C^{6+} ION HYBRID SINGLE CAVITY LINAC WITH DIRECT PLASMA INJECTION SCHEME FOR CANCER THERAPY

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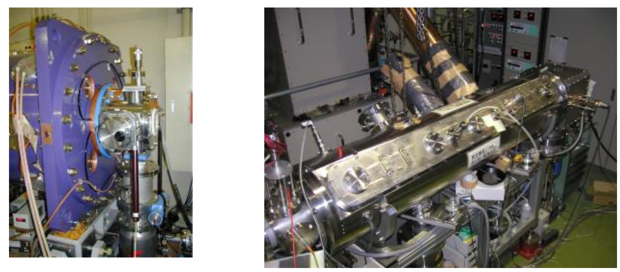
Abstract

We succeeded to accelerate more than 18mA of C^{6+} ions with Direct Plasma Injection Scheme (DPIS) of YAG laser in 2004. We believe that these techniques are quite effective for pulse accelerator complexes (linac and synchrotron) such as heavy ion cancer therapy. We study a new hybrid single cavity C^{6+} linac for heavy ion cancer therapy. This hybrid linac, combined with radio frequency quadrupole (4rod-RFQ) electrodes and drift tube electrodes into a single cavity, is able to downsize the linac system and reduce the peripheral device. High intensity beam of C^{6+} by DPIS have many advantage for the synchrotron of heavy ion cancer therapy. We will present the design procedures of this hybrid linac, which is base on a three-dimensional electromagnetic field simulation.

INTRODUCTION

In order to verify DPIS, accelerator test was carried out using Tokyo Institute of Technology (Titech) RFQ heavy ion linear accelerator and CO_2 laser heavy-ion source in 2001. The accelerated carbon beam obtained 9.2mA of C^{4+} was much higher than designed currents. [1-4] To confirm the capability of the DPIS, we designed and fabricated a new RFQ linac to accommodate 100mA of carbon beam collaboration The Institute of Physical and Chemical Research and Frankfurt University. We succeeded to accelerate very intense carbon ions with the DPIS in 2004. The peak current reached more than 60mA of C^{4+} and 18mA of C^{6+} by CO2 and YAG laser, respectively [5-9]. Fig. 1 shows photographs of Titech RFQ linac and 100 mA Test RFQ linac. We believe that these techniques are quite effective for pulse accelerator complexes such as linear accelerator and synchrotron. The accelerator complexes are heavy ion cancer therapy and heavy ion inertial fusion.

We are studying a new hybrid single cavity linac [10] for Boron Neutron Capture Therapy. This hybrid linac, combined with radio frequency quadrupole electrodes and drift tube electrodes into an interdigital-H (IH) type single cavity, is able to downsize the linac system and reduce the peripheral device. From these matters, we propose a small Hybrid Single Cavity (HSC) linac for injector of heavy ion cancer therapy.



Titech RFQ linac 100 mA Test RFQ linac

Figure 1: Titech RFQ linac in 2001 and 100 mA Test RFQ linac in 2004 succeeded to accelerate high intensity beam by DPIS.

ND-YAG LASE ION SOURCE

A Nd-YAG laser with a wavelength of 1060nm is used for this ion source. The pulse duration is 15ns(FWHM) and its energy is 400mJ. Fig.2 shows charge state distribution of Carbon ion with about 400mJ. Fig.3 shows laser power dependence of charge state distribution of Carbon ion. From these data, C^{6+} ions were produced 40%. C^{6+} ion beam have pulse width of about 2 μ s and about 200mA at injection point of 4 rod of RFQ.

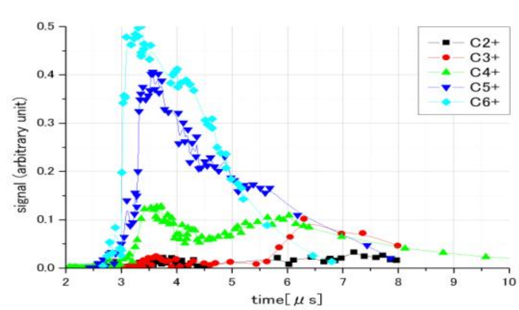


Figure 2: Charge state distribution of the Carbon ion with about 400mJ of YAG laser.

