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OPERATION EXPERIENCE WITH THE TOKYO INSTITUTE OF TECHNOLOGY HEAVY-ION LINAC

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ABSTRACT

A multipurpose heavy-ion linear-accelerator system has been constructed to generate beams for material-science, atomic- and nuclear-physics studies. The system consists of a 1.6-MV tandem as an injector, a high energy gain (E_{out}/E_{in}=10) and a low energy gain (E_{out}/E_{in}=1.4) Wideröe with IH structure. The available beam energy ranges from 2.2 to 3.1 MeV/u by changing the RF input power of the second Wideröe. The accelerating characteristics have been studied, and experiences in the operation during the last 18 months are reported.

INTRODUCTION

A variable-energy heavy-ion linac system has been designed and constructd adopting a combination of a 1.6-MV tandem as an injector and two IH structures. The tandem injector has many advantages: an injection energy of 0.24 MeV/u (=0.02) is available for elements up to chlorine. The beam intensity is rather high(a few μA), and the beam is re-stripped using a carbon-foil stripper before injection to get charge-to-mass ratios (q/A) between 0.25 - 0.37. These high values of injection energy and of q/A have facilitated the design of quadrupole magnets for the drift tubes adopting even the π-π mode. Making use of high shunt impedance of the IH structures, a CW operation has been realized with small transmitters with RF output powers of 100 kW and 12 kW for the first and the second linac, respectively. By changing the RF input power to the second linac we can vary the beam energy in a certain range.

After a brief description of the system, we present in this paper the structure of both IH-Wideröes and the overall performance of the system.

IH STRUCTURE WITH HIGH ENERGY GAIN

This module is designed to accelerate ions with q/A = 0.25 - 0.37 from the injection energy of 0.24 MeV/u to the output energy of 2.4 MeV/u. The detailed specifications of the accelerating structure and the design work using scale models have been published in ref[1]. Figure 1 illustrates schematically the structure. Two pairs of short-circuit wings reduce the effective cross section of the cavity to compensate the local lowering of eigen-frequency in the low energy section. In order to enhance the accelerating voltage, the ridge is L-formed in the high energy section. We call this part "magnetic-flux inducer" in the following descriptions. This principle has been developed by the INS group[2-5].

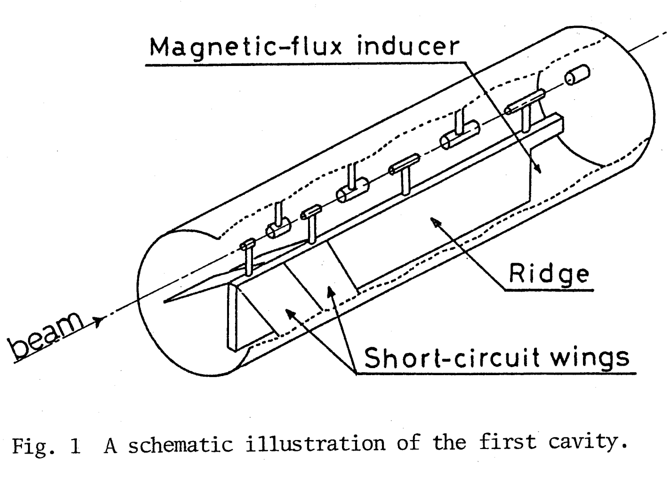

Fig. 1 A schematic illustration of the first cavity.

Figure 2 shows a photograph of the first cavity. The inner diameter and length of the cavity are 1.4 and 7.0 m, respectively. The resonance frequency has been decided to be 48 MHz. A plunger and a capacitive tuner are used for fine and coarse frequency control, respectively. The maximum RF input power amounts to 100 kW. A phase acceptance of 90° has been achieved by choosing a synchronous phase of -30°. Twenty-one drift tubes suspended from the top of the cavity are equipped with magnetic quadrupoles, and 22 drift tubes mounted on the ridge have not any focusing elements. The gap-to-cell-length ratio is 0.4 and is constant throughout the structure. Each end drift tube mounted on the end wall is equipped with a magnetic half lens.

