems, including sparking at the coupler probes, excessive heating of the tuner stems and burning of the tuner fingers were encountered during the four-week commissioning period. Stable operation at 100 kW is now routine. The radiation level on axis was monitored as the power increased and initially, at 100 kW, it was 10 R/h. The level correlates well with the structure vacuum and less with the forward power.

The only hot spots are to be found at the uncooled interface between brazed stainless steel appendages and the main structure body. There is no evidence of circumferential gradients.

Performance at High Power

Thermal detuning of the structure manifests itself as a redistribution of the field. This effect was examined by withdrawing the tuners and allowing the master oscillator frequency to follow the tank resonant frequency as power increased. The results taken with constant inlet water temperature are shown in Table 1. All fields are normalized to 100 kW. Accelerating cell field amplitude, which varies by less than 1% as shown by bead pull measurements at room temperature does not vary systematically with power within experimental error showing that little imbalance has arisen from thermal effects.

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Accelerating Cells (%)</th>
<th>Coupling Cells (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5.91 5.92 6.02 6.02 5.93</td>
<td>6.22 6.31 6.25 6.22</td>
</tr>
<tr>
<td>40</td>
<td>7.54 7.59 7.67 7.50 7.60</td>
<td>7.71 7.83 7.48 7.68</td>
</tr>
<tr>
<td>60</td>
<td>8.65 8.70 8.73 8.69 8.69</td>
<td>8.73 8.73 8.71 8.75</td>
</tr>
<tr>
<td>100</td>
<td>10.0 10.0 10.0 10.0 10.0</td>
<td>10.0 10.0 10.0 10.0</td>
</tr>
</tbody>
</table>

Radial and circumferential cooling of our structure were compared at 50 kW by closing either the circumferential or radial flows and keeping the inlet water temperature constant. In the two cases, radial flow increases by 39% and circumferential by 25% respectively when one circuit is closed because of the increased pressure. The frequency shift with radial flow closed is 280 kHz, 5 times as much as that by closing circumferential flow. This indicates that, although calorimetric measurements show radial cooling is carrying away only 34% of the total power, it is superior for keeping copper surfaces within tolerable limits for high gradient work.

The rapid increase in frequency of 15 kHz/s when the radial flow is turned on is comparable to thermal transients on first power turn-on, and could have significant implications in control.

Two cooling circuits could be envisaged, one for bulk cooling and the other would serve to eliminate stub tuners with the attendant advantage of tuning all cells simultaneously.

Conclusions

Average energy gradients of 1.8 MeV/m present no difficulty for biperiodic structures at 804 MHz. Magnetic slots can provide sufficient coupling for very heavy beam loading and the mechanical simplicity of on-axis coupled structure is proven high power performance makes it attractive for high current applications. Beam tests are needed to examine its performance in circular machines where excitation of beam blow-up modes is regenerative. A cooling system has been designed and tested which could reduce the cooling needs of large machines and gives good prospects for the elimination of troublesome and costly stub tuners in future designs.

References

Summary

The results of a testing program on the disk-and-washer (DAW) structure with tee supports are presented. These results have led to the design of a 2.4-m DAW linac for use as the preaccelerator section of the National Bureau of Standards (NBS)/Los Alamos racetrack microtron (RTM). The structure uses two tee supports for each pair of washers, instead of four, and the structure has a larger diameter than earlier test structures. Two properties of this structure, which make it appear to be ideal for the RTM application, are a high shunt impedance and a high cell-to-cell coupling factor. This coupling factor eases construction tolerances and reduces sensitivity to thermal effects from the high rf heating load that will be imposed upon it. The structure is designed to operate at a 100% duty factor with a 1.5-MV/m accelerating gradient at 2380 MHz. This load would detune most accelerating structures. The tuning procedures, the transverse modes, and their effect on the structures design also are presented.

Introduction

The DAW linac structure is being developed at the Los Alamos National Laboratory for the NBS/Los Alamos RTM. This structure would be useful for a number of electron and proton accelerators because it offers efficient acceleration of particles with velocities greater than half the velocity of light. The structure is a standing-wave linac with an extremely stable field distribution because the operating mode has the stability of a \( \pi/2 \) mode with large cell-to-cell coupling. Other advantages include good vacuum conductance, an all-coaxial structure, high effective shunt impedance, and a high quality factor.

The geometry of the three test cavities and the preaccelerator section has been determined in an iterative procedure with the aid of the rf cavity calculational program SUPERFISH and the results of the frequency measurements and beadpulls on the test cavities.

The tee-shaped washer supports have been selected for their fore/aft symmetry and their small perturbation to the accelerating mode. The washers are supported in pairs from a number of tee-shaped supports. The axis of the supports lie along an equipotential of the accelerating mode as calculated by SUPERFISH.

Test Results

Three cavity designs were tested during the last year. The first two designs had quality factors \((Q)\) considerably lower than anticipated. The third design had a measured \(Q\) of 29,000 for a \(J\)-cell, \(B = 1\) cavity, indicating an effective shunt impedance of 90 M\(\Omega\)/m for a long structure.

Although this is less than the 100 M\(\Omega\)/m we had hoped for, it is certainly adequate for our needs. These results have led to a final design for the 2.4-m long preaccelerator structure, which is now under construction and should be ready for low power tests in December 1981 and full power tests by February 1982.

The dimensions of the three test cavities and the preaccelerator are defined by the half-cell geometry shown in Fig. 1 and tabulated in Table I. A summary of test results are shown in Table II. Changes in the DAW design from the original conception include the use of two (instead of four) tee supports for each pair of washers, and an increased diameter of the structure. These changes were made to increase the structure's shunt impedance. Even though the tees are placed on an equipotential line, they are in a region of high magnetic field and therefore dissipate rf power as a result of surface currents. The rf power loss caused by these stems is cut in half by reducing the number of these stems from four to two. In addition, the perturbation of the accelerating-mode frequency is cut in half. The use of four stems raised the accelerating mode by about 50 MHz. When
two stems are used, this perturbation is only 25 MHz, and the perturbation of the coupling-mode frequency is decreased by more than a factor of 2. The increased diameter of Test Cavity 3 probably caused part of the decrease in this perturbation. Increasing the diameter of the structure lowers the rf losses on the outer wall, which raises the shunt impedance. Finally, the diameter of the bore hole was reduced to further increase the shunt impedance. Beam-transport calculations of the RTM indicated that the smaller bore hole would be satisfactory.

Figure 2 shows the Brillouin diagram of the accelerating mode, as well as some other modes that the DAW Test Cavity 3 supports below 2700 MHz. Above 3000 MHz, there is a very large number of modes possible. Of special concern is the set of TM 11 modes just below the accelerating frequency. The frequencies of these modes are lowered by increasing RC and RD. These TM 11 modes are of most concern because they are the most likely to cause beam blowup. The TE 11 modes do not interact strongly enough with the beam to be of concern for beam blowup. The "acc. stem" modes are modes that exist only because conducting stems are used to support the washers. The stop bands in some of the mode spectrums at a phase shift of \( \pi / 2 \) per cavity are due to the biperiodic distribution of the tee supports.

The accelerating mode and the coupling mode occur at the confluence of the TM 01 and TM 02 modes. The geometry of the DAW structure is designed so that these two mode spectrums join at this point. Because the supports perturb the frequency of the accelerating mode and the coupling mode, minor changes must be made in the geometry to obtain the desired accelerating frequency and to retain a closed stop band, with its implied stability and uniform distribution of accelerating fields. Figure 3 shows a section of DAW structure with locations where material must be added or removed for tuning. Because the stems increase the accelerating-mode frequency, the washer radius initially must be made larger so that the accelerating frequency is lower than that desired. Material then can be removed to tune the structure to the right frequency.

The accelerating frequency rises 20 MHz for each millimeter of material removed from the washer radius. The coupling-mode frequency is lowered 43 MHz when the radius RC is increased by 1 mm. Table II shows the predicted frequencies of the accelerating and coupling mode of the preaccelerator section. The dimensions are given in Table I. A small amount of material has been left on the washer radius for final tuning of the structure 2380 MHz.

In addition to perturbing the frequency of the accelerating and coupling modes, the stems can
consists of two ends and two sections, each slightly longer than 1.1 m. One end piece has an rf coupling iris to the WR-430 waveguide. Only one vacuum port is required, because the structure is so open that vacuum conductance is no problem for a structure of this length. Longer sections will require more vacuum ports.

Acknowledgment

The authors would like to thank F. J. Humphry, P. L. Roybal, and L. C. Wilkerson for their work on the DAW test cavities.

References


Discussion

The accelerating mode has a shunt impedance of about 90 MΩ/m. The TM11 mode is close to the accelerating mode, but it can be lowered by tuning. The structure is very strongly coupled from cell to cell, like 50%, so the drive can be coupled in anywhere and the field level will be the same in every cell. We do the tuning before the final braze. Some fine tuning could be done afterwards; the water temperature can also be used to adjust the resonant frequency about 40 kHz per degree centigrade.
Summary

The primary goal of the experimental program in heavy ion fusion (HIF) at Argonne National Laboratory (ANL) was to demonstrate many of the requirements of a rf linac driver for inertial confinement fusion. During the past three years, most of the construction effort has been applied to the front end. So far, the preaccelerator and first three linac cavities are operational with 20 mA Xe$^+$ beams at 2.2 MeV. The performance of the front end is discussed. The development of an electroplating technique and its use in the Wideroe linacs to reduce the construction costs is described. The future plans and options for the test bed are also presented.

Introduction

When the ANL program was started, there were many uncertainties about how to develop an adequate linac for the rf linac/storage ring approach to HIF. Most of these involved the front end: bright 50 mA heavy ion sources did not exist, the low current limits of linac structures required the development of very high voltage preaccelerators, and the control of emittance growth in the linac structures was uncertain. The RFQ was an interesting, but untested concept.

We started the development of a high current heavy ion front end for two reasons: first, to demonstrate that it was possible and had good long-term reliability; and second, to provide intense beams for a rf linac/storage ring test bed. The initial test bed linac would accelerate more than 40 mA of Xe$^+$ to 220 MeV.

