CONCEPTUAL DESIGN OF A COMPACT 425 MHz INJECTOR FOR HELIUM THERAPY FACILITY

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Abstract

A new 425 MHz injector has been designed for proton and helium therapy facility. The LINAC consisted of a 3.0 m length RFQ and a 2.8 m length IH-DTL, which was designed to accelerate p^+ and He^{2+} beams to 8 MeV/u. The beam dynamics of the linac were designed based on comprehensive 3D electromagnetic field simulations, followed by particle tracking to optimize beam quality and transmission efficiency. Multi-physics analysis investigated thermal effects on cavity resonant frequencies.

INTRODUCTION

In recent years, the physical advantages of helium ions in particle therapy have garnered increasing attention. SARI has proposed a helium ion therapy facility based on a synchrotron [1], and its injector is currently under development. Figure 1 shows the layout of the injector, which consists of an ion source system, an RFQ, and a DTL. Determined based on synchrotron injection requirements, the injector is capable of accelerating 5 mA proton beam and 2 mA He^{2+} beam to 8 MeV/u, with an energy spread of less than 0.3%.

Given the low beam intensity and duty cycle in this application scenario, greater emphasis is placed on cost-effectiveness and reliability. Consequently, the design optimization prioritizes miniaturization while aiming to maintain high transmission efficiency. For ions with $q/A = 1/2$, an operating frequency of 425 MHz has been selected for the injector. The beam dynamics design, RF structure design, and multiphysics thermal analysis of the injector have been completed.

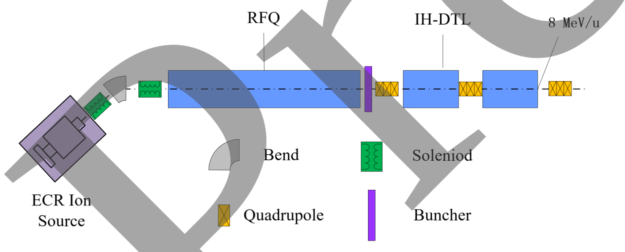

Figure 1: Layout of the injector.

BEAM DYNAMICS

The RFQ is designed to capture the beam from the ion source and provide initial acceleration. Since the RFQ has a lower acceleration efficiency compared to the DTL, transitioning the beam into the DTL earlier helps to improve the overall acceleration gradient of the injector. However, considering that the DTL cells cannot be made too small due to machining constraints, the exit energy of the RFQ is set to 1.6 MeV/u.

RFQ

Beam dynamics optimization was performed specifically for the higher operating frequency of 425 MHz. To improve the beam capture rate, a more gradual variation of the modulation factor is adopted at the RFQ entrance. The beam emittance requirement at the entrance is set to 0.15 mm·mrad to accommodate the smaller beam aperture. Additionally, the acceleration phase in the final section is increased to achieve higher acceleration efficiency. Figure 2(a) presents the simulation results by RFQgen code [2], Fig. 2(b) presents the phase space at RFQ output, showing that the RFQ can accelerate the beam to 1.6 MeV/u within a length of 3 meters, with a transmission efficiency of 94%.

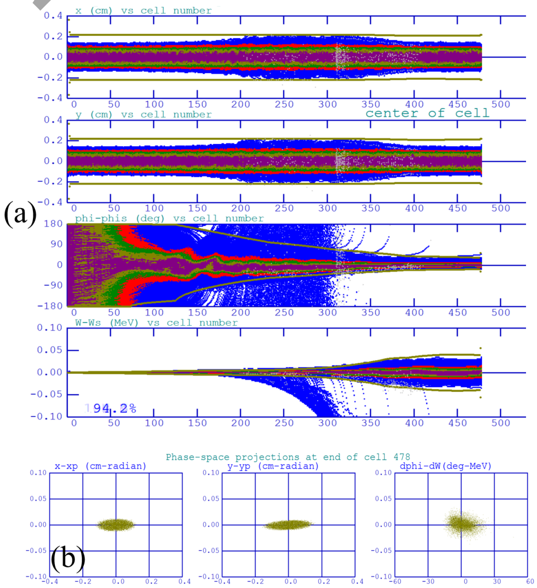

Figure 2: RFQ beam dynamics design.