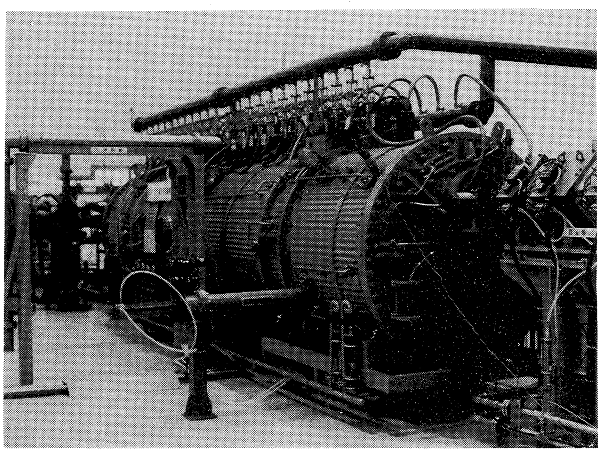

Fig. 2 A photograph of the first cavity.

The maximum field gradient of the quadrupoles has been determined to be 4 kG/cm from beam trajectory calculations using the computer program "LINOR"[6]. The horizontal and vertical acceptances have been calculated to be 90π and 60π mm·mrad for the synchronous ions, respectively. Spiral-plate coils have been adopted for the quadrupoles to clear this value of field gradient. The outer diameter of drift tubes is 10 cm, which has contributed to reduce the stray capacitance. All coils are directly cooled by liquid freon.

Figure 3 shows accelerating-field distributions measured by means of the perturbation method (a) and momentum spectra of accelerated ions of $^{16}O^{4+}$ (b and c). The form of accelerating field in the high energy section has been adjusted by changing L_1 and L_2 (see the inset). We have started from the combination of L_1 = 400 mm and L_2 = 250 mm. The field distribution (a) has been observed. The accelerating field is too low at the high energy section. In order to improve the field flatness the magnetic-flux inducer has been enlarged to L_1 = 440 mm. The result is marked (b) in the figure. The field at the last accelerating gap was raised by 20 %. A spectrum of accelerated particles is represented in Fig. 3b. The peak energy and the FWHM value of the analyzed beam are determined to be 2.32 MeV/u and 0.4 MeV, respectively. The fact that the beam energy is lower than the design value of 2.40 MeV/u is to be attributed to the drop of accelerating voltage at the high energy section.

As a next step we have reduced the distance L_2 by attaching a copper plate to the inducer head. The electric capacity of this part was increased. This method has been proposed by Chabert et al.[7] and is suitable for the fine tuning of field distribution. An

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almost uniform field (c) was obtained. As shown in Fig. 3c a peak is observed at 2.37 MeV/u, which is slightly lower than the design value.

From the particle acceleration experiments, we have deduced a value of 132 MΩ/m for the effective shunt impedance with the optimum RF input power. In this value the effects of the transit-time factor and the accelerating phase are included. Values of the shunt impedance and transit-time factor have been calculated to be 210 MΩ/m and 0.91, respectively. These values have been deduced from the result of the accelerating field measurement.

From proton accelerating experiments the horizontal and vertical emittances have been determined to be 9π mm•mrad and 10π mm•mrad for the 97 % brightness contour, respectively. The beam transmission amounted to 40 % for a DC beam injection. This value has well agreed with the result of the beam trajectory calculation.