At this point, we have demonstrated many of the requirements of the front end. A very bright, single-aperture Penning discharge source capable of 100 mA of Xe$^+$ was developed. A 1.5 MV preaccelerator was constructed and operated with 40 mA beam currents. A buncher and three linac cavities have accelerated 20 mA currents to 2.2 MeV. Fast, non-destructive beam diagnostics were built and operated to tune and analyze the beam. With the projected reduced budgets, the continued construction of a test bed is not possible. Of course, there are always new ideas and developments that should be pursued. Also, the long-term reliability of a facility requires extended operation. Scaled-down program options are now being considered which effectively utilize what has been developed and which address the most pressing uncertainties in the HIF scenarios.

Ion Source and Preaccelerator

A 100 mA low-emittance xenon (and mercury) ion source was developed for this program by Hughes Research Laboratories. It is a Penning discharge, Pierce extraction source with a single 3 cm diameter aperture. Xe$^+$ currents of 100 mA have been extracted with no indication of plasma sheath instability. For typical operation at 40 mA, the aperture in the focus electrode is reduced to 2.1 cm diameter to increase the current density to 12 mA/cm$^2$ and to reduce the gas load in the accelerating column. The voltages and timings of the pulsed source parameters are controlled via fiberoptic light links to the high voltage terminal. In typical operation, this reliable, low-maintenance source produces a 100 µs beam pulse with a 10 µs rise time and 50 µs decay time.

The preaccelerator is a 4 MeV Dynamitron which has been modified extensively for maximum pulsed current operation at 1.5 MeV. A high gradient accelerating column is used to handle the large current density. A more complete description of the preaccelerator has been published. The high gradient column initially had an outer shell consisting of ceramic rings which were epoxy-bonded to titanium rings with indium seals. It originally conditioned to 1.4 MV, but would not operate reliably above 1.2 MV because of excessive gradients between the protective rings along the inside surface of the outer shell.

The high gradient column is now in operation with a new outer shell. The gradients between the inner protective rings were reduced by almost a factor of two. The ceramics are longer, so there are only one-half as many joints. The joints are not bonded; C-rings with lead foil backed up by rubber O-rings make up the vacuum seals, with the entire column spring-clamped in 30,000 pounds of force. The ends of the ceramics are covered with copper foil to produce a uniform electric field across the face of the ceramic. So far, the column has been conditioned to 1.53 MV and 35 mA beam currents of Xe$^+$ have been accelerated to 1.5 MeV. This performance was achieved with one out of fifteen ceramics shorted - apparently it failed because of an internal defect. In general, the column now conditions very easily and deconditions little when turned off for several days. At a convenient time, the shell will be disassembled and a replacement ceramic inserted which should improve the long-term operation of the column at 1.5 MeV. Preaccelerator emittance measurements were performed using nondestructive profile systems at the buncher waist followed by a drift space. The 90% envelope transverse normalized emittances were measured to be 0.027 cm-mrad at 1.5 MeV and 0.019 cm-mrad at 1.0 MeV. While the preliminary value at 1.5 MeV is larger than expected and may be reduced by further optimization, it is still more than adequate for HIF, and an order of magnitude brighter than other high current sources.
Linac Cavities

The front end of the prestripper linac consists of a buncher, five independently-phased 12.5 MHz short, single-stub linac cavities, and three 12.5 MHz double-stub Wideroe linacs to reach 22.9 MeV. The layout through the first Wideroe linac is shown in Fig. 1. The linac is operational through IPC 3 where the energy is 3.2 MeV. The first Wideroe is partially constructed, but is now on hold because of budget constraints. A detailed design of the linac has been published. The parameters of the prestripper linac sections are shown in Table I. The emittances and transmitted currents are results of a beam simulation using the PARMILA code. Note that essentially all of the emittance growth and beam loss have occurred by the end of the first Wideroe tank. For this reason a high priority had been placed on completing at least that much of the linac to study the beam properties.

Electroplating

The first three linac cavities were made of solid copper. We found that the fabrication costs of solid copper were essentially the same as using copper-clad steel because of the additional operations involved with the latter. However, it was clear that a copper electroplate on steel could reduce fabrication costs by at least one-third. To realize the maximum benefit would require the use of plating levelers and brighteners. These avoid the need of final polishing and greatly simplify plating around corners and into apertures. This technique has been very successfully developed at GSI in Darmstadt, West Germany for the large UNILAC cavities. A thorough search of vendors in this country revealed that only one was willing or capable of attempting the internal electroplating of large tanks using similar techniques. After studying the GSI process, the proposed vendor process, and an ANL in-house process, we have arrived at a modified electroplating procedure which encompasses the best features of each without exceeding the plant capability of the vendor. As a test piece and prototype, the tank of stub #1 of the Wideroe has been electroplated successfully with 250 mm of copper. This tank is 0.91 m in diameter and 1.82 m in length with many apertures and flanges. The surface finish was leveled from 1.3 mm on the steel substrate to 0.25 mm after plating. The electroplate thickness was uniform (± 10%) and has excellent adhesion when subjected to heat and vacuum. The electrical conductivity is greater than 90% IACS.

Sparking Limit Test

A voltage sparking test was conducted using IPC 1 to determine the maximum surface electric field strength that could be reliably used at 12.5 MHz in linac design. Specifically, the test was conducted to determine by what factor the Kilpatrick voltage limit could be exceeded without a great danger of sparking. In normal operation at 12.5 MHz, IPC 1 runs spark-free in a clean, high-vacuum environment up to 15 MV/m (1.6 times the Kilpatrick limit) with 30 mA of Xe passing through it. In order to increase the gradient achievable in IPC 1 by nearly a factor of 2, a copper cap was added on one side of the drift tube to reduce its gap from 1.2 cm to 0.66 cm. Sparking tests with 1 ms pulse widths every 1.5 s were conducted for about a month. A spark rate of 1% was measured at 22 MV/m (2 times the Kilpatrick limit) and 28% at 25 MV/m (2.3 times the Kilpatrick limit). At these levels, there is about 2 joules of energy stored in the cavity. Protective circuits turned the rf drive power off on the occurrence of a spark, so that only the cavity-stored energy was dissipated in the spark. After high voltage conditioning, the cap had a sandblasted appearance, with several tiny surface cracks and fissures visible. The results indicate that one should proceed with great caution before designing delicate structures or systems with large stored energy beyond twice the Kilpatrick limit at 12.5 MHz.

Status

IPC 2 AND 3 have internal 5x drift tubes; therefore, they are especially sensitive to the beam particle velocity. When we were limiting the operating voltage of the old accelerating column to 1.2 MV, this sensitivity led us to a two-stage procedure for studying the performance of the low-beta linac through IPC #3 using both xenon and krypton (with natural isotopic abundances).

The acceleration of 30 mA Kr+ demonstrated the correct velocity profile and power and phase control through the linac. The preaccelerator energy was 0.98 MeV and the respective cavity exit energies were 1.09, 1.27, and 1.43 MeV. These energies have the velocities corresponding to the design for xenon from 1.5 MeV to 2.2 MeV.

At present, we are operating with 30 mA Xe+ beams injected at the design energy of 1.5 MeV. The output energy of 2.2 MeV is achieved with nearly the expected power levels and phase angles. Accurate measurements of capture and beam characteristics will be performed using 80- enriched Xe129.
Plans and Options

The program plan has been to install the former Princeton-Penn 3 GeV synchrotron magnet as a stacking ring as soon as the 8.8 MeV Xe beam is available from the first Wideroe tank. Program options must now be considered because of reduced budgets and the introduction of new issues. At anticipated funding levels during this year, it will not be possible to continue any construction. Instead, we will concentrate on design studies dealing with the problem areas in the rf linac/storage ring scenario. One of the primary uncertainties in the storage ring concept for HIF is the potential problem of the longitudinal microwave instability caused by vacuum chamber impedance coupling to intense beams with little momentum variation. Studies are underway to devise experiments to measure the growth rates under controlled conditions.

There is a clear need for a definitive set of experiments to determine the maximum reliable gradients on conditioned electrodes over a wide frequency span. Experience at various laboratories indicates that the Kilpatrick limit is too conservative since it was based on non-conditioned surfaces in diffusion-pumped cavities. However, the same experience does not indicate a consistent pattern of maximum gradient as a function of frequency. We plan to carry out rf sparking experiments over the range of 10-100 MHz in the same apparatus using an existing very wideband power amplifier. It will incorporate a clean vacuum system and study conditioning under realistic conditions. The effects of different materials and surface preparations will be investigated.

An interesting HIF design using a radio-frequency quadrupole (RFQ) linac was recently completed.8 If it can be economically constructed and made operationally reliable, the 12.5 MHz RFQ would accelerate 50 mA of Xe from 0.30 to 10 MeV with only a factor of 2 emittance growth. We are presently working on the electrical and mechanical design of such a RFQ linac9 which, if constructed, could make a direct comparison of its operation with our more standard approach.

We are considering beam experiments which could be done with our present system. These include wall evaporation rates due to particle irradiation, heavy ion ranges in plasma hot cells, and thin foil stability during irradiation. These all have interesting implications for HIF targets and reactors.

The development of improved diagnostics to accurately characterize these intense beams is needed. We plan to continue development in this area.

Finally, a detailed study of the optimal funnelling of beams for filling rings is also needed. Some of the presently advanced scenarios would funnel the beams to such an extent that the cost of the required instantaneous rf power would be prohibitive for a power plant.

References

Discussion

Once substantial pitting occurs, we find the part must be replaced. Outgassing rate measurements on copper-electroplated steel have been made at Los Alamos, and it appears to be the same as electroplated pure copper. Any procurement of this material should specify the required conductivity. We specified it be above 90% copper; it came out about 98%, for both dc and rf measurements. We have not studied the gap dependence of the sparking in this situation. We would like to do a consistent experiment using a wide-band power amplifier from the ZGS.