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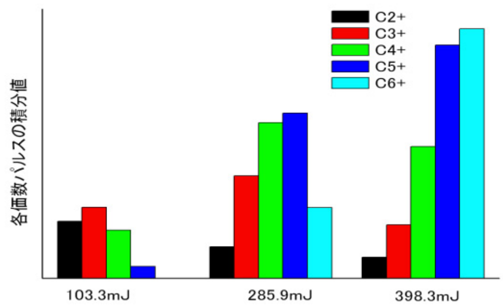

Figure 3: Laser power dependence of the charge state distribution of Carbon ion.

DESIGN AND PARAMETERS

The accelerated particles are set to C^{6+} more than 10 mA (more than $2x10^{10}$ particles/pulse) with YAG laser ion source. The operation frequency in this linac is 80 MHz. The HSC linac accelerate from 25keV/amu up to 2MeV/amu, see Table 1.

Table 1: Main parameters of C^{6+} HSC Linac.

	RFQ	BTL	DT
Accelerate particle		C^{6+}	
Input energy (keV/u)	25	160	160
Output energy(keV/u)	160	160	2000
Cavity diameters(cm)	40	80	80
Cavity length (cm)	104	35	134
Cavity total length(cm)		273	
Operation power (kW)		lower 80	
Beam bore radius(mm)	5	12	7
Cell number	160	(10)	15
Beam focusing	RFQ	TQM	APF
Beam current		10 mA	

The computer code RFQUICK was used to generate the cell parameters for the PARMTEQM calculation [11]. The computer code PARMTEQM was used to simulate the beam dynamics in the RFQ section. Drift tube structure section was calculated by computer code PARMIRA. Beam maching of RFQ and Dorift tube section were calculated by computer code Trace-3D.

The 3D electromagnetic simulation software MW-Studio [12] was used to calculate the resonance frequency, the electric field, the Q value and the wall loss of the cavity.

DESIGN AND CAVITY SIMULATION

The electric field distribution of the HSC(IH) cavity must be constant through out the beam line. However the electric field of the inner IH cavity is increased towards the beam injection side. Because, capacitances of the RFQ section are larger than that of DT section. To adjust this unequal field distribution, we improved the IH cavity geometry. First, in order to modify the cavity diameter at the DT section, the field distribution was spread along the beam output side. Secondly, as the End Ridge Tuner (ERT) length was adjusted, the cavity was made to adopt a constant resonance frequency along the cavity. The electric-field strength was investigated by means of field simulations. Adjustments of realizing cavity at the ERT length were performed. Fig.4 shows modified cavity diameter and End Ridge Tuner.

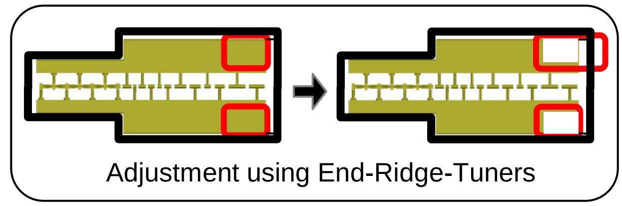

Figure 4: Modified cavity diameter and End Ridge Tuner.

The more the diameter of DT section was increased, the more the frequency of both sides were approached, and electric field was excited from input side to output side when inside diameter was 80-90cm. We calculated the electric field distribution from 280 to 360mm at 20mm intervals of ERT at the exit of the cavity. The optimum electric-field distribution was obtained with ERT length of 320mm as shown in Fig.5,6,7.

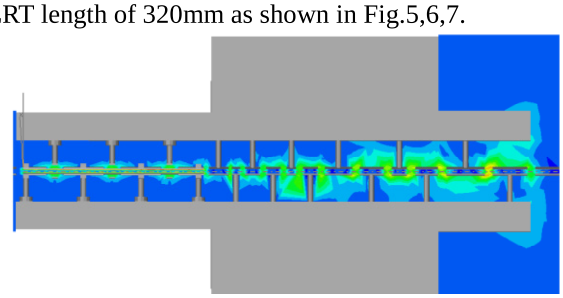

Figure 5: C^{6+} HSC linac cross section and electric field.

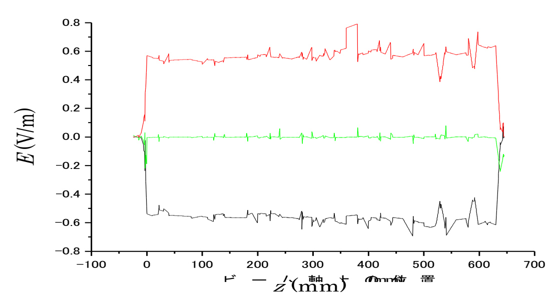

Figure 6: Electric-field distribution of RFQ section.