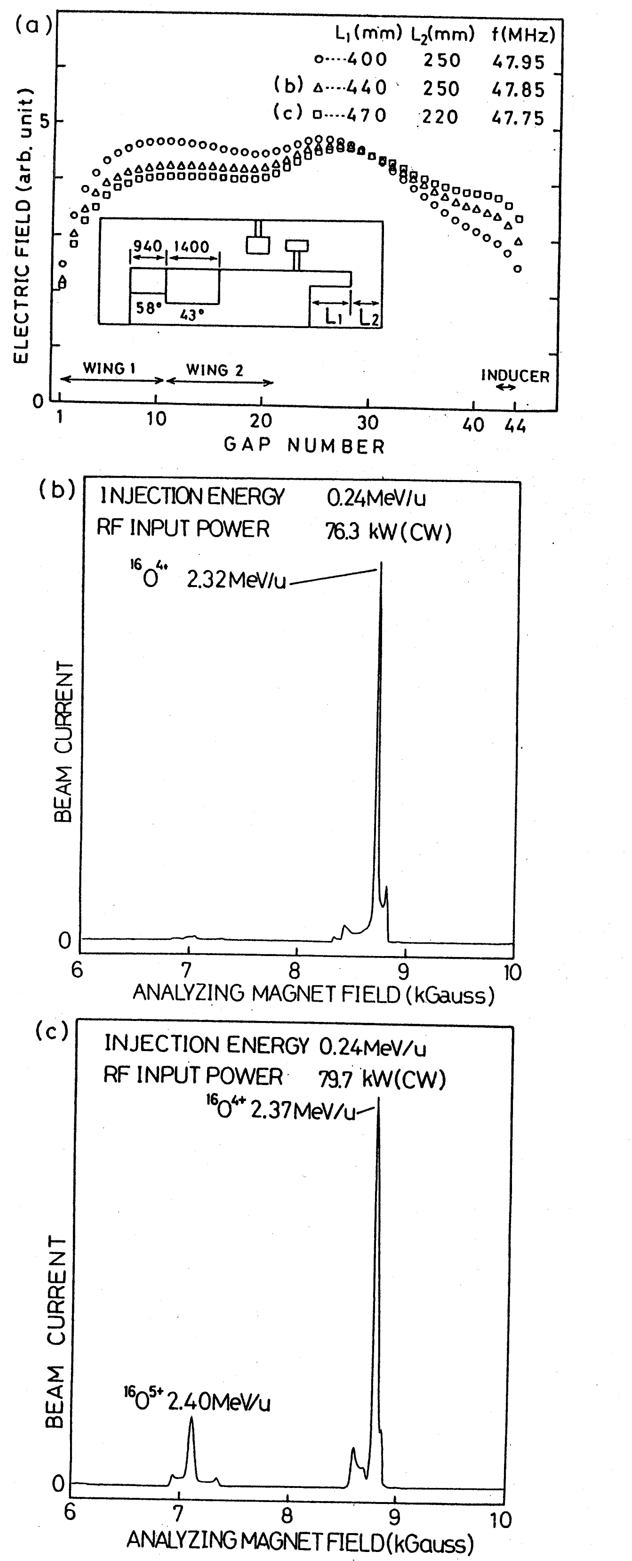

Fig. 3 Accelerating-field distributions (a) and momentum spectra of $^{16}O^{5+}$ beam (b,c) accelerated with the field distributions b) and c).

ACCELERATING CHARACTERISTICS OF THE SECOND LINAC

This machine is designed to accelerate ions from 2.4 MeV/u up to 3.4 MeV/u. The resonance frequency is adjustable between 95 and 96.5 MHz. For a synchronous operation with the first module, the accelerating frequency is fixed to be just two times of that of the first module. Figure 4a illustrates schematically the structure. An array of 21 drift tubes is fixed on a plate sandwiched by two half-cylinder shells to realize an IH structure. The shells and the middle plate are water-cooled to accept an RF power of up to 45 kW. The drift tubes do not contain any focusing elements to reduce the stray capacitance between them. The gap-to-cell-length ratio is 0.5 and is constant throughout the accelerating length.