TABLE I

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>IPC #1</th>
<th>IPC #2</th>
<th>IPC #3</th>
<th>IPC #4</th>
<th>IPC #5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>w/5x</td>
<td>w/5x</td>
<td>w/5x</td>
<td>w/5x</td>
<td>w/5x</td>
</tr>
<tr>
<td>No. of Gaps</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Exit Energy (MeV)</td>
<td>1.66</td>
<td>1.95</td>
<td>2.21</td>
<td>2.54</td>
<td>3.00</td>
</tr>
<tr>
<td>$\sqrt{e_s} e_0$ (cm-m)</td>
<td>0.066</td>
<td>0.067</td>
<td>0.069</td>
<td>0.070</td>
<td>0.071</td>
</tr>
<tr>
<td>$e_0$ (10^{-4} ev sec)</td>
<td>2.87</td>
<td>2.91</td>
<td>2.99</td>
<td>6.76</td>
<td>6.43</td>
</tr>
<tr>
<td>I (mA)</td>
<td>39.9</td>
<td>38.1</td>
<td>37.5</td>
<td>36.9</td>
<td>36.5</td>
</tr>
<tr>
<td>Shunt Imped. (Mu/m)</td>
<td>3.6</td>
<td>6.1</td>
<td>6.4</td>
<td>10.5</td>
<td>15.6</td>
</tr>
</tbody>
</table>
A 70-MeV proton beam would open a new family of medical radioisotopes (including the important \( ^{123}\)I) to wide application. A 70-MeV, 500-\(\mu\)A linac is described, based on recent innovations in accelerator technology. It would be 27.3 m long, cost \(\$6\) million, and the cost of power deposited in the radioisotope-production target is comparable to existing cyclotrons. By operating the rf-power system to its full capability, the same accelerator is capable of producing a 1140-\(\mu\)A beam, and the cost per beam watt on the target is less than half that of comparable cyclotrons. The technology to build such a linac is in a mature stage of development, ready for use by industry.

### Sources of Medical Radioisotopes

Nuclear medicine is a major medical specialty that provides cost-effective, noninvasive, dynamic-function information that is clinically useful in diagnosing human diseases. Although reactors have produced radioactive isotopes of practically every element, studies of reactor-produced isotopes by biomedical investigators have demonstrated the major disadvantages of a low specific-activity dose (plus useless beta-decay radiation) in diagnostic applications. Clever techniques have been developed for recovering the high specific-activity products from uranium fission (\( ^{99}\)Mo, \( ^{131}\)I, and \( ^{133}\)Xe) and from fast-neutron-induced \((n,p)\) and \((n,\alpha)\) reactions (\( ^{43}\)K, \( ^{54}\)Mn, \( ^{58}\)Co, \( ^{67}\)Cu, \( ^{132}\)Cs, etc.). Although \( ^{133}\)Xe and \( ^{99m}\)Tc (formed from the radioactive decay of \( ^{99}\)Mo) continue to occupy major roles in nuclear medicine, in recent years there has been a definite shift from reactors to accelerators as a principal source of radioisotopes for innovative medical applications. Some of the accelerator-produced nuclides gaining in importance include \( ^{201}\)Tl, \( ^{67}\)Ga, \( ^{111}\)In, \( ^{68}\)Ge, \( ^{123}\)I, and \( ^{127}\)Xe.

To achieve the highest possible specific activity for charged-particle-induced reactions, a nuclear reaction is chosen so that the desired radionuclide is a chemical element different from the target. Isotopically enriched targets are usually employed to minimize radionuclidic impurities. The excitation functions for the chosen reaction (and competing nuclear reactions) must be known to optimize irradiation conditions (maximize the product and minimize impurities). This optimization generally leads to a limitation on the target thickness, resulting in lower product yields. As the energy of the accelerated ion increases, a wider range of nuclear reactions is possible, and a greater variety of radionuclides can be made.

In the United States, low-energy accelerators (energies less than 45 MeV) are generally used to prepare medical radioisotopes. A few medium-energy accelerators (100 MeV to 1 GeV) have medical-radioisotope efforts as part of their total programs. There are now 10 accelerators operating (or being installed) in institutions in the United States. There are also 5 university-based accelerators that devote some beam time to preparing medical radioisotopes. In US federal installations, 9 accelerators are used to prepare medical radioisotopes, but 4 are used on an infrequent basis. The radiopharmaceutical industry has a total of 13 operating or planned accelerators. Therefore, in the United States alone, 37 accelerators are used for medical-radioisotope preparation.

A number of useful nuclear reactions require energies in excess of those available from most of the above-mentioned accelerators. Some of these reactions include \( ^{55}\)Mn\((p,\alpha)\)\(^{52}\)Fe, \( ^{75}\)As\((p,\alpha)\)\(^{72}\)Se, \( ^{80}\)Se\((p,\alpha)\)\(^{77}\)Br, \( ^{80}\)Se\((p,\alpha)\)\(^{76}\)Br, \( ^{88}\)Rb\((p,\alpha)\)\(^{85}\)Rb, \( ^{127}\)I\((p,\alpha)\)\(^{123}\)Xe + \( ^{123}\)I, and \( ^{181}\)Ta\((p,\alpha)\)\(^{178}\)W. Even though large research-accelerator facilities produce usable amounts of these difficult-to-obtain radionuclides, it is doubtful that research facilities can routinely supply large amounts of the short-lived nuclides (half-lives of \(\approx 10\) days or less) to the medical community because of periodic or lengthy shutdowns. The present gap between the low-energy machines and the large accelerator facilities could be adequately filled by a proton accelerator at energies of 70 to 90 MeV, and capable of delivering beam intensities of 200 to 500 \(\mu\)A.

The present, state-of-the-art cyclotrons are not capable of producing such beams; however, in this parameter range linear accelerators appear to be an attractive solution. During the past 5 yr under the PIGMI program at Los Alamos, there have been significant advances in linac technology. As a result, proton linacs are being reconsidered for a variety of applications.

### Linear Accelerators

Proton linacs of conventional design require beams that have been bunched, focused, and accelerated to at least 750 keV before injection into the drift-tube linac (DTL). A high-voltage, dc preaccelerator, plus beam transport and bunching systems, are required. This equipment is costly, complex, and requires considerable floor space and ceiling clearance. This entire injection system has become obsolete since the demonstration of the radio-frequency quadrupole (RFQ) accelerator. RFQ linacs can accept high-current proton beams at a very low energy (\(\approx 30\) keV), then efficiently bunch, focus, and accelerate beams to energies required for injection into a DTL. In addition, by injecting into the DTL at higher than conventional energy, larger currents can be accelerated with lower beam loss.

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*Work supported by the US Department of Energy.*
Conventional DTLs operate at a frequency of \(\sim 200\) MHz or lower, and have axial electric field gradients up to \(\sim 2.5\) MV/m. Field gradients as high as 9 MV/m have been demonstrated (by the Los Alamos PIGMI program) in a specially designed 450-MHz DTL structure. This implies that all future linacs will be shorter, with higher accelerating gradients, and that their physical size will be about one-half that of existing machines.

**Cost Analysis**

To evaluate the cost and performance of a radioisotope-production linac, designs for machines were studied that would deliver 500 µA of protons at 70 MeV. Such an accelerator based on the PIGMI design would look like the one in Fig. 1. This linac would consist of the few major components listed in Table I with their estimated cost shown in 1981 dollars.

A suitable ion source and 30-keV prototype injector has been tested. The injector cost in Table I is based on the prototype component, fabrication, and assembly cost, but does not include engineering or development costs. Likewise, the RFQ structure's estimated cost is based on the actual construction cost of similar structures designed and built at Los Alamos. Because such an accelerator would be a production rather than a research facility, the requirement for computer control, although necessary, is minimal. The estimated cost of a distributed-microprocessor control system is based on the cost of components and labor expended on the assembly of these units; it includes the klystron tube, modulator, high-voltage supply, waveguide, and all of the associated controls and instrumentation.

The DTL structure would be a single resonant cavity (with multiple rf-drive points). Assembled from copper-plated steel tank sections, each \(\sim 2.5\) m long, there would be 110 copper-plated drift tubes, each containing a permanent-magnet quadrupole lens, plus 55 post couplers. The cost estimate includes procurement of these components, three rf-drive windows, the support structure, vacuum systems, and temperature-control systems. Salaries for four staff and four technicians required for assembly also are included. No engineering design or development is included in the estimate.

A computer program has been prepared that (based on the estimated cost of the structure and the rf-power supplies, certain electrical properties of the structure, the klystron's power rating, plus some efficiency factors and beam-dynamics considerations) can generate the first-order cost and performance characteristics for DTLs. The cost can be expressed as a function of both structure length (a continuous variable) and the required number of klystrons (a discrete variable). It would be desirable to design short linacs to save on the cost of not only the structure, but also of the

---

**Table I**

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion source/30 keV injector</td>
<td>$125 K</td>
</tr>
<tr>
<td>RFQ linac (0.03 to 2.5 MeV)</td>
<td>$100 K</td>
</tr>
<tr>
<td>Control system</td>
<td>$ 75 K</td>
</tr>
<tr>
<td>DTL (2.5 to 70 MeV)</td>
<td>$ 66 K/m</td>
</tr>
<tr>
<td>The rf power supply (klystron)</td>
<td>$385 K ea</td>
</tr>
</tbody>
</table>

---

![Fig. 1. PIGMI-based radioisotope production linac.](image)
building required to house it. However, the power required is proportional to the accelerating gradient, or inversely to the structure length. Therefore, there is a cost minimum as shown in Fig. 2, a curve generated for the sample case (500 μA at 70 MeV). The cost of the optimized DTL design is $2.3 M, and three klystrons are required. This 18-m-long machine is called Case I. Coincidentally, if the linac were made any shorter, more than three klystrons would be required, and operation would be required at electric surface fields greater than 1.8 times the Kilpatrick limit, a value that is the present level of confidence for reliable operation. Families of curves were generated for PIGMI-based linacs designed to operate over a range of energies and beam currents. Figure 3 shows that an essentially linear relationship exists between cost and final energy for a fixed beam-current requirement. In addition, for a given energy, a fourfold increase in beam current can be achieved for ~20% increase in accelerator cost.

For 70-MeV linacs, machine cost is related to design current, as shown in Fig. 4. The price starts at $2.2 M for a linac that uses all the available power just to excite the structure. These curves also show that for linacs requiring three or more klystrons, there is an inherent redundancy. For Case I, Fig. 4 shows that if one rf power supply were lost, there would be enough reserve power in the remaining two klystrons to accelerate ~100 μA of beam. The 1.5-mA design case (requiring four klystrons and costing $2.7 M) could still accelerate over 1 mA with the loss of one klystron, and could accelerate almost 500 μA with the loss of two. In the medical-isotope business, such insurance might well be worth the extra investment.

