ALTERNATING-PHASE-FOCUSED IH-DTL FOR HEAVY-ION MEDICAL ACCELERATORS

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Abstract

Compact linacs, consisted of a Radio-Frequency-Quadrupole (RFQ) linac and Interdigital H-mode Drift-Tube-Linac (IH-DTL) having the same operating frequency of 200 MHz, were designed for an injector of heavy-ion medical accelerators. For beam focusing of IH-DTL, the method of Alternating-Phase-Focusing (APF) was applied. The total length of the RFQ linac and APF IH-DTL is approximately 6 m. With the two linacs, carbon ions produced by an ECR Ion-Source (ECRIS) could be accelerated up to 4.0 MeV/u. The compact linacs were constructed and installed in NIRS. We have succeeded to accelerate carbon ions with the APF linac for the first time. The present status of the compact linacs as well as results of acceleration tests was presented.

INTRODUCTION

At the National Institute of Radiological Sciences (NIRS), cancer therapy using high-energy carbon ions from the Heavy Ion Medical Accelerator in Chiba (HIMAC) has been carried out since June 1994[1]. Until now, more than 2,600 patients have been treated in NIRS. Due to the successful clinical results over more than ten years, a number of projects on construction of these accelerator complexes dedicated to the cancer therapy have been proposed over the word. Since these existing accelerator complexes are costly and large in size, the development of cost-effective and compact accelerators for a hospital-based complex is needed for the increased use of the heavy-ion therapy.

In the development of the hospital-based accelerator complex, the design of an injector plays a key role, because the existing heavy-ion linacs are quite large. The size of the injector would affect the total size of the complex as well as total costs of construction. Therefore, we developed the compact injector for the heavy-ion medical accelerators.

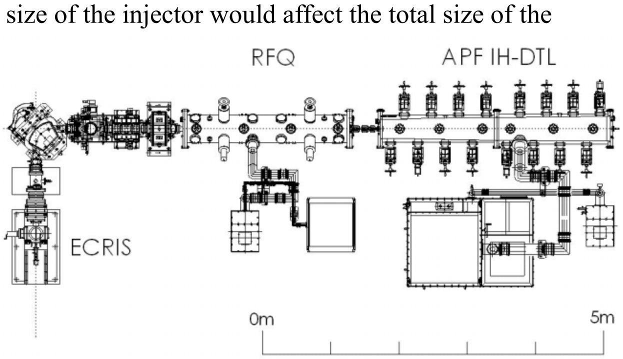

Figure 1: A schematic drawing of the compact injector.

The compact injector consisted of ECRIS and two linacs, which are the RFQ linac and IH-DTL having the same operating frequency of 200 MHz. For beam focusing of IH-DTL, the method of APF was applied. Injection and extraction energies of the two linacs were summarized in Table 1. In the following sections, the present status of the compact injector and results of beam acceleration tests were described.

COMPACT INJECTOR

A schematic drawing of the compact injector was shown in Fig. 1. For an ion source, permanent-magnet 10 GHz ECRIS was employed[2]. Use of the permanent magnets to produce all the required magnetic field allowed us to design considerably simple and cost-effective ion-source, because it would not require any power supply as well as cumbersome cooling system. ECRIS was first manufactured and tested in NIRS. As a result, we found that ECRIS can produce $^{12}C^{4+}$ of more than 400 eμA under an extraction voltage of 30 kV, corresponding to the ion energy of 10 keV/u.

Ions produced by ECRIS were analyzed with a Low-Energy-Beam-Transport (LEBT) line, and carbon ions of $^{12}C^{4+}$ having 10 keV/u were selected. The analyzed carbon ion were transported through the LEBT line and then injected to the RFQ linac. Transverse phase-space matching to the linac was accomplished by adjusting focusing elements, such as an electrostatic quadrupole triplet and magnetic solenoid, installed in the LEBT line. Transverse emittances of carbon ions from ECRIS were measured using the LEBT line in prior to installation of the linacs. Beam transmission through the LEBT line was better than 90%.

Table 1: Major parameters of the compact linacs

Parameters	RFQ	IH-DTL	Units
Injection energy	0.01	0.61	MeV/u
Extraction energy	0.61	4.0	MeV/u
Operating frequency	200	200	MHz
q/m	1/3	1/3	-
Cavity length	2.5	3.4	m
Cavity outer diameter	0.42	0.44	m

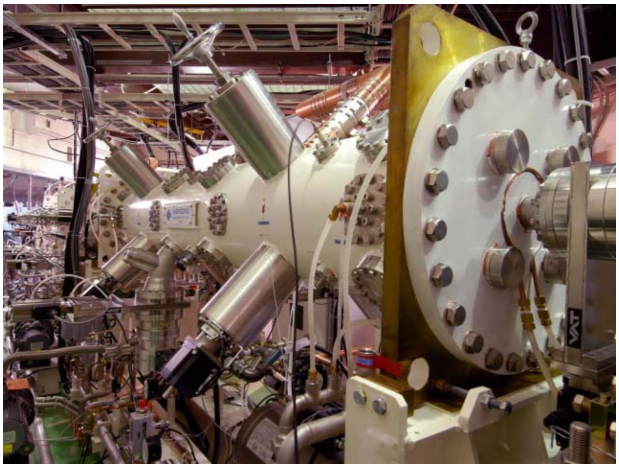

Fig. 2 A picture of the compact RFQ linac (a view from upstream).

