A Heavy Ion Linac Complex for Unstable Nuclei

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Abstract

A heavy ion linac complex for unstable nuclei is under construction at INS. The linac complex consists of a 25.5-MHz split coaxial RFQ (SCRFQ), a charge-stripper section, and a 51-MHz interdigital-H (IH) linac. The SCRFQ with modulated vanes, 0.9 m in diameter and 8.6 m in length, accelerates ions with a charge-to-mass ratio (q/A) greater than 1/30 from 2 to 170 keV/u. The stripper is a carbon foil. The IH linac, 1.34 m in diameter and 5.54 m in total length, comprises four cavities and three magnetic quadrupole triplets placed between cavities, accelerates ions with $q/A \geqq 1/10$, and varies the output energy continuously in the range 0.17 ~ 1.05 MeV/u. The duty factor of the linac complex is 30% for q/A = 1/30 ions.

I. INTRODUCTION

A short-lived nuclear beam acceleration facility, which is a prototype for the exotic nuclei arena (E-Arena) of the Japanese Hadron Project (JHP), has been under construction since fiscal year 1992 at INS. This facility aims to carry forward the R&D of isotope separator on-line (ISOL) and heavy ion linac as well as the studies on nuclear astrophysics, structure of unstable nuclei, etc. The facility is composed of an SF cyclotron, an ISOL and a 1-MeV/u heavy ion linac. The layout of the facility is shown in Figure 1. The radioactive nuclei, produced by bombarding a thick target with a 40-MeV 10-μA proton beam from the existing cyclotron at INS, are ionized in an ion source, mass-analysed by means of the ISOL and transported to the heavy ion linac through a 50 m long beam line. The linac is an accelerator complex composed of a 25.5-MHz split coaxial RFQ (SCRFQ) with modulated vanes, a charge-stripper section, and a 51-MHz interdigital-H (IH) linac. The SCRFQ accelerates ions with a charge-to-mass ratio (q/A) greater than 1/30 from 2 to 170 keV/u. The beam from the SCRFQ is charge-stripped by a carbon foil, and is transported to the IH linac through two magnetic-quadrupole doublets and a 25.5-MHz rebuncher cavity. The IH linac accelerates ions with $q/A \geqq 1/10$ up to 1.05 MeV/u. The output-beam energy is variable between 0.17 and 1.05 MeV/u. The duty factor of the linac complex depends on q/A of the ions: nearly 100% at $q/A \geqq 1/16$, and given by $270 \times (q/A)^2$ at $1/17 \geqq q/A \geqq 1/30$. The main parameters of the linac complex are shown in Table 1.

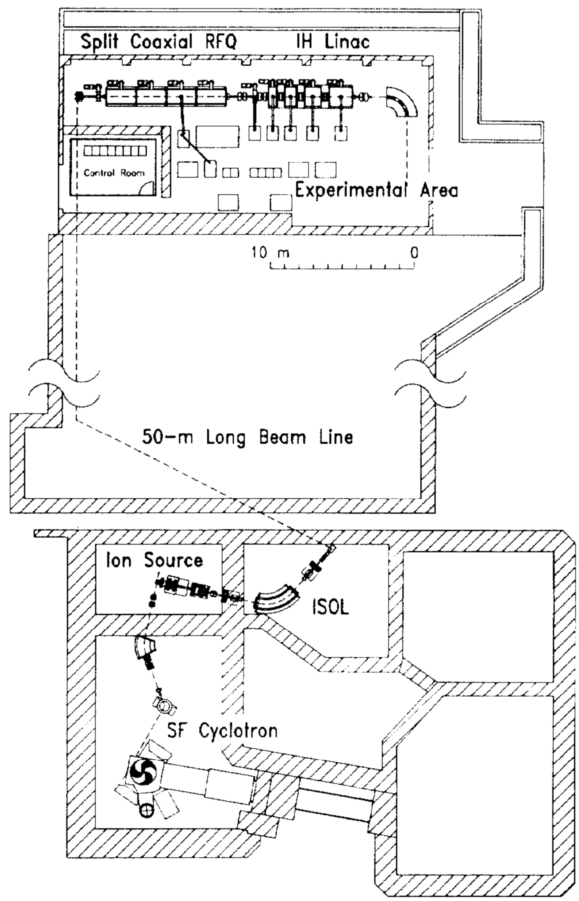

Figure 1. Layout of the radioactive-beam acceleration facility.

