DESIGN OF A COMPACT 8-MeV PROTON LINAC FOR MEDICAL APPLICATION

Yixing Lu, Yusen Guo, Ping Wang†, Xiaoxia Huang, Ruichuang Qin, Yifan Lan, Cheng Wang, Wencheng Fang‡, Zhentang Zhao
Shanghai Synchrotron Radiation Facility, Shanghai, China

Abstract

The compact accelerator is a great trend in accelerator field, which is able to reduce the scale of the facilities based on accelerators, and meanwhile is attractive to medical devices. A compact 8-MeV proton linac was designed, aiming for medical applications like proton therapy. The linac operates at 714 MHz, comprising an electron-cyclotron-resonance ion source (ECRIS), a radio frequency quadrupole (RFQ), a matching section and an interdigital H-mode drift tube linac (IH-DTL). A 35-keV proton beam with the peak current of 6 mA was injected from the ECRIS into the RFQ. A new beam dynamics design of the RFQ ensures the high transmission of the linac, which is over 59%. The linac has the potential of being more compact because the flexible design of the matching section. The manufacturing of the linac is ongoing, which is proposed to complete by the end of this month. The commissioning of the linac is planned to operate in the near future.

INTRODUCTION

Shanghai Synchrotron Radiation Facility (SSRF) has been dedicated to researches on and development of proton therapy technology for more than ten years. The compact proton therapy accelerator [1], proton computer tomography [2-3] and ultra-high dose rate radiotherapy (FLASH-RT) [4], are undergoing research at SSRF for future advanced proton therapy. As a fundamental component of these facilities, a well-performed proton linac is essential to provide a high-quality proton beam. A compact proton linac was proposed to satisfy both demands of high-quality beam and compactness from medical facilities, which should be able to supply beams with a peak current of over 3-mA in order to support proton synchrotrons.

The compact linac consists of an ECRIS, a low-energy beam transport (LEBT), an RFQ, a matching section and an IH-DTL mainly, as shown in Figure 1. A new beam dynamics design was introduced to the RFQ, which ensures the high transmission of the linac. The matching section includes three electromagnetic quadrupoles and a buncher for beam focusing and rebunching respectively. The IH-DTL is designed with a synchronous phase of 0 degree, which becomes the Kombinierte Null Grad Struktur (KONUS) -like structure assembling with the matching section; meanwhile, it keeps the possibility of direct connection between the RFQ and the IH-DTL. This flexible design is likely to make the linac even more compact in the future.

The pulse length and repetition of the linac are 0.2 ms and 100 Hz respectively. The input beam of the linac is 35-keV, with a peak current of 6 mA. The initial RMS emittance is 0.15 $mm \cdot mrad$. At the exit of the 2-meter RFQ, the beam is accelerated to 4 MeV and the transmission is 59% benefitting from a new beam dynamics design. The IH-DTL has 22 acceleration gaps, accelerating the beam to 8 MeV with the synchronous phase of 0 degree. The transmission in the IH-DTL is about 99%. The length of the RFQ is 2 meters and that of the IH-DTL is 0.51 meter, resulting in the total length of the linac from RFQ to IH-DTL being 3.5 meters. The RMS energy spread at the exit of the IH-DTL is 93 keV, meanwhile the RMS beam length is 11 degrees. These parameters meet the requirements of both higher-frequency linacs and synchrotrons to inject.

RFQ DESIGN

RFQs have a strong focusing effect and are able to focus and accelerate proton beams against the high space charge effect. Therefore, RFQs are utilized broadly in low-energy proton accelerators. The frequency of the linac is 714 MHz, where the four-vane type RFQ is suitable. In order to get a high-transmission and short RFQ, the NFSP (New Four-Section Procedure) beam dynamics design is introduced to the RFQ, where an RFQ is divided into four sections as MS (Maximum-Separatrix), MB (Main Bunching), MBA (Mixed Bunching-Accelerating) and MA (Main Accelerating) [5]. This design allows non-constant average vane aperture so that the focusing strength of the RFQ can vary along the beam axis, hence the focusing strength can be higher along with a lower acceleration efficiency when the energy of the beam is low, meanwhile the acceleration efficiency can be higher along with a lower focusing strength when the energy of the beam is high. As a result, the RFQ can be shorter and the transmission can be higher.