The RFQ linac has a conventional four-vane structure. It can accelerate carbon ions up to 610 keV/u. By optimizing cell parameters for acceleration of carbon ions and using the rather high operating-frequency of 200 MHz, we could design the compact cavity; length and outer diameter of the cavity are 2.5 m and 0.42 m, respectively. The construction of the RFQ linac was completed in July 2005 and installed in NIRS. A picture of the RFQ linac is presented in Fig. 2.

For IH-DTL, the APF method was adopted to focus accelerating ions. The method utilizes focusing and defocusing strengths provided with the rf acceleration field by choosing the positive and negative synchronous phases alternately at each gap. By analogy with the principle of strong focusing, both longitudinal and transverse stability of motion would be obtained. Hence, no additional focusing element has to be installed in the cavity making the cavity structure significantly simple. This also indicates that drift tubes can be fabricated smaller and shorter and therefore allowed us to employ higher operating frequency and lower injection energy than ever before with conventional DTLs, such as the Alvarez structure. Although the method has such the attractive features, it has never been practically used since it was first proposed in 50s.

Table 2: Parameters calculated for APF IH-DTL

Parameters	Value	Units
Number of unit cells	72	-
Normalized 90% transverse emittance of the injected beam	0.68	π•mm•mrad
Normalized 90% transverse emittance of the extracted beam	0.86	π•mm•mrad
Normalized 90% longitudinal emittance of the injected beam	1.3	π•ns•keV/u
Normalized 90% longitudinal emittance of the extracted beam	1.6	π•ns•keV/u
Energy spread (ΔE/E)	±0.4	%
Transmission	99.6	%

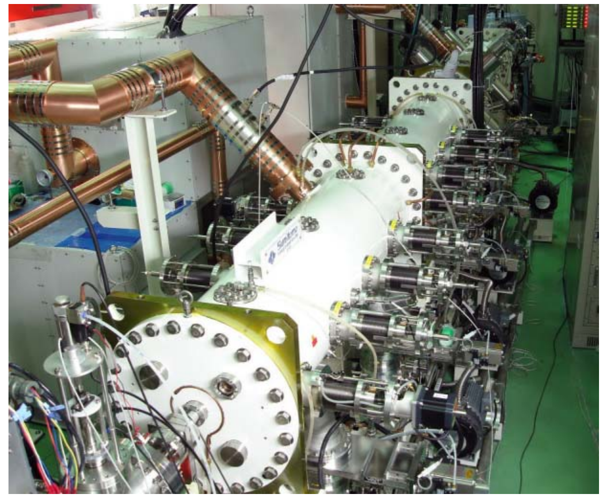

Fig. 3 A picture of APF IH-DTL (a view from the downstream).

Due to the nature of the method, focusing strengths provided by the rf acceleration field are rather weak as compared with these of magnetically focused DTLs. Moreover, beam motion for the APF linac depends strongly on a choice of the alternating synchronous phases, and it is generally difficult to optimize an array of the synchronous phases to obtain sufficient acceptances as well as low emittances of extracted beam.

By using a sinusoidal function to describe the phase array and performing beam dynamics simulations iteratively, we succeeded to optimize the phase array as described in refs. [3,4]. The calculated transmission was reached to as high as 99.6% indicating the sufficient acceptance of this APF structure. Parameters calculated for APF IH-DTL are summarized in Table 2.

The IH structure was used for the cavity of APF IH-DTL. An idea of the IH structure was first proposed in 50s. Although the structure was known to provide better shunt impedance than that of conventional DTLs, IH-DTL has not been used for many decades. A major reason for this is that an electromagnetic (EM) field distribution could not be calculated with existing two-dimensional EM field solvers, because the field distribution in the IH cavity depends strongly on its total structure of the cavity. Therefore, lengthy and costly model studies had been required to determine the final structure of the cavity. With recent development of three-dimensional EM field solvers, it became possible to calculate the EM field in the IH cavity directly. Although these solvers were recently applied to design IH-DTL, accuracy of these solvers was not confirmed. To verify the accuracy of the solver and tuning capability of our inductive tuners, we constructed a full-scale model cavity of APF IH-DTL[4]. Electric field distribution of the model cavity was measured by using the perturbation method and compared with the designed distribution. The result of the comparison indicated that the gap voltages over the model cavity could be controlled with excellent accuracy, while maintaining the desired cavity

