PERFORMANCE OF ALTERNATING-PHASE-FOCUSED IH-DTL

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Abstract

A compact injector, designed for a medical accelerator complex, was constructed. It consists of an Electron-Cyclotron-Resonance Ion-Source (ECRIS) and two linacs, which are a Radio-Frequency-Quadrupole (RFQ) linac and an Alternating-Phase-Focused Interdigital H-mode Drift-Tube-Linac (APF IH-DTL) having the same operating frequency of 200 MHz. The compact injector can accelerate carbon ions of $^{12}C^{4+}$ up to 4.0 MeV/u. Use of the APF IH-DTL enabled us to design the compact injector; the total length of the two linacs is approximately 6m. After installation of the compact injector, beam acceleration tests were performed. We have succeeded to accelerate carbon ions with satisfactory performance. An overview of the compact injector as well as results of the beam acceleration tests is described.

INTRODUCTION

Cancer therapy using energetic carbon ions from the Heavy Ion Medical Accelerator in Chiba (HIMAC) has been carried out at National Institute of Radiological Sciences (NIRS). Until now, more than 2,600 patients had been treated since treatment was started in June, 1994. Successful treatments over more than ten years have demonstrated the effectiveness of heavy-ion therapy. This encouraging result led us to develop a more compact and cost-effective medical accelerator complex for an increased use of heavy-ion therapy.

In designing the accelerator complex, the size of an injector is a concern, because existing heavy-ion injectors are quite large. The size of the injector would affect the entire size of the accelerator complex, and hence total construction costs. Therefore, we developed a compact injector for the medical accelerator complex. The compact injector was constructed, and beam acceleration tests using carbon ions were performed. In this paper, results of the acceleration tests as well as an overview and a design of the compact injector is presented.

OVERVIEW OF COMPACT INJECTOR

The compact injector consists of ECRIS and two linacs, which are the RFQ linac and APF IH-DTL. The operating frequency of both linacs is 200 MHz. A schematic drawing of the compact injector is presented in Fig. 1.

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Carbon ions, produced with ECRIS, are transported and analyzed with a Low-Energy Beam-Transport (LEBT) line, and $^{12}C^{4+}$ having a kinetic energy of 10 keV/u are selected. Having matched the transverse phase space using focusing elements installed in the LEBT line, carbon ions of $^{12}C^{4+}$ are injected to the RFQ linac and accelerated up to 608 keV/u. Then, accelerated and bunched carbon ions traverse a short quadrupole triplet, installed for transverse matching between the two linacs, and are injected to the APF IH-DTL. Finally, carbon ions are accelerated up to 4.0 MeV/u with the APF IH-DTL.

The RFQ linac has conventional four-vane structure. By optimizing for carbon acceleration and employing the rather high operating-frequency of 200 MHz, we could design the compact cavity; the length and outer diameter of the cavity are 2.5m and 0.41m, respectively. Prior to installation of the APF IH-DTL, beam acceleration tests only with the RFQ linac were performed. As a result of the tests, we found that measured energy and phase-space distributions were reproduced fairly well with those calculated with the PARMTEQ code.

For the APF IH-DTL, the APF method was applied to the IH cavity. This would make the cavity significantly simple and cost-effective. Furthermore, the cavity is compact; the length and outer diameter of the cavity are 3.4m and 0.44m, respectively. A design of the APF IH-DTL is described in the following section.

APF IH-DTL

Beam Dynamics

The APF method utilizes focusing and defocusing strengths provided with the rf acceleration field by choosing positive and negative synchronous phases alternately at each gap. By analogy with the principle of strong focusing, both transverse and longitudinal stability

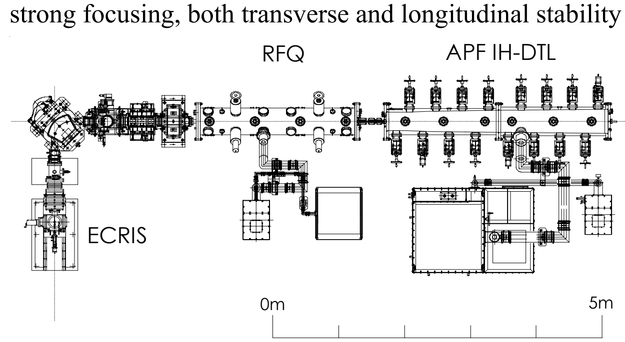


Figure 1: Layout of the compact injector.