Operating Costs

Initial-investment amortization of a particle accelerator is only a part of radioisotope production cost. Linac design Case I would require ~660 kW of primary power, and it would be only 5.3% efficient in converting primary power into beam power. Linac efficiency can be readily improved by lengthening the structure. This reduces the required peak power, but at a substantial cost penalty. It is far more cost effective to lengthen the structure while using the full peak-power capability of the klystrons to accelerate higher peak beam currents. This reduces the duty factor required to accelerate the same average current, and it improves the conversion efficiency. Figure 5 shows that a modest increase in cost for increased structure length results in considerable operating-cost savings. The lower curve shows that the required primary power for Case I can be reduced 40% by raising the peak current from 18 mA to 30 mA.

Table II shows the basic design parameters for two different PIGMI-based linacs. Case I has been optimized for only initial cost. Case II is a slightly longer accelerator designed to accelerate a higher peak current; it is considerably more cost effective to operate at the design average current of 500 μA from Case I. Case II has two attractive additional features. In the event of one

![Fig. 2. DTL cost versus number of klystrons.](image2)

![Fig. 3. DTL cost versus final energy.](image3)

![Fig. 4. DTL cost versus beam current.](image4)
Peak Power = 2.5MW
Average Current = 500 μA
Variable Duty Factor

Fig. 5. Initial DTL cost as a function of operating cost.

Table II
PIGMI DESIGN LINAC PARAMETERS

<table>
<thead>
<tr>
<th>Injection energy</th>
<th>30 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ/DTL transition energy</td>
<td>2.5 MeV</td>
</tr>
<tr>
<td>Final design energy</td>
<td>70 MeV</td>
</tr>
<tr>
<td>Average design current</td>
<td>500 μA</td>
</tr>
<tr>
<td>Frequency</td>
<td>440 MHz</td>
</tr>
<tr>
<td>No. of klystrons</td>
<td>3</td>
</tr>
<tr>
<td>Length (m)</td>
<td>17.9</td>
</tr>
<tr>
<td>Aver. axial electric field (MV/m)</td>
<td>5.1</td>
</tr>
<tr>
<td>Acceleration rate (MeV/m)</td>
<td>3.77</td>
</tr>
<tr>
<td>Peak beam current (mA)</td>
<td>18</td>
</tr>
<tr>
<td>Peak klystron power (MW)</td>
<td>2.5</td>
</tr>
<tr>
<td>Average klystron power (kW)</td>
<td>75</td>
</tr>
<tr>
<td>AC power required (kVA)</td>
<td>658</td>
</tr>
<tr>
<td>DTL cost (K$)</td>
<td>2335</td>
</tr>
<tr>
<td>Total installed cost (K$)</td>
<td>2635</td>
</tr>
</tbody>
</table>

Case I

Case II

No. of klystrons | 3 |
|----------------|--------|
Length (m) | 24.5 |
Aver. axial electric field (MV/m) | 3.7 |
Acceleration rate (MeV/m) | 2.76 |
Peak beam current (mA) | 26 |
Peak klystron power (MW) | 2.2 |
Average klystron power (kW) | 43 |
AC power required (kVA) | 373 |
DTL cost (K$) | 2771 |
Total installed cost (K$) | 3071 |

It is difficult to make an objective comparison between a PIGMI-based linac and accelerators currently available to the radioisotope industry; none are in a comparable parameter range. Table III lists the three highest energy accelerators available (all cyclotrons), their catalog rating, and price. For comparison, PIGMI-based Case II is listed for both the design current, plus for operation at its full-power capability. Any commercial-product selling price usually equals the production cost multiplied by some factor (often 2) to cover operational overhead and amortize the initial development cost. In the case of the PIGMI design, 80% of the development has been completed, and the technology is available to industry. Some investment would be required for technology transfer, and some risk is associated with building the first accelerator of this type. To arrive at a price (for comparison with other accelerators), a 33% contingency was added to the estimated production cost; this figure was multiplied by 1.5 to cover overhead, etc.; that is (3 M + 1 M) * 1.5 = $6 M. The selling price divided by the maximum beam power capability was used to arrive at values for "price per installed watt." The conversion efficiency is the maximum rated-beam power divided by the primary-power requirement.

Table III
RADIOISOTOPE PRODUCTION ACCELERATOR PARAMETERS

<table>
<thead>
<tr>
<th>Accelerator Type</th>
<th>Proton Energy (MeV)</th>
<th>Beam Current (μA)</th>
<th>Primary Power Required (kVA)</th>
<th>Purchase Price ($M)</th>
<th>Price/Installed Power ($/W)</th>
<th>Conversion Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scandatronix MC-40</td>
<td>40</td>
<td>250</td>
<td>480</td>
<td>2</td>
<td>202</td>
<td>2.08</td>
</tr>
<tr>
<td>Cyclotron Corp. CP-45</td>
<td>45</td>
<td>200</td>
<td>350</td>
<td>2</td>
<td>222</td>
<td>2.57</td>
</tr>
<tr>
<td>PIGMI Case 11</td>
<td>70</td>
<td>500</td>
<td>373</td>
<td>6</td>
<td>171</td>
<td>9.38</td>
</tr>
<tr>
<td>PIGMI Case 11</td>
<td>70</td>
<td>1140</td>
<td>658</td>
<td>6</td>
<td>75</td>
<td>12.12</td>
</tr>
<tr>
<td>Sumitomo 930F</td>
<td>75</td>
<td>100</td>
<td>450</td>
<td>6</td>
<td>800</td>
<td>1.67</td>
</tr>
</tbody>
</table>

| 1. Variable-energy, variable-particle cyclotron, internal target. |
| 2. Variable-energy H+ cyclotron |
| 3. Design case |
| 4. Operated at full-power capability |
| 5. Fixed energy cyclotron |

Conclusion

Nuclear medicine is a well-established medical speciality that, with increased availability of accelerator-produced isotopes, promises to hold even greater potential for diagnosing human diseases. To meet this potential, accelerators having higher energy and current capability that are currently available will be required. PIGMI-based linacs appear to be capable of meeting that need. Not only do they appear be cost effective (in terms of initial cost for performance), but also will be more efficient in operation. The
PIGMI accelerator technology is in a mature stage of development, ready and available for transfer to the industry.

References


Discussion

We don't quote building costs because they are very site dependent. The shielding, beam transport, targets, remote handling, etc., might cost as much (or more) as the accelerator itself. We haven't tried to optimize operating costs over a 10- to 15-yr period, because the uncertainties of power costs are too great.

The energy of the radioisotope production linac I describe could be varied down to 25 MeV by dropping the accelerator gradients using the post couplers. The only commercially available cyclotron at these energies is fixed energy. You could arrange to break the linac structure at several places to put in targets, but you would lose the redundant features of multiple klystron drive.

There would definitely be a payback from increasing the klystron efficiency. We are constrained to use the latest linac technology in a framework of commercially available klystrons; we would be way ahead with a more efficient tube.

In terms of technology transfer to industry, we are told that certain proprietary allowances can be given, for example about particular designs and design drawings. On the other hand, we wouldn't give proprietary rights to design codes. This could be worth a lot in getting a head start on competition.
The New England Nuclear Corporation's 45 MeV proton linear accelerator has previously been described in detail. This report will briefly cover the project history and describe current status. Table I summarizes milestones in the project to date. These have been achieved within the original schedule and the initial capital equipment budget of $7.6 Million.

Injector

The cusp-type ion source provided by Culham has produced beam routinely since 10/80. It has operated at 60KV at .1% duty and 55KV at 10% duty (50mA peak current) protons. The source produces a very uniform beam with emittance of about 0.1π mm-mrad normalized. A present disadvantage is a 50% proton fraction. Recent developments on similar sources have improved this considerably, however. Frequent extractor arc-downs at high powers are an operational problem which we are addressing. Beam transport in the terminal is now being optimized in conjunction with optics studies in the low energy beam transport. Figure 1 shows the terminal installation.

Low Energy Beam Transport

LEBT consists of three quadrupole triplets (variable strength permanent magnet) with interspersed diagnostic boxes, double harmonic buncher copied from CERN, and four electromagnet quadrupole singlets for matching into the Linac. As shown in Figures 2 and 3, this system is complete except for the buncher. Beam transmission is 100% through the triplets, although emittance scans show that the optics do not yet correspond to the design. Computer simulation indicates that observed behavior is explained by the beam being over-focused in the accelerating column. This is due to the peak current being lower at the present time than called for in the design. Minor modifications to the terminal optics are being undertaken to solve this problem. The buncher is undergoing RF tests and will be installed after preliminary accelerator transmission studies are complete.

Accelerating Structure

The tank is mechanically complete.

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Milestones</td>
</tr>
<tr>
<td>9/76 NEN decision to investigate (build or buy) linac.</td>
</tr>
<tr>
<td>6/77 First NEN person hired for linac project.</td>
</tr>
<tr>
<td>1/78 Preliminary budget and project approval.</td>
</tr>
<tr>
<td>6/78 Complete design team at NEN, schedule generated.</td>
</tr>
<tr>
<td>10/78 Machine specified, ground breaking, major orders placed.</td>
</tr>
<tr>
<td>10/79 Design complete - first major equipment delivered.</td>
</tr>
<tr>
<td>1/80 Building occupancy.</td>
</tr>
<tr>
<td>10/80 60 KeV beam.</td>
</tr>
<tr>
<td>4/81 780 KeV beam.</td>
</tr>
<tr>
<td>10/81 45 MeV beam.</td>
</tr>
</tbody>
</table>

Fig. 1 Ion source and 90° bending magnet installed in high voltage terminal.
The vacuum system has worked very well, requiring only three hours to pump down to acceptable pressure to apply RF power. The measured tank Q is over 70,000, about 70% of theoretical. R.F. power conditioning required only a few days to achieve required acceleration fields at 2.3 MV/meter, 2.3 MW peak power. This level results in maximum field gradients of 15 MV/m on the drift tubes, just about at the Kilpatrick criterion.

