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Accelerator Complex for Unstable Beams at INS

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1. Introduction

The construction of the prototype facility of the Exotic-arena in proposed Japan Hadron Project(JHP)[1,2] is started in 1992 at INS[3]. The purpose of this facility is to study various technical problems of the Exotic-arena and to perform experiments with respect to nuclear and astro-physics with unstable nuclei beam. The prototype facility will be constructed in the existing building at the present INS campus. Its schematic diagram is shown in Fig 1. Unstable nuclei produced by bombarding a thick target with 40 MeV proton beam (~10 μA) from the existing SF cyclotron are ionized in the ion sources (positive surface ionization, ECR or FEBIAD type), mass-analyzed by an ISOL (M/ΔM~5000), and transported to the following accelerator complex. The accelerator complex consists of an SCRFQ (split coaxial RFQ) and an IH (interdigital H type) linac. Unstable nuclei from the ISOL with an energy of 2 keV/u and a charge-to-mass ratio (*q/M*) greater than 1/30 are accelerated up to 170 keV/u by the SCRFQ. The beam is charge-exchanged by a stripper up to a *q/M* greater than 1/10, and is further accelerated up to 1 MeV/u by the IH linac. The output energy is variable over a range from 170 keV/u to 1 MeV/u by tuning the rf power and phase fed into the IH linac. The construction of the accelerators will be completed during the fiscal year 1994. In this paper, the present status of the accelerator complex is described with emphasis on a design of the IH linac.

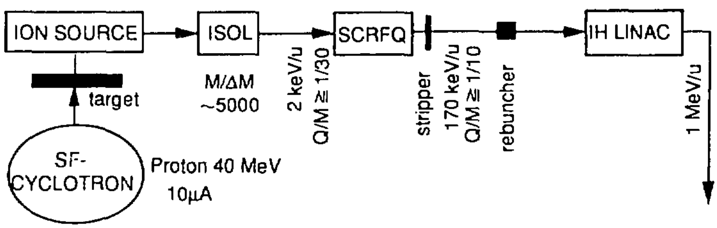

Fig. 1 Layout of the prototype facility at INS.

2. SCRFQ

An RFQ has a merit that it can accelerate a dc beam at very low energy with high transmission efficiency. In the case of accelerating the beam with a small *q/M*, the RFQ must be operated at a low rf frequency. The split coaxial structure keeps a size of the cavity small, compared with other structures such as a four-vane RFQ. In 1984, the development of a SCRFQ was started at INS. This SCRFQ has the following features[4,5]. (1) Modulated-vane electrodes are used to generate ideal accelerating and focusing fields. (2) By employing a multi-module cavity structure, vane electrodes are supported precisely and firmly at several points with stems.

In 1989, a 25.5 MHz-prototype model was constructed to obtain the know-how for the practical use, after the studies with a cold model and a proton accelerating model working at 50 MHz [6,7]. The structure of the prototype model is illustrated in Fig.2. The prototype model consists of three-module cavities with 2.1 m in total length and 0.9 m in inner diameter, and accelerates ions with a *q/M* greater than 1/30 from 1 to 45.4 keV/u. Design parameters of the prototype model are the same as those of the JHP machine except the minimum *q/M* (=1/60). The modulated vanes were machined by two-dimensional cutting technique. The transverse radius ρ_T at the vane tip is constant at the mean aperture radius r_0 = 0.9458 cm. In high power tests, an intervane voltage voltage of 114 kV, (which is higher than the design voltage of 109.3 kV for *q/M*=1/30 ions), was achieved by feeding an rf peak power of 75 kW under a pulse operation (repetition rate 150 Hz) with a duty factor of 9%. Acceleration tests were performed by using three ion species N_2^+,N^+ and Ne^+. The transmission efficiency obtained with a N^+ beam is better than 80% at intervane voltages (normalized by the design value) higher than 1.2. Details of these results are described in ref.[9].

The prototype model will be extended to an 8.5-m, 170-keV/u machine for the practical use. The following improvements or changes will be done[10]. (1) The coupling rings (see Fig. 2) will be removed to reduce the frequency-shift due to the local heating. It was confirmed that the mechanical stability of the electrodes can be kept without them. The flow rate of cooling water, about 300 l/min now, will be increased. By these improvements, the operation at higher duty factor (~30%) will be expected. (2) The injection energy is changed from 1 keV/u to 2 keV/u in order to make the beam transportation from the ISOL easier. (3) In order to achieve higher beam-transmission, the variable-ρ_T geometry of the vane tip will be employed for the low-energy part (the vanes are machined by three-dimensional-cutting technique), and the $\rho_T = r_0$ geometry for the high-energy part (by two-dimensional-cutting technique).

Parameters of the SCRFQ for the practical use is listed in Table 1. Final design of the SCRFQ is now completed.

