Construction of a Heavy Ion Linac for Short-Lived Nuclei

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Abstract

A heavy ion linac for short-lived nuclei is under construction at INS. The linac is an accelerator complex composed 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 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 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.

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 at INS since fiscal year 1992. The short-lived nuclei, produced by bombarding a thick target with a 40-MeV 10-μA proton beam from the existing SF cyclotron, are ionized in an ion source, mass-analysed by means of an isotope separator on-line (ISOL) and transported to a heavy ion linac through a 50-m long beam line. The beam intensity extracted from the ISOL is expected to be $10^7 \sim 10^{11}$ ions/s. The single-charge ions with a charge-to-mass ratio (q/A) greater than 1/30 are accelerated by a 25.5-MHz split coaxial RFQ (SCRFQ) [1] from 2 to 170 keV/u, charge-stripped by a carbon foil, and transported to a 51-MHz interdigital-H (IH) linac [2] through two magnetic-quadrupole doublets and a 25.5-MHz rebuncher cavity. The output beam energy from the IH linac is variable between 0.17 and 1.05 MeV/u. The duty factor of this 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 $1/17 \geqq q/A \geqq 1/30$.

II. SPLIT COAXIAL RFQ

The 170-keV/u SCRFQ is an extended version of a prototype model (25.5 MHz, $q/A \geqq 1/30$, $1 \rightarrow 45.4$ keV/u, 0.9 m in diameter, 2.1 m in length). This SCRFQ was designed on the basis of the result obtained from the beam tests of the prototype [3].

A. Cavity Structure

Main parameters of the cavity are listed in Table 1. The cavity comprises four unit cavities, whose structure is nearly same as that of the prototype as shown in Figure 1.

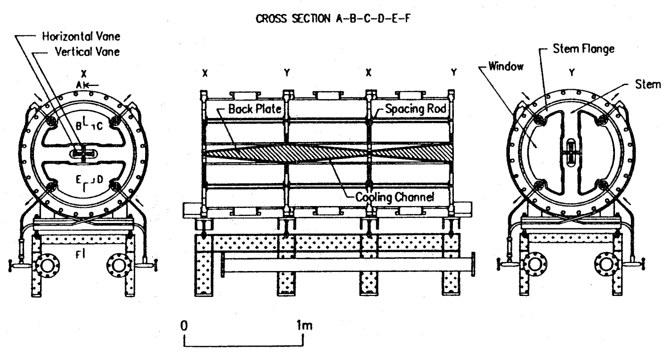

Figure 1. Structure of the unit cavity.

We use the prototype cavity as the fourth unit cavity and fabricate newly three unit cavities. The following improvements were taken in the new cavity: in order to achieve a 30%-duty operation with a maximum peak power of 350 kW, we thickened the water cooling pipes of the cavity, and removed the vane coupling rings installed in the prototype, because they caused appreciable shift of the resonant frequency in high-power operations.

Table 1
Main parameters of the SCRFQ cavity

Frequency (f)	25.5 MHz
Cavity length	8.6 m
Cavity Inner diameter	0.9 m
Vane thickness	3 cm
Stem width near vanes	15 cm
Stem thickness	3 cm
Outer diameter of spacing-rod	3.8 cm
Total capacitance (C)	1548 pF
Total inductance (L)	25.2 nH
Resonant resistance (R_P)	22 kΩ
Intervane voltage (V) (for q/A=1/30)	108.6 kV
Power loss (P) (for q/A=1/30)	280 kW

In the cavity, the rf current flows mainly on the inner surface of the cavity cylinders, the stems and the back-plates of the vanes. The cavity is cooled by eleven water channels running in parallel. Three channels for cooling the cavity cylinders have a flow rate of 10 l/min per channel. Four channels for the stem flanges, the spacing rods, the stems and the diamond–shaped back plates have a flow rate of 44 l/min per channel. Four channels for the stem flanges, the spacing rods, the stems and the triangular back plates have a flow rate of 22 l/min. The flow rate of each channel was determined so as that the temperature increase of the water might be less than 1.4°C under a 30% duty operation with a peak power of 350 kW. For cooling the stems and the back plates, copper pipes, 12.7 mm in outer diameter and 0.8 mm in thickness, are soldered along the stems and around the back plates.