Figure 4 is a plot of $E_z$ on axis as a function of distance down the tank, for a "flat" field, $E_0 = \text{constant}$. The field was "flattened" to better than ±5% by shaping the tuning bar. The steps in the peak $E_z$ at cell 28 and cell 71 are due to changes in tank diameter at these points and the associated change in gap to cell length ratios.

The R.F. System

Three RF amplifier chains using RCA 7835 triodes as final power amplifiers are installed at NEN, along with the transmission line-combiner-splitter system. One amplifier chain is fully operational with a simplified switch for the modulator as an interim solution to a modulator instability problem. This system has performed at full 200 KW average power and 5 MW peak power. Tests were completed on the final modulator system at the manufacturer's at full ratings of 200 KW average power and 5 MW peak. The second RF chain is now being tested with this modulator installed at NEN. The final chain will be tested along with phase and amplitude control servos by Jan. 82. Experience so far indicates that the RF systems and the transmission line elements are very reliable at reduced average power levels. Experience at higher average powers is limited.
Control System

An aspect of the NEN linac not previously described is the control system. All injector, beam line, accelerator, and RF system equipment is controlled by a system of distributed 6800 microprocessors, fiber-optic communication links, and central VAX 11/780 computers. The communications network, some microprocessor I/O cards, and interface are of in-house design. This system has operated for over one year on various sub-systems. A central console with color graphics for engineering system displays, along with the usual complement of tuning aids, has been implemented. Mobile consoles for use in engineering and trouble-shooting sub-systems are available. Program controlled start-up of the ion source is operational, as well as the save/restore function for selected "tunes" or collections of set-points.

Work is underway to condition the accelerating column under program control. Our goal is to continue to develop all tuning procedures to the point where they can be implemented in software to remove the burden from operators. We feel that this effort in the control area, and the extensive use of permanent magnet quadrupoles, are areas where we are testing recent technical advances for the first time on a machine of this type. We hope to make a contribution to the field as a result of our efforts in these areas.

Conclusion

The project is on schedule and within original equipment budget. We have achieved initial full energy beam. The basic equipment is installed to achieve design current and provide very sophisticated control and monitoring. Much work remains to obtain reliable high current operation.

Acknowledgement

Virtually every accelerator laboratory in the U.S.A. and many in Europe have contributed to our equipment designs and operational success. We want to express our appreciation to the people and institutions for this support. We feel that our project is a compelling example of the value to industry of research in the national laboratories.

References


Discussion

We have four electromagnetic quads at the entrance and exit of the linac to give us some matching capability, at different current levels, etc. They may not be necessary, but having the capability is good insurance.
At the last conference, we reported on experimental results of deuteron and helium acceleration achieved with the 20 MeV Saturn linear accelerator operating in the 2βλ mode. This paper gives the results recently obtained with polarized protons accelerated at 5 MeV. Set up of the source, tune up of the very low energy beam transport (15 keV), low energy beam transport (167 keV), linac and high energy beam transport (5 MeV) are also described.

Summary

The 20 MeV Alvarez linear accelerator, designed initially to accelerate protons in the βλ is able to operate in the 2βλ mode in order to produce particles such as deuterons and heliums having the same kinetic energy per nucleus (5 MeV/A). Nevertheless, the efficiencies in this 2βλ mode operation were behind the expected values, although the total intensity given by the Saturn accelerator was good enough for the particle physics program. In the recent past, experimenters expressed interest for polarized protons and deuterons and a polarized proton terminal has been built. Due to housing and cost considerations, the high voltage terminal was limited to 400 kV which led us to operate the linac in the 2βλ mode. We thus undertook theoretical studies in order to investigate the parameters able to limit the linac efficiency.

Theoretical aspects

Since losses could be explained by a reduced longitudinal acceptance and/or an inadequate quadrupole focusing, we willfully decoupled the two possibilities by considering first the longitudinal acceptance problem, assuming that the quadrupole focusing was correct.

A) Longitudinal acceptance

Using the experimental field gradient law and the corresponding transit time factors in the 2βλ mode, we obtained a theoretical acceptance in disagreement with the experimental one (fig. 1); computer simulation of a located gradient disturbance showed that it could occur in the first 15 cells. Indeed, transit time factors are the lowest in this low energy region. Looking carefully into the position of the 3 frequency tuning balls, we established that the low energy region tuning ball setting was likely to produce the expected gradient perturbation. We further corrected the gradient tuning ball position taking into account the low energy frequency tuning ball setting.

It is clear that this field gradient perturbation was also existing in the βλ mode operation, because of the remote control tuning process, and after correction we could measure the theoretical longitudinal acceptance which proved the real existence of the perturbation. Thus, the linac efficiency using the existing buncher reached 70% (fig. 2).
\[ \Delta = h^2 e E \frac{e}{m_0 v^4 f^2 L} \sin \phi \sin \frac{h v g}{L} \]

while the \( \Theta^2 \) parameter corresponding to the quadrupole focusing in given by

\[ \Theta^2 = K \frac{e}{h} \frac{\partial R}{\partial r} \]

where \( h \) is the operating mode
\( e = q/A \)
\( E \) is the mean accelerating field
\( \phi \) is the synchronous phase
\( K \) is a constant
\( \frac{\partial R}{\partial r} \) is the quadrupole gradient

Recalling that the focusing periodicity is FFDD, we can see that operating point of every cell is stable in the diagram (fig. 3) for the 2\( \lambda \) mode.

For any given particles, accelerated in the 2\( \lambda \) mode one has

\[ \Delta_i = \Delta_p \cdot 4 e_i \frac{E_i}{E_p} \cdot \frac{\sin \phi_i}{\sin \phi_p} \cdot \frac{\sin 2n g}{L} \]

where "i" is related to the considered particle and "p" is related to the proton in the 3\( \lambda \) mode acceleration.

Using the relationship:

\[ 4 e_i E_i T_2 \cos \phi_i = E_p T_1 \cos \phi_p \]

one can write the following expression which gives the parameter \( \Delta_i \) for any ion accelerated in the 2\( \lambda \) mode, whatever the \( v \) value. This relationship will permit to represent the operating point of every cell in the same diagram as for protons

\[ \Delta_i = \frac{T_1}{T_2} \frac{\tan \phi_i}{\tan \phi_p} \frac{\sin 2n g}{L} \]

It is clear from fig. 3 that increasing the quadrupole field would not help, since it is not possible to keep all the operating points in a stable region. This proves that the transverse instability is intrinsic to the present linac and that the only way to avoid it, is to change the focusing periodicity to FDFD.

Figure n° 4 shows that it should be easy to obtain a stable beam provided we increase the quadrupole field by a factor of 2.5 (ref. 2).

Experimental results

Experimental studies have been carried out with protons produced by the usual preinjector Amalthee, while the polarized proton terminal was under construction.

The new focusing periodicity (FDFD) made possible only proton acceleration, since current requirements are beyond permitted values for the power supplies in the case of deuteron acceleration. New power supplies will replace the old DC ones. They will be pulsed because of the increasing of thermal heating in the quadrupoles; the drift tubes housing the quadrupoles were filled with a silicon gel in order to insure a good mechanical maintain.

Experimental results with unpolarized protons are given in the following table.

<table>
<thead>
<tr>
<th>2( \lambda ) mode</th>
<th>FFDD Focusing</th>
<th>FDFD Focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>field level</td>
<td>eff. without</td>
<td>eff. without</td>
</tr>
<tr>
<td>with buncher</td>
<td>12.5 %</td>
<td>30 % (( \phi = 36^\circ ))</td>
</tr>
<tr>
<td>without perturbation</td>
<td>0.65</td>
<td>12.5 %</td>
</tr>
<tr>
<td>without ............</td>
<td>0.65</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Under this conditions, the linac efficiency with the buncher has been put to 55 % (fig. 5).
Fig. 5 - Input and output intensities in the 2EL mode (protons)

Remark: the buncher location has been optimised for h = 1 and is evidently not optimised for h = 2 (This is why the efficiency is only 55%).

The new type of running has been kept for polarized proton acceleration with the linac. Additional improvements presently under work will be given further down.

HYPERION - Polarized particle preinjector

A) Description

This equipment is dedicated to produce polarized protons and deuterons, but to date, only proton acceleration has been required by the physicist community.

The polarized proton source is installed in a 400 kV high voltage terminal (fig. 6). It contains:

- an atomic source (ground state type) including a dissociator (f = 20 MHz) operating at room temperature; a conventional sextupole, longitudinally tapered; a set of RF transitions (for protons 2 RF transitions (65.2 MHz and 1430 MHz) giving the required 2 polarisation states: they can be replaced by 3 RF transitions in the case of deuteron production given the whole polarisation states: (10.8 - 343 and 415 MHz).

- a high field gradient ionizer supplied by ANAC from which ions are extracted at about 13 keV. The ionizer is running DC. Only the dissociator is pulsed (gas and RF) and operates with a beam pulse width of 20 msec duration.

- an electrostatic beam transport at 13 keV (VLEBT) made of a set of Einzel lenses. Along this transport the longitudinal polarization of the beam coming out of the ionizer is turned to a vertical polarization after the beam is deflected by means of an electrostatic deflector and crosses a solenoid.

Because of uncertainties on the energy spread of the beam at the exit of the ionizer, the initial spherical deflector giving the 90° deflection has been replaced by an electrostatic mirror of which the transparency is 80 %.

Fig. 6 - 400 kV terminal

This change allowed a better transmission to the accelerating column (low gradient column 4 kV/cm)

The beam transport line to the linac needs 4 bending magnets having a deviation of 51° and 2 triplets (fig. 7).

B) Experimental results

- graphite targets are used to measure the beam intensity (bias voltage of 30 V). The first one is located about 1 meter downstream of the ionizer. Right behind of this target, a bending magnet can provide beam analysing species.

- the other targets and beam diagnostics as scintillators and position detectors are all located after acceleration at 187 keV takes place.

- the following results are given for a standard operation

  total ionizer current
  atomic jet contribution
  divided in 2 species
  dissociation rate (fig. 8)

  40 mA
  35 mA
  28 mA
  7 mA
  80 %
Fig. 8 - Beam coming from the ionizer

- Thus the $H^+$ beam entering the linac is composed of 90% of protons from the atomic source
  - beam intensity at linac input 12\(\mu\)A
  - beam intensity at linac output 6.5\(\mu\)A
  - linac efficiency 54% 

- This standard beam leads to \(4 \times 10^8\) accelerated polarized protons per cycle having a polarization of 80% measured at 800 MeV.