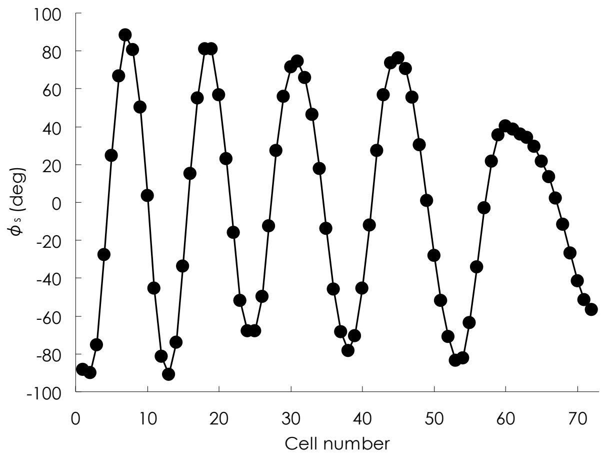
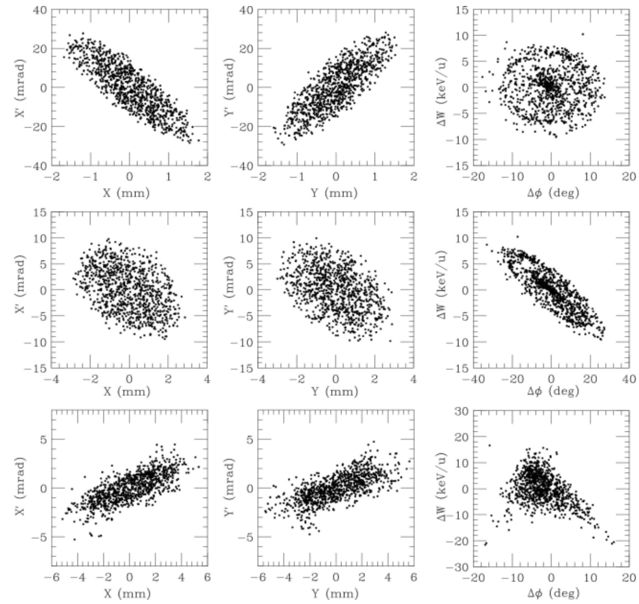


Figure 2: Synchronous phases as a function of the cell number.

of motion would be obtained just with the rf acceleration field. Hence, the cavity would not require any additional focusing elements as well as cumbersome water-cooling equipments.

Due to the nature of this method, beam dynamics of the APF linacs would depend strongly on a choice of the alternating synchronous phases. Therefore, major effort in the design of the beam dynamics was dedicated to optimize an array of the synchronous phases[1,2]. Fig. 2 shows the optimized synchronous phases as a function of the cell number. As can be seen in the figure, the phases were varied up to ϕ_s=±90 degrees, whereas the phases for conventional linacs, such as the Alvarez structure, would be kept to be constant around ϕ_s~30 degrees.

With the optimized phase array, transverse and longitudinal phase-space distributions of beams could be calculated as shown in Figs. 3. Figures in the upper row show the phase-space distributions of the carbon beam extracted from the RFQ linac. These distributions were calculated with the PARMTEQ code. The average energy was E_{ave}=608 keV/u. Figures in the middle row show the distributions after the quadrupole triplet, installed in between the two linacs. These distributions correspond to those of the injected beam to the APF IH-DTL. Finally, the distributions for the extracted beam from the APF IH-DTL are shown in the lower row. The average energy was calculated to be E_{ave}=4.0 MeV/u. With the distributions, normalized vales of the 90% transverse and longitudinal emittances were estimated to be 0.86 π·mm·mrad and 1.6 π·ns·keV/u, respectively. The energy spread would be less than ΔE=±16 keV/u, corresponding to $\Delta E/E$<±0.4%.