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IH-DTL

A buncher and a quadrupole triplet are placed between the RFQ and the IH-DTL. The IH-DTL consists of two tanks, with the beam dynamics optimized based on the KONUS method [3]. A lower bunching phase is adopted to ensure transmission efficiency. Additionally, the rate at which the beam falls into the negative phase is reduced to minimize transverse beam divergence.

Figure 3 presents the beam tracking simulation results calculated with the TraceWin code [4], incorporating the 3D electromagnetic field distribution. Here, (a) shows the beam envelope, (b) displays the beam energy distribution along the z-axis, and (c) illustrates the beam phase space at the IH-DTL exit. The transmission efficiency of the IH-DTL is 98.7%.

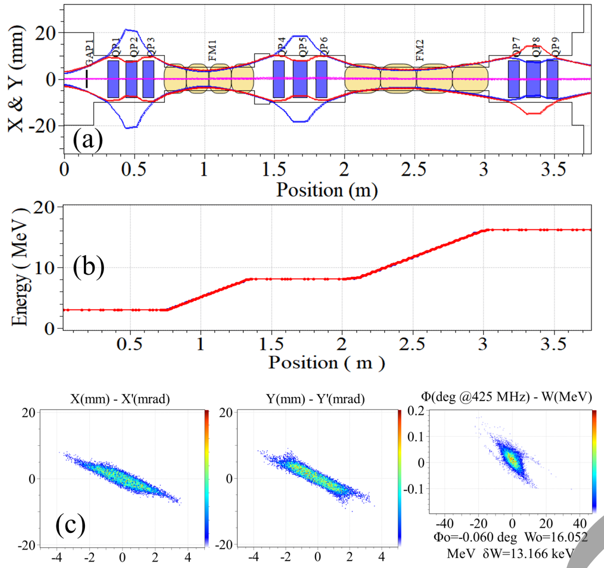

Figure 3: IH-DTL beam dynamics design.

Table 1 summarizes the main parameters of the injector.

Table 1: Main Parameters Of the Injector

Parameters	**Value**
Operating Frequency	425 MHz
q/A	1/2
Output Energy	8.03 MeV/u
Energy Spread	0.184 %
Emittance	0.16 pi·mm·mrad
Duty Cycle	0.2 %
Transmission	92.9%

The total length from the RFQ entrance to the IH-DTL exit is 6.1 m. The output beam energy is 8.03 MeV/u, the emittance is 0.16 pi·mm·mrad, the energy spread is 0.184%, and the total transmission efficiency is 92.9%, all of which meet the injection requirements of the synchrotron.

RF DESIGN

RF simulations were performed using CST Microwave Studio, where the modeling and 3D electromagnetic field calculations for the RFQ and the two IH-DTL tanks were completed. RFQ cavity is 4-vane type, Fig. 4(a) shows the 3D model of the cavity. By optimizing the undercut, the magnetic field distribution along the z-axis shown in Fig. 4(b) was obtained. Additionally, a smoother cross-sectional shape was designed to achieve a higher quality factor (Q) and thereby reduce the peak power. Table 2 lists the RF parameters of the RFQ: the inter-vane voltage is 60.5 kV, the Kilpatrick factor (Kp) is 1.85, and the peak power is approximately 185 kW.

Benefiting from the smaller input emittance and the higher operating frequency, the IH-DTL is designed with a smaller beam aperture and a higher acceleration gradient, which contributes to achieving a higher shunt impedance. Figure 5(a) presents the 3D models of the two IH-DTL tanks, and Fig. 5(b) shows the accelerating electric field distribution along the z-axis for both cavities. Table 3 summarizes

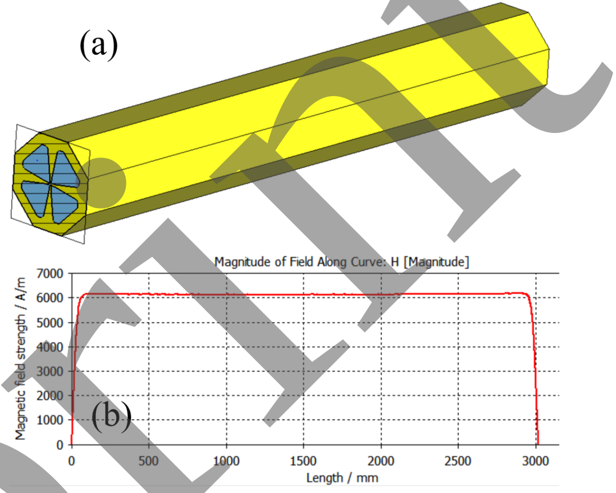

Figure 4: RF design of the RFQ.

