DESIGN OF INJECTOR FOR CARBON CANCER THERAPY

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Abstract
An injector consisting of a Radio Frequency Quadrupole (RFQ) and Drift Tube Linacs (DTLs) was designed for cancer therapy systems. The extraction energy of the RFQ was 0.6 MeV/u, the extraction energy of the DTLs was 6 MeV/u, and the frequency was 200 MHz. To employ a compact solid-state power amplifier system, we designed one high-Q RFQ and three high-Q DTLs, with triplet quadrupole magnets between the DTLs.

INTRODUCTION

A number of carbon cancer therapy facilities have been planned for construction around the world. Some of them need a multi-ion irradiation system. In carbon cancer therapy facilities constructed in Japan, carbon ions are accelerated by an injector and a synchrotron. The injector consists of an Electron-Cyclotron-Resonance (ECR) ion source, a Radio Frequency Quadrupole (RFQ), and an Interdigital H-mode (IH-mode) Drift Tube Linac (DTL) employing the Alternating-Phase-Focused (APF) method [1-3]. C4+ ions from the ECR ion source are accelerated up to 4 MeV/u by the RFQ and the IH-DTL, and are converted to C6+ ions by a carbon foil stripper after the IH-DTL. The charge-to-mass ratio of the linac in those systems is 1/3.

The injector system was designed for not only C4+ ions but also multi-ions from He to Ar. In this system we could accelerate the ions of charge-to-mass ratio of higher than 1/3, and the operating frequency was 200 MHz. The ions were accelerated to 4 MeV/u for general carbon cancer therapy by the RFQ and two DTLs, and to 6MeV/u by an additional DTL for multi-ion irradiation. Triplet quadrupole magnets were employed between RFQ and DTL's tanks for transverse focussing of the ion beam. To apply the solid-state amplifiers, the RF power of the tanks was designed below 200 kW and the high-Q machining process was applied.

INJECTOR SYSTEM

Figure 1 shows the 6 MeV/u linac system which consists of the RFQ and three DTLs, without the ECR ion source and a low energy beam transport line. Triplet quadrupole magnets are employed between linac tanks to focus the ion beam. The carbon foil stripper is provided after the DTL3. The charge-to-mass ratios of the DTLs are 1/3, and the operating frequency is 200 MHz. Solid-state amplifiers are employed in the RF power sources for the RFQ and the DTLs to reduce maintenance costs. We used a solid-state amplifier developed for an R&D program in Yamagata University, shown in Figure 2. The RF power is 150 kW, and this can be increased to 200 kW. It showed stable operation in tests involving beam acceleration for a C6+ RFQ [4, 5].

Figure 2: Solid-state amplifier developed for R&D program in Yamagata University.

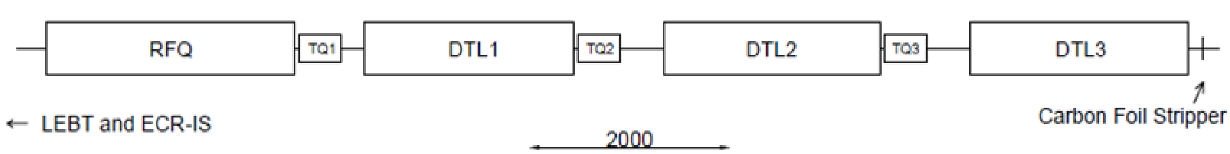

Figure 1: Layout of RFQ and DTLs.

shaving process is applied to the tank with the electrode. Figure 3 shows the structure and parts of the RFQ which was used in a Yamagata University R&D program in 2014. The three parts are combined using O rings and RF contacts. This structure has a number of advantages; for example, a copper plating process is unnecessary, and the assembly process is simple and short. In addition, the Q-value of the tanks is high because the contact parts are reduced. The measured unloaded Q-value of the RFQ for the R&D program in Yamagata University was above 90% of calculated unloaded Q-value.