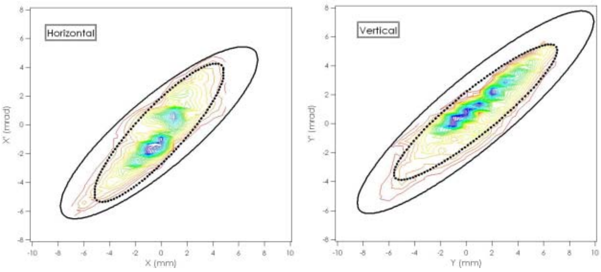

Figure 4: Measured transverse phase-space distributions of carbon ions ($^{12}C^{4+}$) extracted from APF IH-DTL. Solid and dotted curves show results of the 100% and 90% emittance fits.

frequency, once tuning with the inductive tuners has been performed.

Based on the model cavity, the design of the high-power cavity for APF IH-DTL has been developed. The construction of APF IH-DTL and rf amplifiers has completed in February 2006. A picture of APF IH-DTL is shown in Fig. 3. The electric field was measured and tuned with the inductive tuners. After the tuning, most of the gap voltages were tuned to the designed voltages within a few percent of accuracy. The quality factor was measured to be 12,000 corresponding 80% of the calculated value (Q_c=15,000). The required rf power was estimated to be 360 kW assuming 80% of Q_c.

BEAM ACCELERATION TESTS

The RFQ linac was first constructed and installed in conjunction with ECRIS. In prior to installation of APF IH-DTL, beam acceleration tests only with ECRIS and the RFQ linac were performed. Energy and phase space distributions of the extracted carbon beam having the energy of 610 keV/u were measured and compared with those calculated with the PARMTEQ code. As a result, we found the measured distributions were fairly well reproduced with the calculated distributions.

After the beam acceleration tests of the RFQ linac, APF IH-DTL was installed downstream of the RFQ linac. In between the RFQ linac and APF IH-DTL, a magnetic quadrupole triplet was installed for matching of transverse phase space. The total length of the triplet was approximately 38 cm. Matched beam would be injected to APF IH-DTL and finally accelerated up to 4.0 MeV/u.

After commissioning of the entire compact injector system completed in March 2006, an rf power, generated by the three rf amplifiers having maximum output of 500 kW, was delivered to the cavity of APF IH-DTL. After a few days of conditioning, the designed power of 360 kW was successfully fed into the cavity without any problem.

The beam acceleration tests were subsequently performed, and we have succeeded to accelerate carbon ions. Extracted beam was measured with a beam analyzing line located downstream of APF IH-DTL. Beam intensity of $^{12}C^{4+}$ ions extracted from APF IH-DTL was measured to be as high as 390 eμA, which would be twice as much as that required for the treatments.

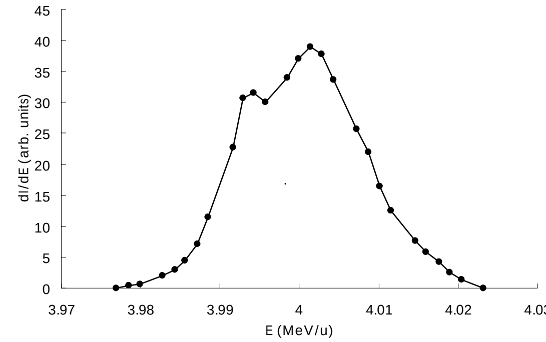

Fig. 5 A measured energy distribution of $^{12}C^{4+}$.

The beam transmission of the entire injector system, including LEBT, the RFQ linac and APF IH-DTL, was reached up to 79%. With the known transmission of LEBT and the RFQ linac, the transmission through APF IH-DTL was estimated to be almost 100%.

Transverse phase-space distributions were measured with a pair of a slit and profile monitor installed in the beam analyzing line. The results were presented in Fig. 4. The distributions were fitted with an elliptical function as shown by the curves in Fig. 4. The normalized 90% emittances for the both coordinates were estimated by the fit to be approximately 1.0 π•mm•mrad, which was slightly higher than the calculated value given in Table 2. The energy distribution of accelerated $^{12}C^{4+}$ ions was measured as shown in Fig. 5. The average energy and spread were roughly E_{ave}=4.0 MeV/u and $\Delta E/E$=±0.4%, respectively, which were reproduced well with those calculated. We note here that these measured parameters would suffice requirements given by our design of the synchrotron ring.

SUMMARY

The compact injector, consisting of ECRIS and two linacs, which are the RFQ and APF IH-DTL, was designed and constructed. The acceleration tests were performed, and we have succeeded to accelerate carbon ions with the APF linac for the first time. The results of the tests further demonstrated its excellent performance.

The total length of the two linacs was reduced to approximately 6 m, which is considerably shorter than that of the existing heavy-ion linacs. With this successful result, the final design and construction of the hospital-based complex have been started.

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