Improvements to increase the intensity of the polarized source are underway.

- 1°) as shown on fig. 9, pulsed operation of the dissociator did not increase the beam intensity compared to the DC operation mode. Since it is not the case at ANL and at CERN (ref. 3), we do think that it is due to a difference between the bottles used at these labs. Our kind of bottle seems not to be suitable to a fast pulsed gas flow. Consequently a new dissociator device having new bottle and new oscillator has been built and is under test on a bench.

- 2°) cooling of the nozzle at 4°K should give a net increase of intensity which combined with the new dissociator will lead to a gain of a factor 2.

Conclusion

As far as polarized proton acceleration is concerned (2BA operating mode, FDFD periodic focusing) the linac efficiency has been put to 55%. It was previously 20% (2BA operating mode, FFDD periodic focusing). Calculations show that a second single harmonic buncher will improve the linac efficiency up to 80%. The last bending section will have to be achromatic in order to deal with the momentum spread generated. The achromatism is obtained by 3 quadrupoles and modified magnetic wedges.

The improvements of the source itself combined to the installation of the second buncher will give a factor of 3 in intensity.

In 1982, new pulsed power supplies will allow deuteron operation in the FDFD focusing periodicity and the linac efficiency for this mode would be of the order of 80%.

References

(1) L. SMITH, R. GLUCKSTERN, Focusing in linear ion accelerators R.S.I. vol. 26, n° 2
(2) J.M. LAGNIEL, Augmentation du rendement du linac L.N.S/SM 80/46 - INJ. 16 internal report
(3) E.F. PARKER, N.Q. SESOL, R.E. TIMM, Operating results and improvements on the ZGS polarized proton source
(4) P.F. SCHULTZ, E.F. PARKER, J.J. MADSEN, Polarized proton source improvements at the ZGS
(5) J.P. AUCLAIR, P.A. CHAMOUARD, J.L. LEMAIRE, Linac efficiency and beam qualities in p,d, \(^3\)He and \(^4\)He acceleration Proceedings of the 1979 Linear accelerator conference
(6) J.P. AUCLAIR, Groupe ment des particules dans le linac L.N.S./SM 79-51 - INJ. 08 - internal report.
Summary

The performance of the interlaced standing wave accelerator structure has been reviewed in detail with a testing model and a computer program.

Introduction

Nowadays medical linear accelerators have found wide applications in radiotherapy in the world. According to the form of the trajectory of the electron beam, medical linac can be divided into two types: bent beam and straight beam machines. The straight beam machines have many advantages over the bent beam ones owing to its small size and compact structure. But the length of the accelerating tube in straight beam machines should not exceed 30 cm otherwise the isocentric height will be unacceptable. In order to obtain higher energy electron beam in such a short tube, it must have the possibility to withstand very high electric field gradient. The interlaced side coupled standing wave structure (IL) proposed by V. Vaguine of Varian Associates has obtained the highest accelerating gradient in comparison with other accelerating structures. But since the efficiency of IL structure is approximately 20 percent lower than the common side coupled structure (SC), the relative advantage of IL structure becomes apparent only in the range of higher accelerating gradient (above 40 MV/m). Meanwhile the 3 mm beam hole diameter seems too small to make a longer accelerating tube. So it would be worthwhile to study the performance of the IL structure in more detail.

Influences of the geometrical parameters of the IL cavity

The typical one quadrant cross sections of IL, IL with nose cone and SC are shown in Fig. 1. The web wall thickness tw is determined by mechanical rigidity and thermococonductivity. In IL cavity the web wall thickness also affects the coupling between two cavity chains. A web thickness of 3 mm which was adopted by Vaguine has been kept constant in our calculations. Each time when we change one parameter the other parameters will remain unchanged.

Calculated data for each parameter are shown graphically in Fig. 2-3. The resonant frequency is kept at 2998 MHz. The relationship between resonant frequency and various geometrical parameters in shown in Fig. 4. It can be seen that the effect of the variation of geometrical parameters on the effective
Table 1. Comparison of IL cavity with and without nose cone with SC cavity.

<table>
<thead>
<tr>
<th></th>
<th>L (mm)</th>
<th>tw (mm)</th>
<th>θ</th>
<th>R_H (mm)</th>
<th>R_N (mm)</th>
<th>R_W (mm)</th>
<th>Δx (mm)</th>
<th>Z (MΩ/m)</th>
<th>T (MΩ/m)</th>
<th>ZT²/Q</th>
<th>E_p/E_o</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>50</td>
<td>1.5</td>
<td>30⁰</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td>3.5</td>
<td>162.6</td>
<td>0.822</td>
<td>109.7</td>
</tr>
<tr>
<td>IL with nose cone</td>
<td>25</td>
<td>1.5</td>
<td>30⁰</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>110.4</td>
<td>0.958</td>
<td>101.4</td>
<td>8115.8</td>
</tr>
<tr>
<td>IL</td>
<td>25</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
<td>1.5</td>
<td>-</td>
<td>0.5</td>
<td>104.8</td>
<td>0.921</td>
<td>88.9</td>
<td>7050.9</td>
</tr>
</tbody>
</table>

shunt impedance is very slight while the effect on the parameter E_p/E_o is quite apparent. The effects of beam hole and rounded corner radius on resonant frequency are also very slight. The only sensible parameter on resonant frequency in IL cavity without nose cone is the cavity radius R_c.

The IL cavity with nose cone has been calculated in order to be compared with the SC cavity. The results indicate that there is also an unsharp optimum length of nose cone. (see Fig. 3b) As in the case of IL cavity, the IL cavity with nose cone can not attain the same efficiency level of SC cavity either. Meanwhile in this case the parameter E_p/E_o increases rapidly. The comparison of physical parameters is listed in Table 1.

Influence of the direct coupling between two cavity chains

The IL structure is composed of two separately independent cavity chains. The beam hole at the web wall center is used only for transmission of accelerated electron beam. When the beam hole radius increases, the direct coupling between two cavity chains also increases. The relationship between the direct coupling coefficient K' and the beam hole radius has been measured as shown in Fig. 5.

Since there are not sensible dimensions in IL on resonant frequency except R_c, we have tested mechanical compressive method. It is observed that a total frequency shift of only 0.4 MHz can be obtained under appropriate pressure.

The equivalent circuit of IL structure with direct coupling between two cavity chains is shown in Fig. 6. The diagrammatic sketch with unequal number of cavities in two chains is shown in Fig. 7.

Fig. 6. Equivalent circuit of IL structure with direct electrical coupling.
For homogenous and lossless case, the coupled resonator equations of Fig. 7 can be written as:

\[
\begin{align*}
X_0 (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} X_1 + \frac{K'}{2} \frac{\omega_2^2}{\omega_1^2} X_0 &= 0 \\
X_1 (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} (X_0 + X_2) &= 0 \\
X_2 (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} (X_1 + X_3) + \frac{K'}{2} \frac{\omega_2^2}{\omega_1^2} (X_0 + X_2) &= 0 \\
X_3 (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} (X_2 + X_4) &= 0 \\
X_4 (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} X_3 + \frac{K'}{2} \frac{\omega_2^2}{\omega_1^2} X_2 &= 0 \\
X_0' (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} X_1' + \frac{K'}{2} \frac{\omega_2^2}{\omega_1^2} (X_0 + X_2) &= 0 \\
X_1' (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} (X_0 + X_2') &= 0 \\
X_2' (1 - \frac{\omega_2}{\omega_0}) + \frac{K}{2} X_1' + \frac{K'}{2} \frac{\omega_2^2}{\omega_1^2} (X_1 + X_3) &= 0
\end{align*}
\]

Where \( \omega_a = \frac{1}{L_1 C_1}, \omega_b = \frac{1}{L_3 C_2} \),

\[
\begin{align*}
K &= \frac{M}{\sqrt{L_1 L_3}} \quad K' = \frac{C_s}{C_1 + C_s} \\
\sqrt{2L_1} \sin \lambda n_1 \sqrt{2L_2} \sin' \lambda n_2 &= 0, n=0,2,4...
\end{align*}
\]

\[
\sqrt{2L_1} \sin \lambda n_1 \sqrt{2L_2} \sin' \lambda n_2 = 0, n=1,3...
\]

The solutions of \( \frac{n}{N} \) mode case will be the superposition of following two groups of solutions:

\[
\begin{align*}
\{ X_0 = -X_2 = X_4, \quad X_1 = X_3 = 0 \\
X_0' = X_2' = 0 \quad X_1' = 0 \quad \omega_2 = \omega_4 = \omega_c \}
\end{align*}
\]

\[
\begin{align*}
\{ X_0 = X_2 = X_4 = 0 \quad X_0' = -X_2' \\
X_1 = -X_3 = \frac{-K'}{4} X_0' \quad X_1' = 0 \quad \omega_2 = \omega_a = \omega_c
\end{align*}
\]

It can be seen that a small amplitude of fields will appear in the coupled cavities which will lower the efficiency of the accelerator.

The amplitude of \( X_0 \) and \( X_0' \) will be determined by the hybrid coupler which may be designed to obtain equal amplitude of \( X_0 \) and \( X_0' \).

Influences of the detuning effects of two cavity chains

The energy gain \( V \) can be represented by the following formula:

\[
V = UT
\]

Where \( U \) = Equivalent voltage at cavity. \( T \) = Transit time factor.

When the detuning of two cavity chains takes place, it leads to the decrease of field amplitude and the transit time factor which will in turn decrease the beam energy gain.

\[
\Delta V = \frac{\Delta U}{U} + \frac{\Delta T}{T}
\]

Let \( f_1, f_2 \) represent the \( \frac{1}{2} \) mode resonant frequency of two cavity chains respectively, \( f_0 \) is the frequency of HF source. We can define:

\[
f_0 = \frac{1}{2} (f_1 + f_2) \quad \Delta f = \frac{1}{2} (f_1 - f_2)
\]

\( 2\Delta f \) is the frequency difference between two cavity chains.