The input beam emittance is $0.15\,\pi \cdot mm \cdot mrad$ and its energy is 35 keV. The peak current injected into the RFQ is 6 mA. The vane voltage of the RFQ is 67 kV and the peak surface field is 47.38 MV/m, which is around 1.9 times as high as the Kilpatrick limit. The minimum aperture radius is 0.91 mm. Smaller minimum aperture can strengthen the focusing effect of the RFQ and improve

† Email address: wangping@sari.ac.cn.
‡ Email address: fangwc@sari.ac.cn

Preprint

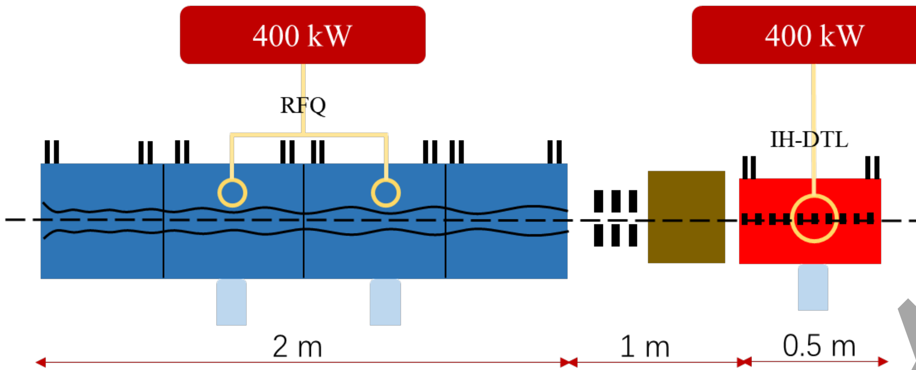

Figure 1: Layout of the injector.

transmission efficiency, in risk of high breaking down rate. The maximum modulation factor of the RFQ is 3. The final synchronous phase of the RFQ is $-20°$. Higher synchronous phase can increase the acceleration gradient of the acceleration section, thus the length of the RFQ can be shorter In this study, the final synchronous phase is $10°$ higher than what is commonly applied. As a result, the length of the RFQ is 2 meters and the RF power needed is 300 kW. In the RFQ, the proton beam is accelerated to 4 MeV with a transmission efficiency of 59.1%. The results of the beam dynamics calculation are shown in Fig. 2.

The 3-D modeling and electromagnetic simulation was done with CST MWStudio. There are 32 tuners in the RFQ, 8 in each quadrant. The cavity diameter and end cut were optimized according to the frequency and the electric field. Finally, the frequency of the model is 714 MHz, with all the tuners inserted to a depth of 5 mm. Dipole stabilizing rods (DSRs) are placed on the angular bisector of two vanes in a quadrant, and the frequency difference between