Table 1 Main parameters of the SCRFQ.

resonant frequency	25.5 MHz
energy	2 --> 170 keV/u
charge-to-mass ratio	≥ 1/30
duty factor	30%
repetition rate	20～1000 Hz
normalized emittance (out)	0.6 π mm · mrad
longitudinal emittance (out)	37.5 π keV/u · deg
tank diameter	0.9 m
vane length	8.6 m
mean aperture radius	0.9458 cm
intervane voltage	108.6 kV (q/M = 1/30 ions)
maximum surface field	178.2 kV/cm (2.5 Kilpatrick)
maximum rf power	280 kW
transmission	91%

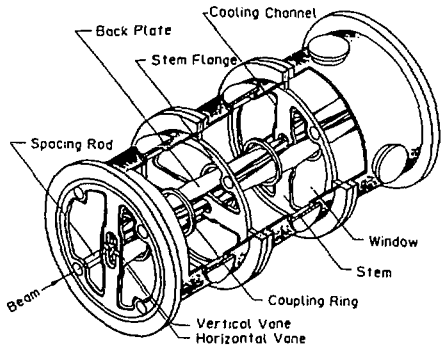

Fig.2 Strucure of the prototype SCRFQ.

3. IH Linac

With increasing of beam energy, the acceleration by the RFQ becomes less efficient. The IH linac is suitable for the post-accelerator of the SCRFQ, since the shunt impedance of the IH linac in the energy range required in our facility is higher than those of other linacs such as an Alvarez type. The beam from the SCRFQ is charge-exchanged by a stripper, and injected into an IH linac. The IH linac has following characteristics. (1) It accelerates the heavy ions from low energy (170 keV/u). (2) Synchronous phase is selected as -25 deg to assure the stable longitudinal motion in spite of the strong transverse rf defocusing force in the accelerating gaps. (3) To obtain high acceleration efficiency, a π-π mode is adopted as an acceleration structure, and no transverse focusing element is installed in the drift tubes. (4) The IH linac is divided into four tanks. Transverse focusing elements are placed between tanks. (5) Output energy is continuously varied in the IH linac. The parameters of the designed IH linac are listed in Table 2.

The resonant frequency of the IH linac is chosen to be twice as high as that of the SCRFQ. Its longitudinal acceptance is half of that with the same frequency as the SCRFQ. The length of drift spaces where magnetic quadrupole triplets are placed should be as short as possible to keep the phase spread in these spaces small. In the present design, the length of the drift spaces is

Table 2 Parameters of designed IH linac.

	tank-1	tank-2	tank-3	tank-4
resonant frequency (MHz)	51	51	51	51
charge-to-mass ratio	≥ 1/10	≥ 1/10	≥ 1/10	≥ 1/10
energy (keV/u)	170 ～ 292	292 ～ 471	471 ～ 721	721 ～ 1046
synchronous phase (deg)	-25	-25	-25	-25
tank diameter (m)	1.34	1.34	1.34	1.34
tank length (m)	0.59	0.84	1.15	1.53
cell number	9	10	11	12
effective shunt impedance (MΩ/m) *	751	510	345	244
maximum peak power (kW)	5.1	11	22	40

* Reduction due to surface roughness and contact resistance is assumed to be 40%.

taken to be 48 cm. Figures 2 (A) and (B) show the calculated results of the energy and phase oscillations. In the calculation, the longitudinal emittance at the entrance of tank-1 is chosen to be 200 π keV/u·deg which is nearly three times larger than the predicted beam emittance from the SCRFQ.

Figures 2-(C) and (D) show the calculated transverse beam envelopes. The transverse and longitudinal emittances of the input beam are chosen to be 0.6 π mm·mrad (normalized) and 200 π keV/u·deg, respectively. The transverse emittance of the unstable nuclei is small, estimated to be less than 0.1π mm·mrad at the exit of the ISOL[11]. But an acceptance larger than this value is required, considering the emittance growth at the charge stripper, or the possibility for the acceleration of the stable-nuclei beams from other ion sources. The acceptance of 1.7 π mm·mrad is achieved by setting the bore radius of quadrupole magnets at 20 mm. Strong field gradients (about 5 kG/cm at maximum) and compact sizes are required for the quadrupole magnets to be placed in the 48 cm long drift spaces. Now these quadrupole magnets and its housing are being designed on the basis of calculation using the computer codes POISSON and TRIM.

The output energy of the IH linac can be continuously varied by tuning the rf power and phase in each tank. Its variation of output energies results from separating the IH linac into several tanks. Figure 3 shows the output energy and its spread as a function of the gap voltage. The output energy is continuously variable from 170 to 1046 keV/u. For example, if a certain energy in the range from 471 to 721 keV/u is needed, the gap voltage of tank-3 is varied without operating tank-4. The energy spread ($\Delta T/T$) is ±2~6% except at the exit of tank-1. Its spread, however, can be made smaller by adjusting the rf phase as well as the gap voltage.