Table 1
Main parameters of the heavy-ion linac complex

Input energy	2 keV/u
Output energy (variable)	170 ~ 1046 keV/u
Energy spread (half width)	2 ~ 5%
Beam emittance (normalized)	0.6π mm·mrad
Intensity (radioactive nuclei)	10^7 ~ 10^{11} ions/s
Charge-to-mass ratio (q/A)	$\geqq$ 1/30
Mass number	$\leqq$ 60
Duty factor (for q/A=1/30)	30%
Repetition rate	20 ~ 1000 Hz
Total length	17 m

II. SPLIT COAXIAL RFQ

The accelerating cavity, 0.9 m in diameter and 8.6 m in length, is under construction. Main parameters of the SCRFQ are listed in Table 2. This SCRFQ is an extended version of a prototype model (25.5 MHz, $q/A \geqq 1/30$, 1 → 45.4 keV/u, 0.9 m in diameter, 2.1 m in length). The design of the new SCRFQ is based on the experience gained through the operation of the prototype [1]. The 8.6 m long SCRFQ comprises four unit cavities, whose structure is nearly same as that of the prototype. We fabricate three unit cavities and connect them together with the prototype cavity.

Table 2
Main Parameters of the 25.5-MHz SCRFQ

Frequency (f)	25.5 MHz
Charge-to-mass ratio (q/A)	$\geqq$ 1/30
Kinetic energy (T)	2 → 172 keV/u
Normalized emittance (ε_N)	0.6π mm·mrad
Vane length (L)	8.585 m
Number of cells (radial matcher)	172 (20)
Kilpatrick factor (f_K)	2.49
Intervane voltage (V)	108.6 kV
Mean bore radius (r_0)	0.985 cm
Min. bore radius (a_{min})	0.539 cm
Margin of bore radius (a_{min}/a_{beam})	1.2
Focusing strength (B)	5.5
Transmission efficiency (for q/A=1/30 ions):	
at 0 mA input	91.4%
at 1 mA input	90.6%
at 2 mA input	90.2%
at 5 mA input	83.2%

The modifications and improvements introduced to the new SCRFQ are as follows. 1) The duty factor for q/A = 1/30 ions was 10% at the prototype, whereas 30% at the new RFQ. For such a high-duty operation with a maximum peak power of 350 kW, we have thickened the water cooling pipes of the cavity. Furthermore, the vane coupling rings installed in the prototype have been removed, because they caused appreciable shift of the resonant frequency in high-power operations. 2) The energy of the input beam is 1 keV/u at the prototype, whereas 2 keV/u at the new RFQ. Since the beam emittance has become smaller, the beam transport from the ISOL to the SCRFQ will be easier. 3) As for the vane-tip geometry of the prototype, the transverse radius of curvature is constant at the mean bore radius, $\rho_T = r_0$ (0.946 cm) [2]. At the new RFQ, however, ρ_T is variable in the low-energy part (up to the center of the 76th cell), and $\rho_T = r_0$ (0.985 cm) in the high-energy part. The vanes in the first unit cavity are machined by means of a three-dimensional cutting technique; the cutter is a ball-end-mill. A two-dimensional cutting technique is applied to the other vanes; the cutter edge is shaped to the transverse cross section of the vane tip. 4) For the both vane-tip geometries, we have made a correction on the aperture parameter a and modulation m (A_{10} correction). These parameters were optimized in the beam dynamics design by using the PARMTEQ program. In the PARMTEQ simulation, the electric field is derived from the two-term potential function by Kapchinskii and Teplyakov. The actual electric field generated by the vanes is, however, different from that used in the simulation; particularly, the A_{10} coefficient is different. The A_{10} term is important among the multi-pole terms, because it is the principal term yielding the acceleration field. Through acceleration tests on the prototype RFQ without A_{10} correction, we verified that the A_{10} correction is indispensable to $\rho_T = r_0$ vanes.

III. INTERDIGITAL-H LINAC

The IH linac, 1.34 m in diameter and 5.54 m in total length, comprises four cavities and three quadrupole triplets, as illustrated in Figure 2 [3]. The main parameters of the IH linac are listed in Table 3.

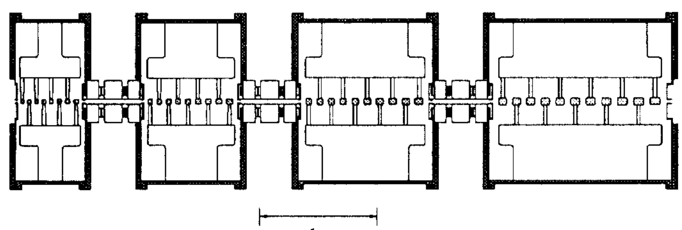

Figure 2. Schematic view of the IH linac.