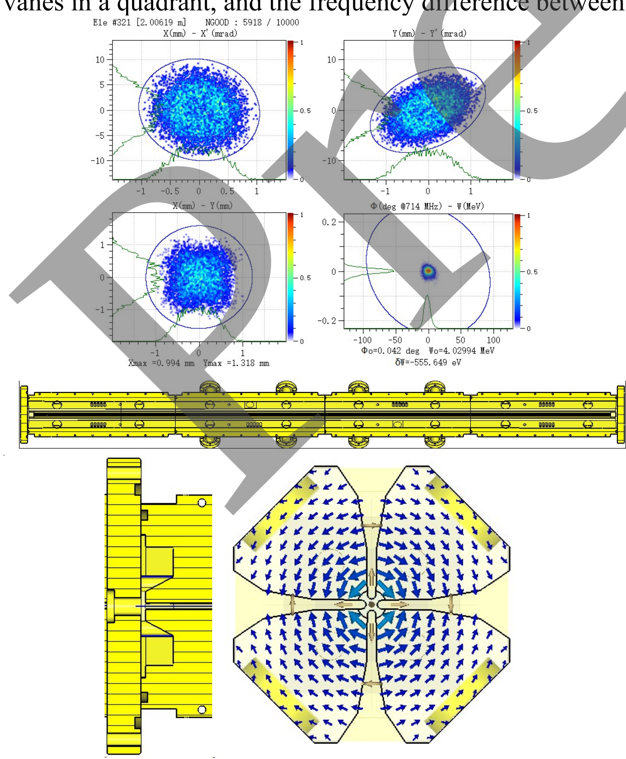

Figure 2: Beam dynamics results of the RFQ.

Table 1: Main Parameters of the RFQ

Parameters	Value
Type	4-vane
Frequency	714 MHz
Input energy	35 keV
Input peak current	6 mA
Input beam emittance (rms)	$0.15\,\pi \cdot mm \cdot mrad$
Output energy	4 MeV
Minimum aperture	0.91 mm
Maximum modulation factor	3
Vane voltage	67 kV
Peak surface field	47.38 MV/m
Final synchronous phase	$-20\,°$
Power	300 kW
Length	2 m
Transmission	59%

the TE210 mode and TE111 modes is over 5 MHz when all the 8 rods are 50 mm long.

Main parameters of the RFQ are shown in Table 1.

DTL DESIGN

The IH-DTL is mainly used to accelerate proton beams with velocity β of about 0.1. It has a higher gradient, and the magnets are a separate part, thus avoiding the insertion problem.

KONUS beam dynamics is characterized by the high acceleration gradient in its main acceleration section at 0 degree. The electric field on axis is the maximum when the synchronous phase of the beam is 0 degree, but the acceleration is unstable at such circumstance. The energy of the proton beams should be higher than the reference energy of the structure and the phase shifts. With the bunching section and the focusing section, the beams can be shaped and a new reference energy will be assigned to the next main acceleration section. Different from the classic KONUS beam dynamics, the bunching section is separate from the main IH-DTL cavity in this study. A buncher along with the electromagnetic quadrupole constitutes the matching section between the RFQ and the IH-DTL. This design allows future promotion that the matching section can be removed to reduce the length of the linac.

Preprint

The frequency of the IH-DTL is 714 MHz, the same as that of the RFQ, and its aperture is 5 mm. The synchronous phase is 0 degree and the total length of the IH-DTL is 51 cm with 22 cells. The IH-DTL accelerates the beam to 8 MeV with a transmission of over 99%. At the exit of the IH-DTL, the RMS energy spread is 93 keV and the RMS beam length is 11 degrees.

Thereafter, the 3-D modeling and electromagnetic simulation was conducted for the IH-DTL. The cavity diameter and end cut were designed and optimized. There are 12 tuners in the IH-DTL, 6 in each side and totally symmetric. The frequency of the IH-DTL is 714 MHz and the electric field is shown in Fig. 3.

Main parameters of the IH-DTL are shown in Table 2.