Equivalent voltage at a high Q resonant system can be written as

\[
U_0 = \frac{1+jQ_L \Delta f}{f_0} \frac{U}{U_0} = \frac{1}{2} U_0 (2\Delta f)^2
\]

\[
\cos \Delta \phi = 1 + \frac{Q_L (2\Delta f)^2}{f_0^2}
\]

Where \( U_0 \) is the equivalent voltage at resonance. \( \Delta \phi \) is the phase shift caused by the detuning.

When the number of accelerating cavity \( N \) is small, the electrons are not so tightly bunched that the influence of the cavity phase shift is not apparent. When the electron beams are being bunched aggressively the influences of the phase shift also increases. When the electron beams are well bunched, further increase of \( N \) would not apparently change the effect of detuning phase shift. Similar to the case in the travelling wave tube, we may suppose that the effect of detuning phase shift changes exponentially with \( N \). When \( N=1 \), the IL structure has been turned into a single cavity, the effects would disappear.

So that \( \Delta T/T \) can be presented in the following equation.

\[
\frac{\Delta T}{T} = \left( \frac{\Delta V}{V} \right) \frac{E(z) \cos (2\pi f z) dz - \int_0^{\pi} E(z) \cos (2\pi f z) dz}{E(z) dz}
\]

or \( \frac{\Delta T}{T} = -\frac{1}{2} e^{-\frac{\pi^2}{4}} Q_L^2 \left( \frac{2\Delta f}{f_0} \right)^2 \)

The relative energy decrease can be written as:

\[
\frac{\Delta V}{V} = -\frac{1}{2} (1 + e^{-\frac{\pi^2}{4}}) Q_L^2 \left( \frac{2\Delta f}{f_0} \right)^2
\]

The above formula is very close to dynamic calculation results obtained by computer program as shown in Fig. 8.
Power feeding into IL cavity chains with unequal number of cavities

When the two cavity chains have unequal numbers of accelerating cavities, the RF power in two chains should be in proportion to the numbers of the accelerating cavities of the two chains.

The hybrid coupler of the TEM/Her quadrature type is shown in Fig. 9.

The outputs from two arms of hybrid coupler are always in quadrature but their power ratio depends on the length of coupler slot.

The relationship between the power ratio and the slot length can be presented as:

\[ L_c = \frac{1}{\pi} \frac{\lambda_2 \lambda_0}{\lambda_0 - \lambda_2} \tan^{-1} \left( \frac{P_1}{P_2} \right) = \frac{i}{\pi} \frac{\lambda_2 \lambda_0}{\lambda_0 - \lambda_2} \tan^{-1} \frac{N_2}{N_1} \]

Where \( \lambda_2-H_0 \): mode guide wavelength
\( \lambda_0 \): free space wavelength.
\( N_1, N_2, P_1, P_2 \): cavity number and power needed in two cavity chains.

When \( N_1=N_2 \), \( L_c = \frac{1}{4} \frac{\lambda_0 \lambda_2}{\lambda_0 - \lambda_2} \) it is the slot length for 3db hybrid coupler.

The measurement results are highly consistent with the above equation. (Fig. 10)

Conclusion

The IL standing wave structure is a hopeful structure in medical linac with straight beam trajectory. But there are still some problems to be cleared. The following points have been analysed in this paper:

1. Except the cavity wall radius there are no other geometrical parameters sensible to resonant frequency. The mechanical compressive method can give limited frequency shift. The IL structure and IL with nose cone can not attain the same efficiency level of SC structure under lower accelerating gradient.

2. The IL structure needs two separate cavity chains. The increase of direct coupling between two cavity chains owing to the larger beam hole radius will lead to the decrease of efficiency.

3. The detuning of two cavity chains will lead to the decreasing of equivalent voltage and the transit time factor which will in turn decrease the beam energy gain.

4. A IL structure with unequal number cavities of two chains could be fed by the hybrid coupler with appropriate slot length.

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References

CONSTRUCTION PROGRESS OF THE PHOTON FACTORY 2.5 GeV ELECTRON LINAC


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Construction of the Photon Factory 2.5 GeV injector linac was started in April 1978. Assembling of the first sector (500 MeV) of the linac was almost completed in June 1981 and the first 500 MeV electron beam was accelerated in this sector in July 1981. Assembling of the remaining four sectors of the linac is in progress and acceleration of the full 2.5 GeV beam is scheduled for the end of 1981. Initial performance of the first sector and some technical developments are also described.

Introduction

The Photon Factory (PF), a synchrotron radiation facility at KEK, was funded in April 1978 on a four year program. The PF accelerator consists of a 2.5 GeV injector electron linac and a 2.5 GeV storage ring dedicated to synchrotron radiation research. The linac will be used not only for the injector of the 2.5 GeV storage ring but also for other purposes; as the injector for lower energy storage rings, as a picosecond and nanosecond range pulsed light source and as the electron and positron injector for "TRISTAN". The 6 GeV accumulator ring for the TRISTAN rings was authorized by the government during the 1981 fiscal year.

The linac was designed to be able to accelerate an electron beam current of 50 mA to the energy of 2.5 GeV with a total rf power of 840 MW and to 3.0 GeV with 1,200 MW of power. The main accelerator is divided into five sectors and each sector consists of eight acceleration units. The acceleration unit is composed of four 2m long accelerator guides (mounted on a cylindrical supporting girder), high power wave guide system, a 30 MW klystron and a modulator with controller.

Construction progress and test operation of the first sector

As the linac building was completed at the end of March 1980, installation of the acceleration units and klystron modulators began in April 1980. By the end of March 1981, more than seventy percent of the components had been delivered and some had been installed. The 30 MeV injector and the first sector of eight acceleration units with klystrons and modulators were almost completed by the end of June 1981.

Fig. 1 Building of the PF Linac.

In July, the first 500 MeV beam was accelerated at a beam current of 50 mA, and at 87 mA the beam energy was 470 MeV with a total rf power of 180 MW. During the test operation, since the control system was not complete except for the focusing system, phasing of the rf system could not be done well enough to get optimum performance.

Technical developments

Accelerator guide

In order to facilitate mass production of the accelerator guides within the short time scheduled, a disk loaded traveling-wave type was chosen. The guide was designed with a quasi-constant gradient structure (that is the disk hole diameter decreases linearly along the length with a step of 75 μm). This makes automatic production of the guides and division of the guides into five different types easy. The first cell of each type guide starts from fifth cell of its predecessor. Consequently, the beginning of each type guide has a different HEM11 mode characteristic. This reduces the cumulative

Fig. 2 View of the first sector.
beam blow-up effect caused by repetition of the same structure throughout the whole length of the linac.

The accelerator guides have been made by means of an electroplating method. Improvements in machining have been realized recently enabling the final precision machining of the accelerator guide parts to be automated. Disks and cylinders have been machined by special lathes with diamond bits and vacuum chucks. Precision machining was accomplished by reducing rotational vibration of the lathe spindle by using hydraulic bearings. Overall dimensional accuracy of the disks and cylinders is within ±2μ and the surface roughness of the finished parts is less than 200 Å.

Due to the high precision machining and modified electroplating method, any tuning of the accelerator guides, for example dimpling of each cell of the guides was eliminated.

Fig. 3(a) shows an example of phase errors of the guides made at the beginning of the fabrication period and 3(b) shows an example after the fabrication process had stabilized.

Fig. 3 Phase errors of the guides.

(a) 

(b) 

Coupler 

The coupler for the accelerator guide is a cavity type with two semi-fixed plungers to tune the rf matching and to correct the electric field and phase distortions caused by asymmetry of the coupler cavity. The structure of the coupler, is shown in Fig. 4(a) and the measured electric field distributions are shown in Fig. 4(b). This makes it possible to simplify the structure of the wave guide feed system, that is connecting all of the wave guides on one side of the accelerator guides.

During the test operation of the first sector, no dominant direction of beam deflection was experienced.

Fig. 4 a) Structure of the coupler. 

b) Electric field distributions of the coupler.

Electron gun 

In order to produce faster and thinner electron beams, a new electron gun was developed. It involves the use of a grid-cathode assembly of a commercial planer triode. The assembly is composed of an oxide coated cathode 1cm in diameter and a mesh control grid with a thin Kovar brim 3.2 cm in diameter which is used as a vacuum seal. (Fig. 5).

It is suitable for the emission of a very short pulse beam (<2ns) at a current of more than 5A, and has other notable advantages; the cost is very low, the replacement is very easy, the grid control voltage is within the range of semiconductors (<200 V) and the coaxial terminals can be exposed to the air.
Beam position monitor

As a microwave beam-position monitor, a TM_{10} cylindrical cavity which resonates at 2856 MHz, was developed. Both horizontal (x) and vertical (y) displacements of the linac beam are simultaneously detected by the single cavity with X and Y rf output ports.

The basic concept is illustrated in Fig. 6. A compact microwave circuit module was also developed for this monitor. The block diagram of the circuit is shown in Fig. 6. Sensitivity of the monitor is about 0.1 V/mm and a 0.1 mm displacement of the beam is detectable.

RF dummy load

Ceramic type SiC has excellent properties as an rf absorber. A simple and low cost rf dummy load was developed using SiC plates. Such plates are available for use at high temperatures and have low out-gassing in vacuum.

Four SiC plates were mounted inside of a wave guide as shown in Fig. 7. Heat generated at the plates is conducted to the aluminum plate holder and absorbed through a water cooled waveguide wall. VSWR of the dummy load is less than 1.05 at room temperature and temperature variation of the load is shown in Fig. 8. The load can take a peak rf power of 10 MW and average power of 300 W in vacuum.

Reference

1. A. Enomoto et al
THE ZEBRA (ZERO ENERGY BREEDER ACCELERATOR) PROGRAM AT CRNL - 300 mA-10 MeV PROTON LINAC

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Summary

ZEBRA is being designed as a test accelerator at CRNL to demonstrate operation of an injector for an electronuclear breeder that could produce fissile fuel for nuclear power reactors. Problems and characteristics of launching a high-current beam will be investigated by the 100% duty cycle 300 mA-10 MeV proton linac. The program of work including design and testing of 100% duty cycle intermediate steps prior to ZEBRA construction are described. These steps include a 270 MHz RFQ for field breakdown measurements, a 100 mA-1 MeV RFQ at 270 MHz, a 20 mA-3 MeV drift tube linac at 270 MHz, a 270 MHz high power resonant load and various low power experiments. Extension of the program in the long term is described to give a basis for the injector program.