A flat accelerating-voltage distribution has been realized by means of E-formed magnetic-flux inducers located at each end of the middle plate (see Fig. 4b). The magnetic field is enhanced in the end spaces by these windows to compensate the voltage drop which is a characteristic phenomenon for IH structures.

This structure has a synchronous phase of 0°. Two pairs of quadrupoles serve to focus the ion beam: The one is located in the upstream and the other in the downstream line of the resonator tank.

For the coarse control of the resonance frequency two plates (80 × 400 mm^2) are suspended from the top of the upper half shell. A plunger type tuner is used for the automatic frequency control. A loop tuner is located in the lower half shell as a supplement of the plunger tuner.

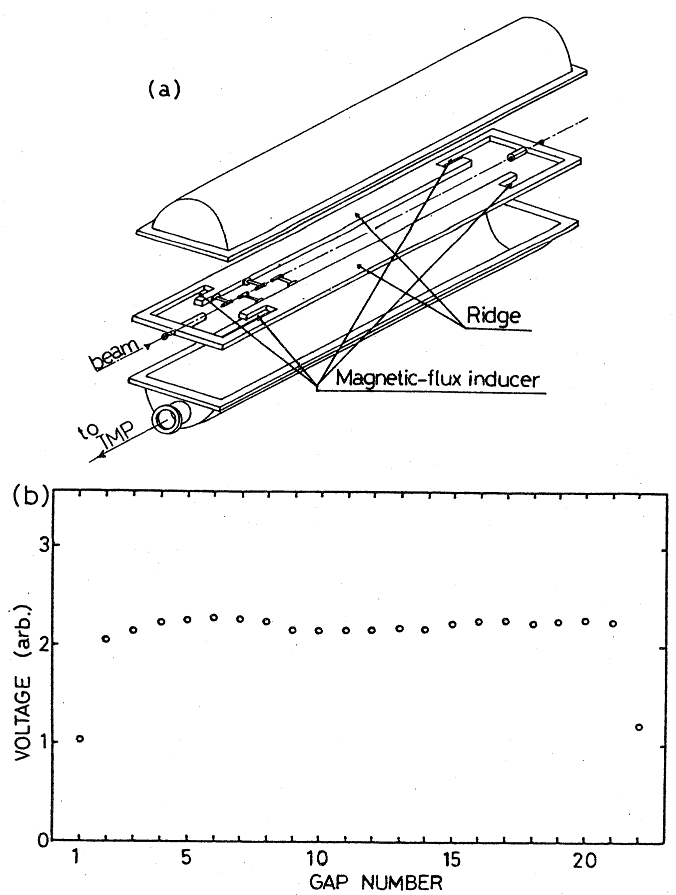

Fig. 4 A schematic illustration of the second cavity and the accelerating field distribution.

Energy spectra of the accelerated $^{16}O^{5+}$ and $^{16}O^{6+}$ beams have been measured by means of Rutherford scattering on gold. As typical examples Fig. 5 represents spectra of $^{16}O^{6+}$ as injected (a), of an accelerated beam with an input RF power of 10 kW (b) and of a decelated beam with the same RF power (c), where sharp peaks are observed at 2.43, 3.06 and 2.16 MeV/u, respectively.