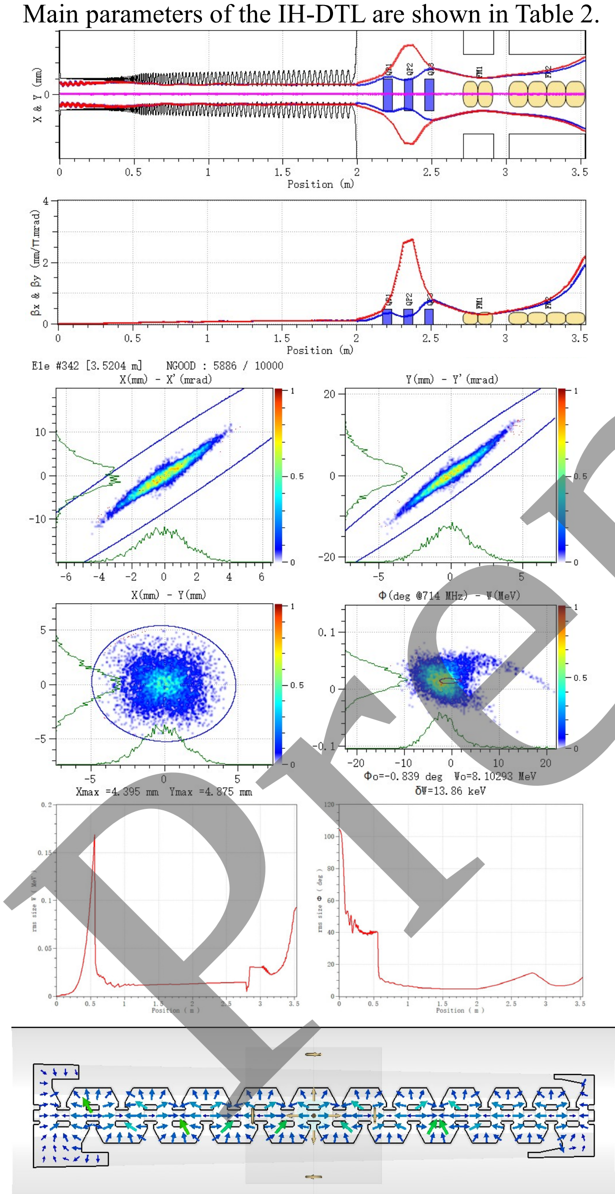

Figure 3: Beam dynamics results of the IH-DTL.

Table 2: Main Parameters of the DTL

Parameters	Value
Type	IH
Frequency	714 MHz
Input energy	4 MeV
Output energy	8 MeV
Aperture	5 mm
Peak surface field	~40 MV/m
Number of cells	22
Length	51 cm
Transmission	>99%

CONCLUSION

The design of the compact 8-MeV proton linac has been completed in SSRF, aiming for medical applications. The linac operates at 714 MHz, comprising an ECRIS, an RFQ, a matching section and an IH-DTL, accelerating proton beams from 35 keV to 8 MeV. The input peak current is 6 mA and the transmission at the exit of the linac is 59%. The NFSP beam dynamics design contributes to the high transmission of the linac. At the same time, the linac has a potential of being more compact because the flexible design of the matching section.

Now, the manufacturing of the linac is ongoing, which is proposed to complete by the end of this month. The commissioning of the linac is planned to operate in the near future. The proton linac can be applied to both linacs and synchrotrons and promise a stable performance. The research on the compact proton linac also significantly benefits the study on complete proton accelerators and proton facilities. More advanced medical proton accelerators are going to be studied and developed.

REFERENCES

[1] Y.-X. Lu, W.-C. Fang, Y.-S. Guo, and Z.-T. Zhao, "Conceptual design of a 714-MHz RFQ for compact proton injectors and development of a new tuning algorithm on its aluminium prototype," *Nucl. Sci. Tech.*, vol. 35, no. 1, Jan. 2024. doi:10.1007/s41365-024-01376-7

[2] Y.-Q. Yang *et al.*, "A new imaging mode based on X-ray CT as prior image and sparsely sampled projections for rapid clinical proton CT," *Nucl. Sci. Tech.*, vol. 34, no. 8, Aug. 2023. doi:10.1007/s41365-023-01280-6

[3] Y.-Q. Yang *et al.*, "Static superconducting gantry-based proton CT combined with X-ray CT as prior image for FLASH proton therapy," *Nucl. Sci. Tech.*, vol. 34, no. 1, Jan. 2023. doi:10.1007/s41365-022-01163-2

[4] W.-C. Fang *et al.*, "Proton linac-based therapy facility for ultra-high dose rate (FLASH) treatment," *Nucl. Sci. Tech.*, vol. 32, no. 4, Apr. 2021. doi:10.1007/s41365-021-00872-4

[5] C. Zhang, Radio-Frequency Quadrupole Accelerators: From Protons to Uranium Ions. Springer Nature Switzerland, 2023. doi:10.1007/978-3-031-40967-7

Preprint