Table 3
Main parameters of the IH linac

Cavity number	I	II	III	IV
Resonant frequency (MHz)	51	51	51	51
Min. charge-to-mass ratio	1/10	1/10	1/10	1/10
Synchronous phase (deg)	−25	−25	−25	−25
Max. output energy (keV/u)	292	471	721	1046
Cavity diameter (m)	1.34	1.34	1.34	1.34
Cavity length (m)	0.59	0.84	1.15	1.53
Number of cells	9	10	11	12
Max. gap voltage (kV)	200	250	315	370
Effective shunt impedance (MΩ/m)	751	510	345	244
Max. peak power (kW)	5	11	22	40

The IH linac has the following characteristics: 1) it accelerates ions from a very low energy of 170 keV/u; 2) synchronous phase is chosen at $-25°$ to assure the stable longitudinal motion in spite of the strong transverse rf defocusing force in the accelerating gaps; 3) to obtain high shunt impedance, a $\pi-\pi$ mode is adopted as an accelerating periodic structure, and no transverse focusing element is installed in the drift tubes; 4) the IH linac is divided into four cavities to set the transverse focusing elements locally, and to vary the output energy easily; 5) the output energy is continuously varied by changing the rf power and the phase in a last cavity of the working ones.

The quadrupole triplet is placed in short space of 47.5 cm to make the decrease of the longitudinal acceptance small. As a result, the longitudinal acceptance is 200π keV/u·deg, which is nearly three times as large as the predicted beam emittance from the SCRFQ. The transverse emittance of the radioactive beams is estimated to be less than 0.1π mm·mrad. However, an acceptance larger than this value is required, considering the emittance growth at the charge stripper and the acceleration of stable nuclei from other ion sources. The acceptance of 2.4π mm·mrad is achieved by selecting the bore radius of quadrupole triplets as 20 mm. The quadrupole triplet, 9, 14 and 9 cm in pole length, requires high field gradient such as 55 T/m at maximum. The axial length of the four cavities is shorter than or near the diameter needed for a resonant frequency of 51 MHz. To estimate the rf characteristics, an equivalent circuit analysis was performed. The analysis predicts that diameters of the four 51-MHz cavities are kept in the same size by adjusting the radius of the drift tubes of each cavity in the range of 2~4 cm, and by adjusting the sizes of magnetic flux inducers.

IV. CHARGE STRIPPER SECTION

By considering budgetary and space limitations, we designed a compact stripper section, 3 m in total length, as shown in Figure 3 [4].

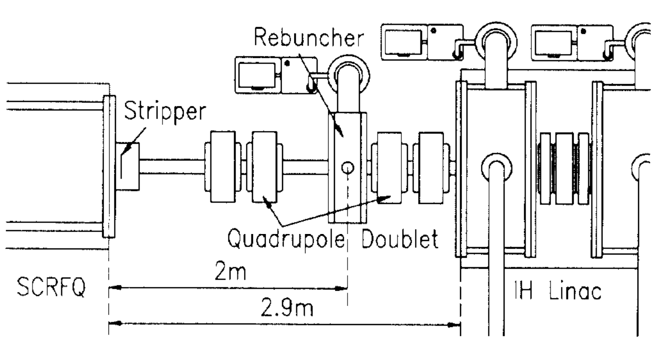

Figure 3. Layout of the stripper section.

In the design of the stripper section, a $^{12}C^+$ ion beam is used, because $^{12}C^+$ ion has larger energy-deposit and energy-straggling per nucleon in the stripper than other ions. The energy loss is about 6 keV/u and the energy-straggling is about ±1 keV/u when the beam with an energy of 170 keV/u passes through a carbon foil, 10 $\mu g/cm^2$ in thickness.

Since the transverse emittance-growth in the stripper is proportional to the beam size, the stripper is placed just behind the SCRFQ, where the beam size is relatively small. The emittance-growth rate of the beam is about 1.6 in the horizontal plane and about 1.2 in the vertical one. The longitudinal matching of the beam is done by means of a rebuncher cavity. It is convenient for matching that the position of the rebuncher is near to the SCRFQ, because the debunching due to the drift space becomes small. The distance between the SCRFQ and the rebuncher is uniquely determined as a function of the distance between the rebuncher and the IH linac, when the longitudinal matching is satisfied. As a result, the distance between the SCRFQ and the rebuncher is determined to be 2 m, since the space longer than 0.9 m is necessary to set a doublet between the rebuncher and the IH linac.

V. STATUS AND PERSPECTIVE

Two unit cavities and a 350-kW power amplifier for the 170-keV/u SCRFQ were constructed in fiscal year 1992. Construction of a unit cavity, conversion of the prototype and whole assembling will be performed this year. By using a half scale model cavity, the rf characteristics of the IH linac are being investigated. On the basis of the model studies, the cavities and the rf power amplifiers will be constructed this year. The design of the charge stripper section was almost completed. As the rebuncher, a spiral loaded cavity working at 25.5-MHz is being developed.

VI. ACKNOWLEDGMENTS

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