Figures 3: Calculated phase-space distributions of the extracted beam from the RFQ linac (upper row), the injected beam to the APF IH-DTL (middle row), and the extracted beam from the APF IH-DTL (lower row).

IH Cavity

The IH structure was applied to the cavity of this APF linac. Although this structure has been used in the last 25 years, it had not been developed for several decades since it was first proposed in 50s. One reason for the delay of the developments against the Alvarez structure was that an electric-field distribution in the IH cavity could not be calculated with existing two-dimensional electromagnetic field solvers, because the field distribution depends strongly on the total structure of the cavity, including its cell table. With the advent of three-dimensional electromagnetic field solvers, it became possible to calculate the electromagnetic field distribution in the IH cavity. Although the solvers were recently applied to design the IH cavity, accuracy of the solvers was not yet confirmed. Therefore, we constructed a model cavity of the APF IH-DTL[3]. The electric field distribution was measured using the perturbation method and compared with that calculated with the solver. As a result, we found that the solver would provide tolerable accuracy and that the field distribution could be precisely adjusted, once tuning with fifteen inductive tuners was performed.

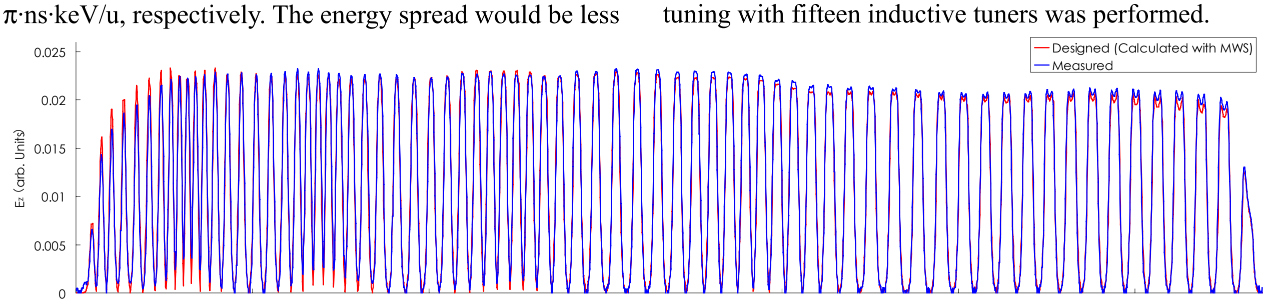
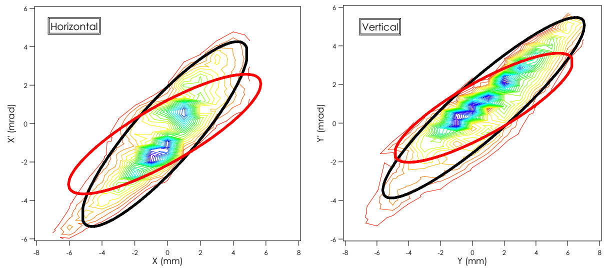


Figure 4: Measured and designed electric field distributions for the high-power cavity of the APF IH-DTL.



Figures 5: Measured transverse phase-space distributions. The red curves show the calculated distributions.

Based on the model cavity, a high-power cavity was designed and constructed. The electric field distribution was measured and adjusted using sixteen inductive tuners. The measured electric field after the tuning is presented in Fig. 4. For comparison, the designed distribution is also plotted in the figure. We found that the electric field over the cavity was precisely tuned to that designed. The cavity frequency after the tuning was 200.1 MHz. During operation, the cavity frequency would be further tuned to the designed frequency of 200.0 MHz with automatic frequency tuners. A quality factor was measured to be Q_m=12,000, corresponding to 80% of the calculated value, Q_c=15,000. Assuming 80% of the calculated Q_c, a required rf power is estimated to be 360 kW.