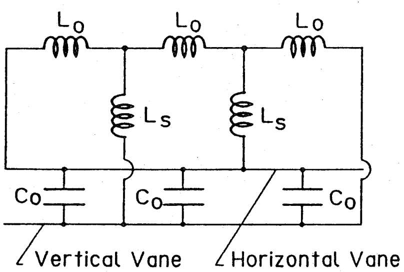

Figure 2. Equivalent circuit of the unit cavity.

When the all coupling rings are removed from a unit cavity, the electrostatic capacitance between vanes decreases from 453.2 to 386.7 pF. Without changing the dimensions of the unit cavity, we intend to adjust the resonant frequency of the 8.6–m long cavity to 25.5 MHz by using the stem inductance. The unit cavity is a three module cavity as shown in Figure 1. The equivalent circuit for the unit cavity is illustrated in Figure 2. The total inductance of the unit cavity is given by a tank inductance (L_0) and a stem inductance (L_S) as follows:

$$L = \frac{L_0(L_0 + 3L_S)}{3L_0 + L_S} \tag{1}$$

From the rf measurements of the prototype, the tank inductance and the stem inductance were obtained to be L_0 = 201 nH and L_S = 29.3 nH.

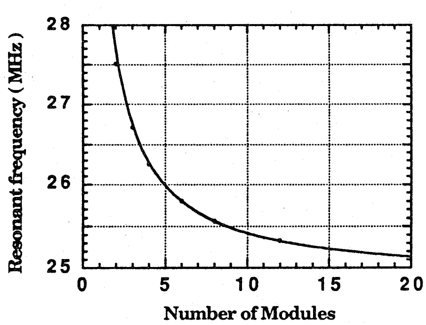

Figure 3. Resonant frequency as a function of the number of modules.

By using these values, we estimated a resonant frequency of the 8.6–m long cavity (12 modules) to be 25.33 MHz as shown in Figure 3. If the experimental value is different from 25.33 MHz and higher than 25.45 MHz, we will roughly tune the resonant frequency to 25.45 MHz by attaching the capacitive tuners on the stems. If the experimental value is lower than 25.45 MHz, the tuning will be done by adjusting the area of the stem–flange windows. The fine tuning to 25.5 MHz will be performed by means of the piston tuners.

B. Vane Structure

The improvements on the vane structure are as follows: the vanes in the first unit cavity are machined by means of a three–dimensional cutting technique, and for the other vanes a two–dimensional cutting technique is adopted. For the both vane–tip geometries, we made a correction on the aperture parameter a and modulation m (A_{10} correction) to bring the actual field close to an ideal one. A detailed description on the vane is elsewhere [1].

III. INTERDIGITAL–H LINAC

In the design of the IH linac, the following principles were adopted to accelerate ions with a $q/A \geqq 1/10$ from 0.17 to 1.05 MeV/u, to vary the output energy continuously between 0.17 and 1.05 MeV/u, and to obtain the high shunt impedance: 1) accelerating periodic structure is a π–π mode; 2) synchronous phase is not 0° but −25° to assure the stable longitudinal motion; 3) no transverse focusing element is installed in the drift tubes, and 4) cavity is divided into four cavities to set the transverse focusing elements locally, and to vary the output energy easily. The cavity structure is illustrated in Figure 4.

