NEW TYPE OF INJECTOR FOR CANCER THERAPY

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Abstract. We performed a compact design for a 100 MHz Hybrid Single Cavity (HSC) for an injector of cancer therapy. The proposed designs are conventional four-rod structure and Drift Tube Linac (DTL) in a single Inter-digital H-mode (IH) cavity. This compact linac injector, running at frequency of 100 MHz, accelerates C\textsuperscript{6+} beams with 20 mA from 0.02 MeV/u up to 4 MeV/u. The total length of HSC is designed to be less than 4 meters.

1. Introduction

Compared with traditional structures, firstly, the HSC model consists of RFQ structure and DT structure without MEBT. Secondly, the IH structure provides the higher shunt impedance and acceleration gradient. In the structure, the E-field is focused in the connection parts of 4-rod and first DT.

For DTL section, the section adopts the Alternative Phase Focus (APF). DTL adopts the Alternative Phase Focus (APF) to achieve three-dimensional focusing without the installation of quadrupole lenses into the drift tubes.

Furthermore, traditional structures have complex control systems and huge injectors. Compared with traditional types, HSC adopts Direct Plasma Injection Scheme (DPIS). The DPIS could easily create enough C\textsuperscript{6+} ions to the linac by adjusting the distance from target to laser.

2. Beam dynamics

In this part, the beam dynamics was divided into 3 sections, RFQ section, DTL section, and HSC section [1, 2]. The RFQ section accelerates the C\textsuperscript{6+} with 20 mA from 0.02 MeV/u up to 0.6 MeV/u. The DTL section accelerates C\textsuperscript{6+} from 0.6 MeV/u up to 4 MeV/u. The RFQ section was designed using RFQGen code, whereas DTL and HSC using PIMLOC, as described in the following.

3. RFQ Section and DTL Section

The RFQ section is divided into 4 sections: radial matching section (RMS), shaper section (SH), gentle buncher section (GB), and accelerator section (ACC) [3]. The length of IH-RFQ is 1 m.

\textsuperscript{1} Work supported by the NSFC under Grant No. 11475232 and No. 11535016.
The original main parameters are given in Fig. 1.

![Figure 1](image1.png)

**Figure 1.** The original parameters in RFQ section.

We want the length to be as short as possible, meanwhile ensuring the acceptable transmission and beam quality. To achieve this aim and realize an efficient bunching, we adopt some basic ideas, as follows: Firstly, we must vary the transverse focusing strength $B$ along the beam direction because of the corresponding space-charge conditions at different positions. Traditionally, the transverse $B$ should be increasing with the space-charge force until the transverse defocusing force is weakened. After that it should go down. Secondly, the evolution speeds of the synchronous phase and the modulation parameters can also improve the bunching process.

Following this important conditions, we could get the optimized parameters, shown in Fig. 2.

![Figure 2](image2.png)

**Figure 2.** The optimized parameters in RFQ section.

Figure 3 gives the transmission efficiency, which is almost over 95%, at last cell. Moreover, we can’t ignore the beam losses, both longitudinal and transverse losses. In order to reduce the beam losses, increasing the longitudinal acceptability in the first several cells is an effective way. As shown in Fig. 4, beam loss have been significantly reduced after optimization.
The main parameters of RFQ and the final parameters are summarized in Table 3. The output of RFQ section is adopted convergent design for following DT injection, shown in Table 3.

The DTL section works according to the Phase Focus (APF) principle. Drift tube linac (DTL) with APF is a compact version compared with traditional DTLs. It can achieve three-dimensional focusing without the installation of the quadrupole lenses into the drift tube. It means that inter-gap RF field is used to achieve not only acceleration but also beam focusing in APF DTL [4, 5, 6]. On the one hand, if the synchronous phase is greater than 0 degree, it will mainly offer transverse focusing, which is higher than longitudinal focusing. On the contrary, it mainly offers longitudinal focusing. But, we can’t deny the fact that it is small longitudinal acceptance in DTL. So, the number and value of negative phase must be increased in the first several gaps. Fig. 5 gives the phase in each gap.

The voltage in each gap and the length of each gap are shown in Fig. 6. When we change the gap length and coefficient, the length of DT is changed subsequently. To insure the minimum
Table 1. Design Parameters of the RFQ Section.

| Parameters       | Value                      |
|------------------|----------------------------|
| Inter-vane voltage | 85 (kV)                   |
| Vane length      | 1050 (m)                   |
| Synchronous phase | $-90^\circ$ to $-30^\circ$ |
| Modulation factor | 1 to 2.1                  |
| Transmission efficiency | 95.2 %                 |
| Ellipse parameters |                           |
| $(\alpha_x, \alpha_y)$ | 1.8456, $-1.3395$      |
| $(\beta_x, \beta_y)$ | 18.0319, 13.0393 (cm/rad) |
| $(\text{Emit}, \text{u}, \text{rms } x, y)$ | (cm-mrad) |
| $(\text{Emit}, \text{u}, \text{rms } z)$ | (MeV-deg) |

Table 2. The Input Parameters of DTL.

| Parameters       | Value                      |
|------------------|----------------------------|
| Ellipse parameters |                           |
| $(\alpha_x, \alpha_y)$ | 1.8456, $-1.3395$      |
| $(\beta_x, \beta_y)$ | 18.0319, 13.0393 (cm/rad)   |
| $(\text{Emit}, \text{u}, \text{rms } x, y)$ | (cm-mrad) |
| $(\text{Emit}, \text{u}, \text{rms } z)$ | (MeV-deg) |
| $\Delta w$      | 0.03 (MeV)                 |
| $\Delta p$      | 30 (Deg)                   |

The number of simulated particles is 10000. After setting the basic parameters in PIMLOC and tracing the particles, we could get the results of simulations, shown in Table 3, which satisfies the whole design requirements.

Table 3. The Parameters in DTL.

| Parameters     | Value                      |
|----------------|----------------------------|
| Voltage        | 199.2 kV                   |
| Cell number    | 24                         |
| Length         | 1853 mm                    |
| Bore radius    | 13 mm                      |
| DT radius      | 30 mm                      |
| Minimum length of DT | 13 mm                   |

The minimum length of DT is over 1 cm, which satisfies engineering requirements. The output at the end is given in Fig. 7. Transmission efficiency is over 90%.
4. HSC Section

The parameters of HSC were determined by output parameters of RFQ and DTL sections. But the distance between the exit of RFQ section and the first DT (L-RFQ-DT) is extremely important for the transmission efficiency, which changed along the distance. In our research, the highest transmission efficiency occurred between 30 mm and 60 mm.

Moreover, the length of ion source to RFQ section (L-IS) is also an important factor. The injection phase is related to the two factors, L-RFQ-DT, L-IS. So, the appropriate length is vital for the whole HSC.

The output of HSC, shown in Fig. 8, satisfies the design aims. The transmission efficiency is over 80%.

After optimizing the main parameters of HSC, the final parameters are summarized in Table 4.
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Figure 7. The output at the last gap.

Figure 8. The results of HSC.

Table 4. The Final Parameters in HSC.

| Parameters | Value |
|------------|-------|
| L-IS       | 10 (mm) |
| L-RFQ-DT   | 59 (mm) |
| L-Pure-Q   | 30 (mm) |

5. Summary and future plan

We have studied a new HSC type linac which is a practical and efficient machine to accelerate high intense ion beams. We discussed the E matching designs for reducing the concentrated electric field distribution.

In the next step, we will optimize multi-physical fields of HSC using Ansys.
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