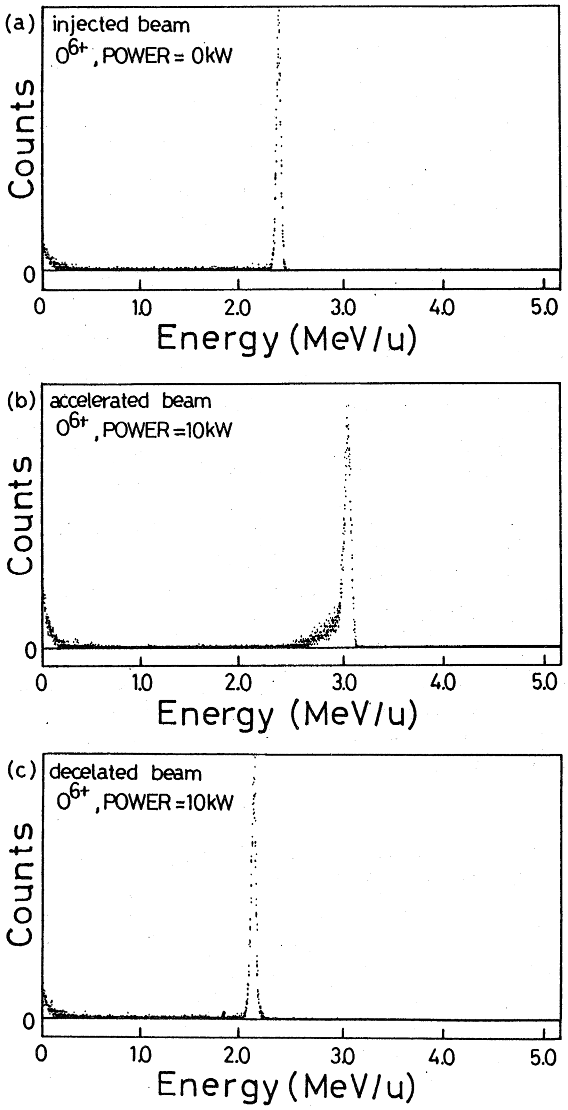

Fig. 5 Energy spectra of accelerated beam. a) as injected, b) RF phase relation for full acceleration, c) RF phase relation for full decelation.

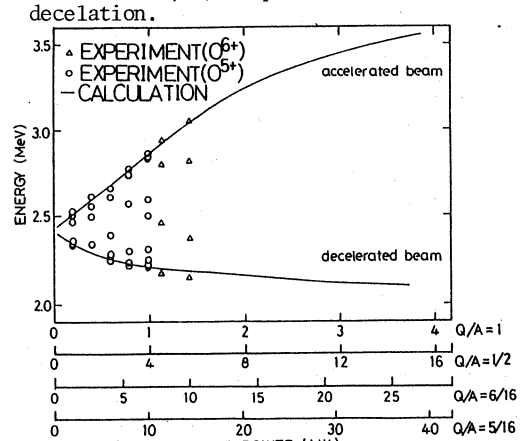

Fig. 6 The available energy region of the Tokyo Institute of Technology Heavy-ion Linac. Parameters are RF input power, charge-to-mass ratio of ions and the RF phase difference between the first and the second cavities.

Figure 6 summarizes results of the experiments. The maximum and the minimum energies are plotted as a function of input RF power. The parameter is the RF phase difference between the first and the second cavities. The theoretical values (curves) reproduce the experimental results where the effective shunt impedance has been assumed to be 130 MΩ/m. This value agrees almost with the value of 132 MΩ/m which has been deduced from perturbation measurement of the cavity. However, this result did not reach a value of 149 MΩ/m which was predicted from the scale-model experiment.

CONCLUSION

We have successfully constructed an IH linac with a high energy gain keeping the advantages of high shunt impedance and low construction cost. The combination of short-circuit wings and a magnetic-flux inducer has been proven to be a reliable method to control the accelerating-field distribution in a long IH type cavity.

We had to, however, overcome many technical problems from the design work until the beginng of operation. The fundamental accelerating parameters such as resonance frequency and accelerating-voltage distribution depend very sensitively on other parameters including electric capacity of the drift tubes. Control devices of accelerating-voltage distribution are indispensable. The RF power loss concentrates on these control devices and destroys them. A precise prediction of heat generation is, however, very hard because of the asymmetric geometry of the IH structure.

Detailed calculations of RF current distribution are indispensable for the power loss estimation and heat-engineering design. We are now calculating three-dimensional solutions of the electromagnetic equation for the IH cavities by means of a computer program developed by Hara et al.[8]

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