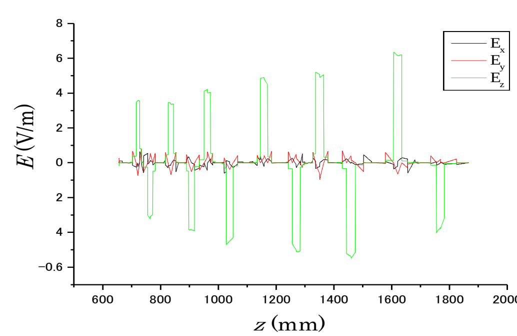

Figure 7: Electric-field distribution of DT section.

ELECTRIC-FIELD BETWEEN RFQ AND DT SECTION

In the HSC linac, electric-field distribution in the gap region between the back-end of the 4-rod(RFQ) and injection side of DT region must be considered as shown in Fig.8-A. This electric-field have a negative effect on the acceleration beam as shown in Fig.9-A. We studied an improved electrode of drift-tube shape in which three quadrupole magnets, was inserted into this gap as shown in Fig.8-B. The electrode was able to reduce the excitation of the electric-field at the gap between 4 rods and drift tube as shown in Fig.9-B.

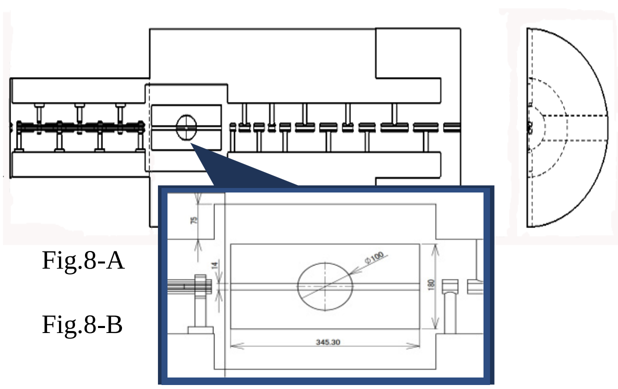

Fig.8-A

Fig.8-B

Figure 8: C^{6+} HSC linac cavity cross section (A) and inserted electrode (B).

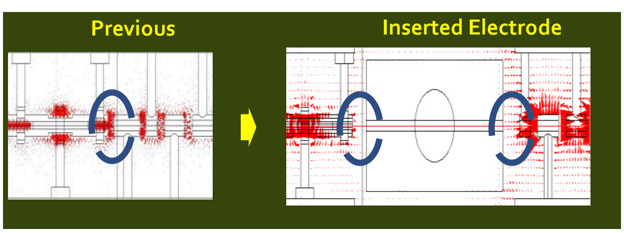

Fig.9-A Fig.9-B

Figure 9: Excited electric-field at the gap between 4 rods and drift tube. A: Previous; B: Inserted Electrode.

HEAVY ION SYNCHROTRON OF CANCER THERAPY

DPIS techniques are quite effective for pulse accelerator complexes (linac and synchrotron) such as heavy ion cancer therapy. High intensity beam of C^{6+} by DPIS have many advantage for synchrotron.

A) Effects of C^{6+} ion injection

1.Striper foil system is not necessary by C^{6+} ion injection. 2.Emittance growth is decrease by decrease of energy loss and energy straggling. 3.Injection energy of synchrotron is decrease to 2-3 MeV/u by no decrease of ions. 4.Operation of synchrotron is easy with no change of energy that is happened by decrease of stripper foil thickness.

B) Effects of one turn by injection of high intensity C^{6+}

1. Mulch turns injection system is not necessary by more than 10^9 ions of C^{6+}. 2. Magnets (bending magnet, quadrupole magnet and sextapole magnet) of synchrotron are compacted by small size beam of one turn injection.

The heavy ion synchrotron is compact and use low electric power. Therefore facility of heavy ion cancer therapy will be able to smaller than present size.

CONCLUSION

We study a new hybrid single cavity (HSC) C^{6+} linac with DPIS for heavy ion cancer therapy. This HSC linac accelerate C^{6+} ion from 25keV/amu up to 2MeV/amu.

Electromagnetic simulation of the cavity was done by MW-Studio. Acceleration cavity is 40cm (RFQ section) and 80cm (DT section) in diameter and 273cm in length. The operation frequency is 80MHz. Acceleration current is 10mA of C^{6+} ($2x10^{10}$particles/pulse). For this beam intensity of C^{6+}, The heavy ion synchrotron is compact and use low electric power. Therefore facility of heavy ion cancer therapy will be able to smaller than present size.

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