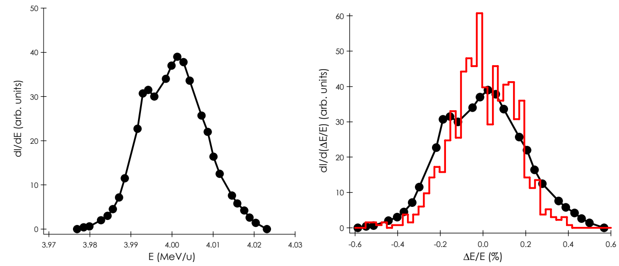
Once the tuning was completed, rf power, generated by rf amplifiers, was delivered to the high-power cavity. After a few days of conditioning, the estimated rf power of 360 kW was successfully fed into the cavity. Major parameters of the APF IH-DTL are listed in Table 1.

BEAM ACCELERATION TESTS

After installation of the entire compact injector system, completed in March, 2006, beam acceleration tests using carbon ions were performed. As a result of the tests, we observed beam intensity of 390 eμA for accelerated $^{12}C^{4+}$ ions. The beam transmission of the entire injector system, including the LEBT line, RFQ linac and APF IH-DTL, was measured to be 79%. Considering the known transmission of the LEBT line and RFQ linac, the transmission only for the APF IH-DTL was estimated to be almost 100%, which is consistent with the calculated transmission of 99.6%.

Table 1: Major parameters of the APF IH-DTL.

Parameters	Value	Units
Injection energy	608	keV/u
Extraction energy	4.0	MeV/u
Operating frequency	200	MHz
Charge-to-mass ratio	1/3	-
Number of unit cells	72	-
Cavity length	3.44	m
Cavity inner diameter	0.283-0.364	m
Cavity outer diameter	0.40-0.44	m
Maximum gap voltage	350	kV
Maximum surface field	23.6	MV/m
Kilpatric value	1.6	-
Calculated unloaded *Q*	15,000	-
Measured unloaded *Q*	12,000	-
Required power	360	kW
Energy spread ($\Delta E/E$)	±0.4	%
Maximum duty	0.4	%



Figures 6: Measured energy and ΔE/E distributions. The red histogram shows the calculated energy distribution.

Transverse phase-space distributions of the accelerated carbon beam were measured with a pair of a slit and profile monitor. The measured distributions are shown by the contour plots in Figs. 5. The distributions were fitted with an elliptic function to determine a beam emittance. A result of the fits providing the 90% emittances is shown by the black solid curve. The calculated transverse phase-space distribution, as shown in the lower row of Fig. 3, is also plotted by the red curves in Figs. 5. We found the measured and calculated distributions were roughly agreed with each other. A normalized 90% emittance, obtained by the fit, was approximately 1.0 π·mm·mrad, which is slightly larger than the calculated value.

The energy distributions of the accelerated beams were measured as shown in Figs. 6. The average energy and energy spread were E_{ave}=4.0 MeV/u and $\Delta E/E$=0.4%, respectively. The calculated energy spread was also shown by the red histogram in the figure. As can be seen in the figure, the measured distribution was roughly agreed with the calculated distribution.

SUMMARY

The compact injector for medical accelerators was designed and constructed. It consists of ECRIS and two linacs, which are the RFQ linac and APF IH-DTL, and can accelerate carbon ions up to 4.0 MeV/u. The total length of the two linacs was reduced to approximately 6m, which is considerably shorter than existing heavy-ion linacs. Beam acceleration tests were performed, and we have succeeded to accelerate carbon ions with satisfactory beam quality. The results of the acceleration tests have demonstrated the excellent performance of the compact injector.

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