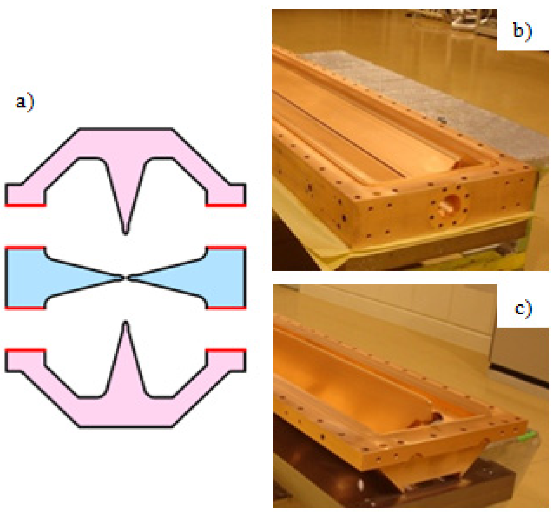

Figure 3: Structure and parts of the RFQ. a) Structure of tank and electrode. b) Center part with two electrodes. c) Upper and lower parts with one electrode.

RFQ DESIGN

The RFQ for C4+ was designed using parmteqm. The tank length was similar to those of RFQs installed in Japanese cancer therapy facilities. Figure 4 shows a beam simulation. The transmission was 94.3 %.

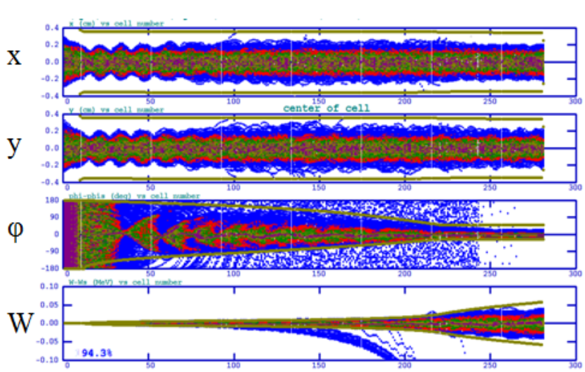

Figure 4: RFQ beam simulation.

The main parameters of the RFQ are summarized in Table 1. The duty and the structure of tanks applied the same value and scheme as the C6+ RFQ for the R&D program in Yamagata University, and the maximum surface field was below 1.77 kilp. of the C6+ RFQ. The minimum bore radius was 2.5 mm, to allow for easy beam commissioning. The RF power was estimated to be 92 kW, allowing the 150 kW solid-state amplifiers to be employed.

Table 1: Main Parameters of RFQ.

Parameter	Value	Unit
Injection energy	10	keV/u
Extraction energy	606	keV/u
Tank length	2464	mm
Number of cells	281	
Focusing power	4.6	
Synchronous phase	-25	degrees
Average bore radius	3.6	mm
Minimum bore radius	2.5	mm
Vane voltage	72.	kV
Maximum surface field	1.73	kilp.
Normalized acceptance	~1.0	π mmmrad
Transmission	94.3	%
Calculated Q	13800	
RF power (Q100%)	92	kW
Duty	0.4	%

DTL DESIGN

The DTL section consisted of two DTLs for accelerating the ions from 0.6 to 4 MeV/u, and an additional DTL for accelerating the ions to 6 MeV/u. To achieve a compact design, the DTLs employed the IH-mode. In order to apply the solid-state amplifiers, the RF power of each tank was designed below 200 kW. The goal of the transmission of all DTLs was above 90 %.

The injection energy of DTL1 was too low to go through the tank without transverse focusing. The transverse focusing of DTL1 employed the APF method. Since the energies of DTL2 and DTL3 were sufficient for going through the tanks, the synchronous phase was fixed at -10 degrees, and the transverse focussing effect was applied by the triplet quadrupole magnets between the tanks. The DTLs were optimized by RF simulation using CST Microwave Studio, and beam tracking was optimized using the General Particle Tracer.

The main parameters of the DTLs are listed in Table 2. The tank length of all DTLs was below 2200 mm. The inner radius of the tube was 8 mm, in order to apply the shaving process of the center part with the tube. The duty and the maximum surface field applied the same value as the compact APF IH-DTL of NIRS. The tanks have 3 parts, which consist of a center, a left and a right part like the C6+ RFQ. The center part has the tubes, stems and ridges.