Table 2: RF Parameters Of the RFQ Cavity

Parameters	**Value**
Operating Frequency	425 MHz
Length	3019.3 mm
Vane Voltage	60.5 kV
Average Aperture	2.18 mm
Kp	1.85
Q	9581
Peak Power Loss	185 kW

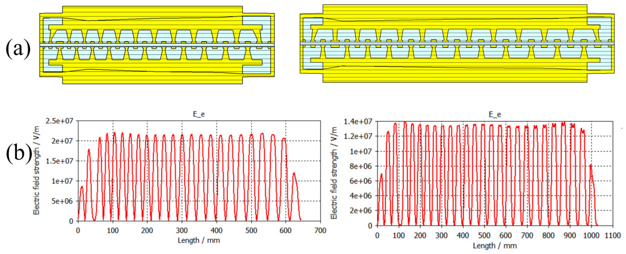

Figure 5: RF design of the IH-DTL.

Table 3: RF Parameters Of the IH-DTL Cavities

Parameters	**TANK-1**	**TANK-2**
Operating Frequency	425 MHz	
Length	643.8 mm	1027.6 mm
Gap Number	24	26
Drift Tube Aperture	10 mm	
Max. z-axis E-field	18.8 MV/m	18.7 MV/m
Q	10767	12289
Peak Power Loss	180 kW	392 kW
Effective shunt impedance	215 MΩ/m	154 MΩ/m

the RF parameters of the IH-DTL. The maximum accelerating electric field at the center of the drift tubes is 18.8 MV/m. The peak power losses are 180 kW and 392 kW, respectively, and the effective shunt impedances are 215 MΩ/m and 154 MΩ/m, respectively.

MULTI-PHYSICS ANALYSIS

The preliminary water cooling schemes for all cavities were designed, and electromagnetic-thermal-structural simulations were performed using COMSOL Multiphysics to analyze the impact of RF power on the resonant frequency of the cavities. Figure 6(a) shows the temperature distribution of the RFQ cavity at a 1% duty cycle, with a maximum temperature rise of 1 °C and a frequency shift of 1 kHz.

Figure 6(b) presents the temperature distribution of IH-DTL Tank 1 at a 0.2% duty cycle, where the maximum temperature rise is 2 K and the frequency shift is 13 kHz. Figure 6(c) illustrates the temperature distribution of IH-DTL Tank 2 at a 0.2% duty cycle, with a maximum temperature rise of 3 K and a frequency shift of 16 kHz. The simulations indicate that the temperature rise and frequency shift for all cavities are within acceptable ranges.

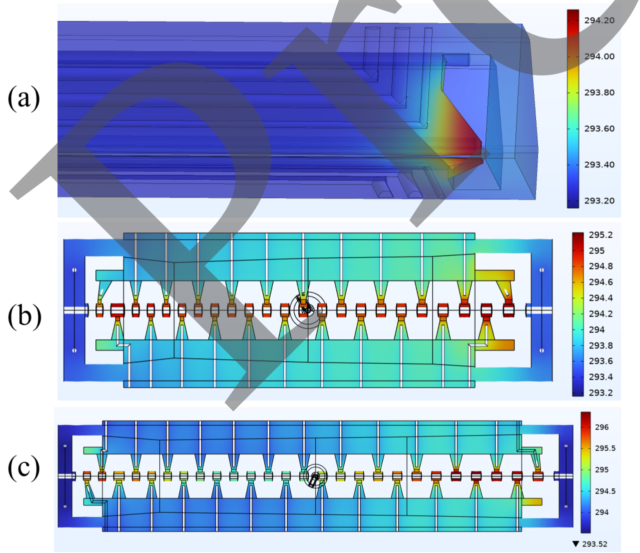

Figure 6: Temperature distribution of RF Cavities.

CONCLUSION

In conclusion, a compact 425 MHz injector for particle therapy has been successfully designed and optimized. The LINAC, comprising a 3-meter RFQ and a 2.8-meter IH-DTL, achieves an output energy of 8.03 MeV/u with a transmission efficiency of 92.9%. Multi-physics analyses confirm the thermal stability of the cavities under operational duty cycles. The mechanical design of each cavity is in progress.

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