The structure of four tanks is different from that of ordinary IH linacs, that is, axial length of the four tanks is shorter than or near the diameter needed for resonant frequency of 51 MHz. To estimate the resonant characteristics, equivalent circuit analysis was performed. In this analysis, the capacitance and inductance for accelerating cells and end cells were approximately obtained. The analysis predicts that diameters of four 51MHz-tanks are kept in the same size (134 cm) by adjusting the radius of the drift tubes of each tank in the range of 2~4 cm, and by adjusting the sizes of magnetic flux inducers. Predicted effective shunt-impedances are shown in Table 2 together with maximum peak powers. The view of the designed IH linac is shown in Fig. 5. Low power tests using a model will be performed during this fiscal year.

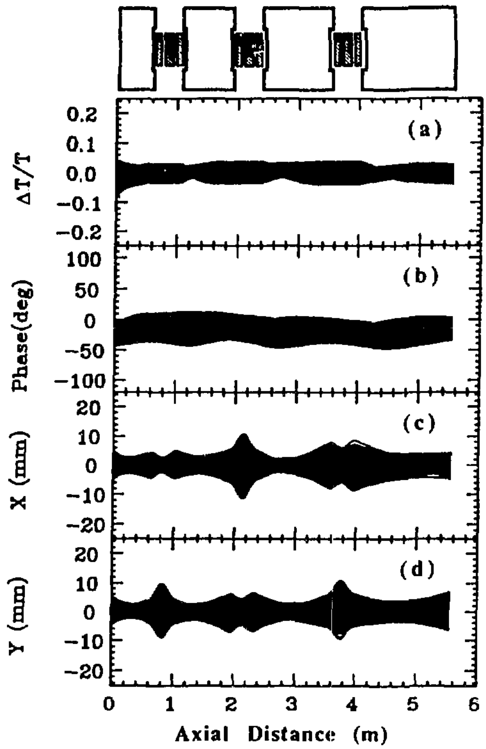

Fig. 3 Calculated beam profiles.

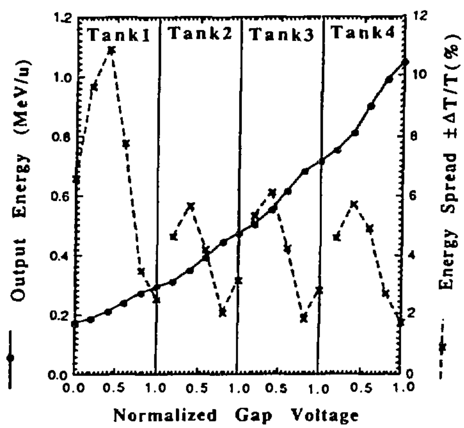

Fig. 4 Output energy and its spread as a function of normalized gap voltage.

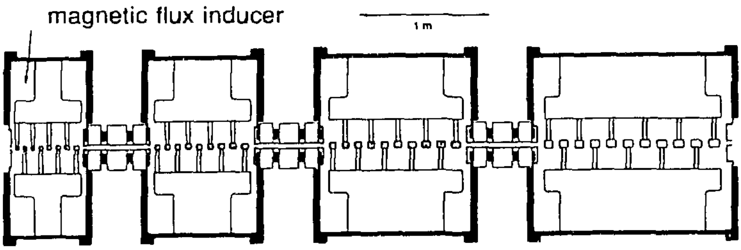

Fig. 5 View of the designed IH linac.

4. Charge Stripper and Beam Matching between SCRFQ and IH linac

Beam accelerated up to the energy of 170 keV/u by the SCRFQ is charge-exchanged by a stripper placed downstream of the SCRFQ, in order to increase the acceleration efficiency of the following IH linac. A carbon thin foil will be used as a stripper because of the easiness of the construction. For the beam of a low velocity, energy loss and its spread due to passing through the foil can not be neglected. Therefore very thin foil (5~10μg/cm^2) must be used as a stripper. The transverse emittance growth due to the multiple scattering depends on the beam size at the stripper position as well as the thickness of the foil. Therefore the stripper is placed just behind of the exit of SCRFQ where beam sizes of both x-and y-directions are small. Considering the charge state distribution after passage through the carbon foil, a transmission efficiency is expected to be 30~50% for the ions with mass less than 30[12].

A buncher is necessary for the matching of longitudinal phase space between the SCRFQ and the IH linac. The correction of energy loss in the stripper as well as rebunching of the beam is performed in this buncher. The resonant frequency for the buncher, the same frequency (25.5MHz) as the SCRFQ, should be chosen to obtain better matching condition, since it reduces the effect of an aberration[13]. As a candidate for the buncher, a spiral cavity is proposed to keep the size of resonator small. The mechanical stability and the resonant characteristics are now being investigated. Two sets of magnetic quadrupole doublets are placed for the transverse matching. The length of about 3 m is taken for matchings.

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