A plot of the synchronous phase vs. the gap number of DTL1 is shown in Figure 4. The longitudinal focusing effect was applied by negative phase sections, and the transverse focussing effect was applied by positive phase sections. The ion beam was transported to repeatedly pass

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Table 2: Main Parameters of DTLs

Parameter	DTL 1	DTL 2	DTL 3	Unit
Extraction energy	2	4	6	MeV/u
Frequency	200	200	200	MHz
Tank length	2100	2150	2200	mm
Number of gap	30	34	27	
Synchronous phase	alternative	-10	-10	degrees
Tube innner radius	8	8	8	mm
Maximum surface field	1.6	1.6	1.6	kilp.
Transmission	87	96	98	%
RF power (goal)	< 200	< 200	< 200	kW
Duty	0.4	0.4	0.4	%

through negative and positive phase section. The amplitude of the phase shift was 60 degrees. We are optimizing the phases to increase the transmission.

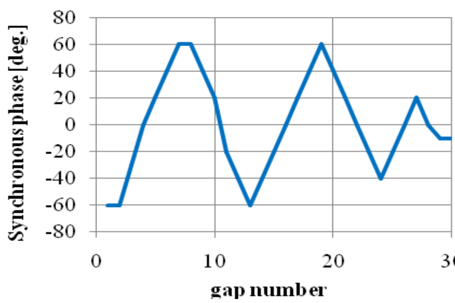

Figure 5: Synchronous phase of DTL1.

The beam simulation of DTL3 is shown in Figure 6. The energy spread was estimated to be within ±0.4 % at a transmission of 98%.

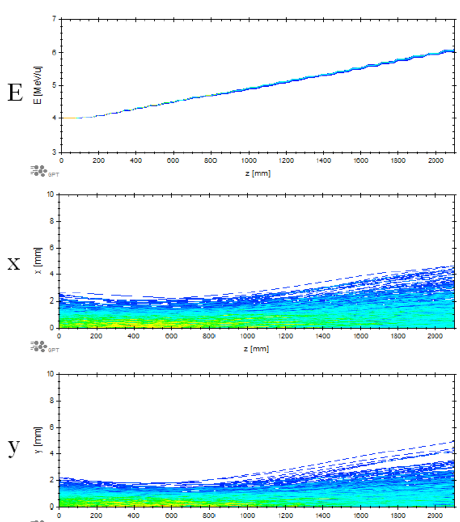

Figure 6: Beam simulation of DTL3.

CONCLUSION

We designed the injector system for not only C4+ ions but also multi-ions from He to Ar. The designed 6 MeV/u linac system consisted of an ECR ion source, a low energy beam transport line, an RFQ, and three DTLs. The three DTLs employed the IH-mode, and DTL1 had a transverse focusing effect using the APF method. Solid-state amplifiers were employed in the RFQ and the DTLs to reduce maintenance costs. The machining process of the RFQ and the DTLs used a shaving process of the tank with the electrode, to achieve a simple assembly process and a high Q-value. We are optimizing the 3D design and the beam tracking.

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REFERENCES

[1] Y. Iwata et al., "Performance of a compact injector for heavy-ion medical accelerators", *Nucl. Instr. Meth., A*, vol. 572, pp. 1007-1021, 2007.

[2] Y. Iwata et al., "IH-DTL as a compact injector for a heavy-ion medical synchrotron", in *Proc. LINAC 08*, Victoria, BC, Canada, 2008, paper WE204.

[3] Y. Iwata et al., "The compact injector as the second injector of the HIMAC", in *Proc. LINAC10*, Tsukuba, Japan, 2010, paper MOP060.

[4] K. Sako, et al., "Development of C6+ laser ion source and RFQ linac for carbon ion radiotherapy" in *Proc. ICIS15*, New York, USA, 2015, paper MonPE34.

[5] K. Sako, et al., "Beam acceleration test of C6+ ion source and RFQ linac for carbon ion radiotherapy" in *Proc. PASJ2016*, Chiba, Japan, 2016, paper WEOL02.