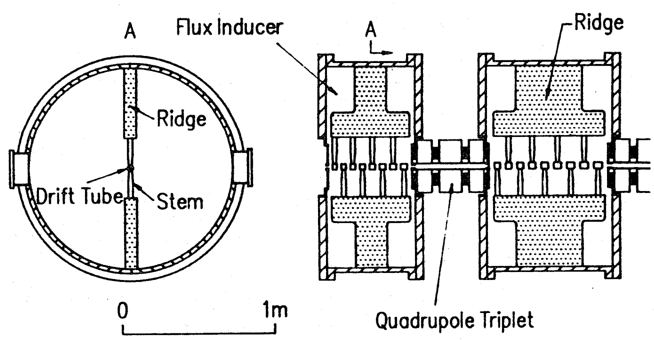

Figure 4. Cavity structure of the IH linac.

A. Beam Dynamics

Beam from the SCRFQ has a transverse emittance (normalized) of 0.6π mm·mrad at maximum and a longitudinal emittance of 75π keV/u·deg. The subject we have put emphasis on is to make the acceptances of the IH linac as large as possible. The both acceptances greatly depend on each cavity length and drift-space length between cavities. A quadrupole triplet is best as the transverse focusing element placed in the drift space. Each optimized cavity length is given in Table 2. The drift-space length was determined to be 47.5 cm, by considering the technical feasibility of the quadrupole triplet. As a result, the transverse acceptance of 2.4π mm·mrad and the longitudinal acceptance of 200π keV/u·deg were obtained. Through a beam simulation, it was verified that the output energy was continuously varied by changing the rf power and the phase in a last cavity of the working ones.

Table 2
Design parameters of the IH cavities

Cavity number	I	II	III	IV
Frequency (MHz)	51	51	51	51
Cavity length (m)	0.59	0.84	1.15	1.53
Cavity inner diameter (m)	1.34	1.34	1.34	1.34
Number of cells	9	10	11	12
Ridge height (cm)	47	47	47	47
Ridge width (cm)	8	8	8	8
Drift-tube diameter (cm)	3.6	4.4	5.2	6.0
Bore diameter (cm)	2.0	2.4	2.8	3.2
Stem diameter (cm)	3	3	3	3
Effective shunt impedance (MΩ/m)	751	510	345	244
Max. gap voltage (kV)	200	250	315	370
Max. peak power (kW)	5	11	22	40

B. Cavity and Quadrupole Triplet

The design parameters of the cavities are listed in Table 2. The inner diameter of four cavities is constant, while the axial length is different from each other. Each gap length between drift tubes is constant over a cavity and equal to one half of the first cell length. We estimated a resonant frequency at each cell by using a capacitance obtained approximately by SUPERFISH and an inductance calculated analytically in an assumption that the magnetic flux density might be constant in the cavity. Both end structures of the cavity, i.e. the magnetic flux inducer and the gaps between the end wall and ridge, are determined experimentally so as that the longitudinal field distribution becomes flat over a cavity.

We designed the quadrupole triplet compactly to make the drift space as short as possible. Therefore, the quadrupole triplet, 2 cm in bore radius, 19 cm in yoke radius and 9, 14 and 9 cm in pole length, requires high field gradient such as 55 T/m at maximum. As a coil, a hollow conductor, 4×6 mm^2 in outer size and 2×4 mm^2 in inner size, is wound 34 turns on a pole. Power supplies, 300 A and 35 V at maximum, are used for these magnets.

IV. CHARGE STRIPPER SECTION

We designed a compact stripper section [4] by using a $^{12}C^+$ ion beam, 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 μg/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 horizontal and vertical beam radii are 7 and 4 mm. 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 distances between the SCRFQ and rebuncher, and between the rebuncher and IH linac were determined to be 2 and 0.9 m, so as that it might be possible to set a quadrupole doublet behind the rebuncher.

V. STATUS

The construction of the 170-keV/u SCRFQ will be completed this fiscal year. A 350-kW rf amplifier for the RFQ has been already constructed. The IH linac will be constructed from this year on the basis of the studies performed by means of half scale model cavities. The basic design of the charge stripper section was almost completed. As the rebuncher, a 25.5-MHz spiral loaded cavity is being developed.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

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