Introduction

A high-current, low-energy, 100% duty-cycle (cw) proton linear accelerator called ZEBRA (Zero Energy Breeder Accelerator) will be the first stage of a Canadian development program that could lead to a full-scale accelerator breeder. The rationale for the 300 mA-10 MeV ZEBRA project and its associated research and development program was developed in context of the Canadian nuclear power program.

Four important fields of study (other than economics) that must be addressed are a) launching of the required beam current with characteristics dictated in part by high-energy linac sections, b) activation of the accelerating structure from lost beam, c) run-up, control and operation of the facility and d) design, control and operation of the target-blanket system. The last item, although significant, will not be discussed in this paper. Obviously, design and operational characteristics of the target-blanket have to be considered in the overall facility economics and optimization.

ZEBRA will provide information on the first three study areas. Estimates of breeder activation will be determined not only from accelerator performance but from beam dynamics predictions. These predictions will be made after agreement is achieved, in fine detail, between experimental beam measurements and calculated results using improved computer beam dynamics codes.

Accelerator Breeder

In the early part of the twenty-first century it will probably be necessary to produce fissile fuel for nuclear electrical-generating stations by electronuclear methods. One method, the accelerator breeder, is promising not only in an economic sense but also in most aspects of the technology required to produce beams geared to the target-blanket system. What needs to be demonstrated is the reliability, controllability and operation of all aspects of an accelerator in a facility designed for this purpose and under the constraints required of an industrial facility, i.e. > 80% availability. To do this, it is necessary to study in detail the first 10 MeV of beam acceleration where most of the significant beam effects and limitations occur. ZEBRA operation is considered an important link in obtaining the necessary background data to establish the fundamental feasibility of an accelerator breeder.

Economic studies on the production of 239Pu or 233U, to be used as top-up enrichment for nuclear power reactors operating on an advanced CANDU (CANadian Deuterium Uranium) thorium cycle, have demonstrated that the proton beam energy impinging on a high Z target should be at least 1 GeV. For calculational purposes a 80 mm radius liquid Pb-Bi target was surrounded by a 2.1 m radius blanket with a 0.9 m void separating the target from the sodium-cooled carbide fuel.

Beam power incident on the Pb-Bi target should be at least 300 MW to produce sufficient fuel (1 M per year at 80% availability) for support of a 10 GWe electrical system. Figure 1 shows fissile fuel costs in 1981 Canadian dollars to produce 239Pu as a function of the proton energy for three beam powers. The curves show that the optimum beam energy is ~ 1 GeV. Fuel costs have been determined using realistic cost estimates, 20% engineering and management charges, 20% contingency and an 11% capital charge rate that includes operating and maintenance charges.

Currents significantly higher than 300 mA would be more difficult to produce because beam funneling would have to be considered. Higher energy at the same power offers the advantage of reduced current at only a slight economic penalty (fuel from a 150 mA-2 GeV facility is only 11% more expensive than that from a 300 mA-1 GeV facility). In the future an energy higher than 1 GeV may be necessary for various reasons including increased fuel production, lower beam loss and better target penetration.

Figure 2 shows schematically an energy self-sufficient 300 mA-1 GeV accelerator breeder facility, including some of the optimized parameters and estimated costs that used assumptions listed in Table 1. If the equilibrium plutonium concentration were increased to 2% from the 1.3% case illustrated in the figure, ~ 110 MWe could be delivered to the electrical grid. The optimized accelerating gradient of 2.1 MeV/m results in a linac that is 80% beam-loaded and that requires ~ 375 MW of rf power.

A program, with major review stages, that leads to an operating accelerator breeder facility is illustrated in Fig. 3. Although the first stage is only 1% of the breeder energy, ZEBRA will investigate the important area of launching the full 300 mA beam current. Other features of ZEBRA are described in the following section.
After successful ZEBRA operation, the second stage would begin in the early 1990's, with construction of a 70 mA-200 MeV accelerator facility, EMTF (Electronuclei... Materials Test Facility). The cw accelerator parameters are optimized to provide users with a useful flux of $10^{15}$ n/s/cm$^2$ from a Pb-Bi target. This facility would be used for materials and fundamental research as well as for accelerator development. The energy of the facility determines the point at which a change to more efficient, coupled-cavity structures would occur. EMTF would be designed so that beam current could be increased to 300 mA at a later date by adding rf power. Higher current operation would permit beam splitting, part of the beam could be used for investigating beam-loaded operation of the higher frequency coupled-cavity tanks while not reducing average flux from the materials test facility target. In parallel with developments in accelerator technology there is a need for a good deal of development work on the 14 MW target.

Initial EMTF design was for 300 mA at 100 MeV but subsequent studies showed that the target would perform much better with a higher energy beam. The 70 mA current was determined from an optimization of parameters and economics and is considered adequate to study characteristics of the drift-tube portion of an accelerator breeder.

The third stage of the development program, to commence in the early 2000's after successful operation of EMTF, is designed to test a target-blanket assembly at as low a power as will give meaningful target engineering results. Fortuitously, the 1 GeV proton current required is < 70 mA (similar to EMTF) for 70 MW input to a 150 MWe target-blanket assembly. This upgrade of EMTF to full energy would be designed so that in the future 300 mA of protons could be accelerated by adding more rf power.

The fourth and final stage would be a full-scale breeder facility with electrical generation from the target-blanket system. Costs for this facility are given in Fig. 2. The determination of accelerator parameters that are suitable begin with ZEBRA tests, a facility that is being designed on limited information available for cw structures.

ZEBRA

For proper determination of accelerator breeder parameters, accelerating structures have to be operated cw under conditions similar to those of the breeder. ZEBRA models the first stage of such an accelerator and results will not only be useful for the future breeder program but also for other high current cw linacs. In addition, ZEBRA will be used to study high beam loading, to develop diagnostics for monitoring and understanding accelerator operation, to investigate engineering techniques, to check shielding and activation estimates, to study emittance growth, multi-tank control and beam start-up and to test remote-handling methods. An energy of 10 MeV is high enough to fully exploit the accelerator in tests of the concepts listed above but is barely high enough to adequately investigate beam loss. Higher energies, such as 20 MeV, would result in a more expensive facility that would yield very little extra information.

Parameters for ZEBRA are shown in Fig. 4. Detailed design and construction are expected to begin in 1984. Reasons for parameter choices other than the current and energy are given in reference 3. Leading up to ZEBRA is a set of activities depicted in Fig. 4 that will test some of the ZEBRA requirements. Three main components of this experimental program are the ion source and injector, the radiofrequency quadrupole (RFQ) structure and the drift-tube linac (DTL) structure. Not shown in this figure are the important developments required in beam diagnostics and control systems.

Reference 4 describes development work underway on ISTS and ITE for a suitable ion source and injector that will not only provide required current at the correct emittance but will produce variable current over a fixed voltage range. A biased RFQ is no longer a consideration, because combining high voltage and rf problems in one structure completely overshadows the small savings possible for the injector power supply.

A copper 270 MHz RFQ "sparker" is under construction to determine cw field breakdown levels and associated consequences. A frequency of 270 MHz is being used for all pre-ZEBRA tests because of the availability of a > 400 kW rf source. The 360 mm long vanes are not modulated and have the same 5 mm bore radius as the 270 MHz RFQ1.

RFQ1 has been designed using low power measurements on a 500 MHz RFQ model and beam dynamics calculations. Detailed design and construction awaits "sparker" measurements this winter. The 2.5 m RFQ will accelerate 100 mA of 50 kev protons to 800 keV to test space-charge limits and beam loss. Design rf power is 260 kW with RFQ vane fields limited to the Kilpatrick limit6. A 40-60 kv injector will provide variable currents up to 135 mA.

The present 3 MeV DTL6 has provided very useful information on drift-tube stem to outer wall joints, engineering techniques, vacuum manifolds, cooling, windows, beam monitors and rf system operation. An improved replacement tank, 2BLAT, will be used to verify techniques and components to be employed on ZEBRA. Prior to 2BLAT construction, rf coupling studies7 and post-coupler model studies8 will be completed to provide necessary details. At most, 20 mA of protons will be accelerated by this structure because of injector and transport line limitations.

An important component for pre- and post-ZEBRA tests is the 270 MHz resonant load9 under construction. This aluminum structure has been designed to test many types of joints and rf devices including drift-tubes, post-couplers, tuners and windows with a variety of ports. Extra ports were included for future experiments and for viewing cw operation.

Conclusions

Prior to construction of an accelerator breeder, information is required on cw operation of structures under similar conditions. The 300 mA-10 MeV ZEBRA facility being investigated at CRNL will provide much data related to launching the beam for a breeder accelerator. In addition, control system requirements, beam diagnostic devices and beam loss estimates will be determined. Construction of this...
accelerator, the first stage of a four stage program, should begin in 1984 and cost about $13 M (1981).

A number of pre-ZEBRA tests have started at CRNL including an RFQ "sparker" to determine rf breakdown levels, a 100 mA-800 keV RFQ to determine current limits, a resonant load to high power test cw components and an improved drift-tube linac to test engineering techniques and permanent magnet quadrupoles. The results of these experiments will put the design of an accelerator breeder on a much firmer foundation.

Table 1

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Fig. 1 Fissile fuel costs in $/g versus proton beam energy in GeV for three beam powers with fissile fuel production rate given for each curve.

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References

7. J.C. Brown and R.M. Hutcheon, "Design Considerations for a Developmental High Power Coupling Loop to Drive a Resonant Load", ibid.

Fig. 2 Schematic layout of an accelerator breeder facility.

Fig. 3 Stages in the development of an accelerator breeder facility.

Fig. 4 Set of activities leading up to ZEBRA system.
Discussion

We thought about a biased RFQ, but three considerations make the idea unattractive: first is the combination of rf and high-voltage problems that it is better to avoid; second, Shubaly's method for ion source operation means biasing isn't needed; and third, when the energy is taken back out, the match into the drift-tube linac isn't as good.

If you are interested in the by-products from fuel production, you should refer to the Japanese literature. The waste from electronuclear breeding compared to the breeder reactor is reduced by a factor of 5 to 10. The amount of waste produced is directly related to the thermal power of the target to first order.
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