THE BEAM DYNAMICS DESIGN OF THE PROTON SYNCHROTRON LINEAR INJECTOR FOR PROTON THERAPY*

J. Qiao[1], Y.H. Pu†, X.C. Xie
Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[1]also at University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

A compact room-temperature injector is designed to accelerate 20 mA proton beam from 30 keV to 7.0 MeV for the purpose of Proton Synchrotron Linear Injector for Proton Therapy. The main feature of this linac injector is that the 4-vane Radio Frequency Quadrupole (RFQ) and the Drift Tube Linac (DTL) section are matched by one triplet and powered by one RF power source. The beam is matched from the first RFQ section to the second DTL section in traverse and longitudinal directions. The overall accelerating gradient of this design has reached up to 1.6 MV/m with transmission efficiency of 96%. This injector combines a 3 m long 4-vane RFQ from 30 keV to 3.0 MeV with a 0.8 m long H-type DTL section to 7.0 MeV. In general, the design meets the requirements of the Proton Synchrotron and the Terminal treatment.

INTRODUCTION

Proton accelerator gradually becomes the focus of treatment due to the characteristics of protons with certain energy in cancer treatment [1]. In order to reduce costs and widely promote this application, a compact synchronous-based linear injector was designed and investigated. This linac mainly consists of an ECR proton source, a low energy beam transport, a 3.0 MeV Radio Frequency Quadrupole (RFQ), a simplified MEBT and a 7.0 MeV Drift Tube Linac (DTL). The specific composition layout of this injector is shown in Fig. 1. In this paper, the design results of RFQ and DTL are mainly presented.

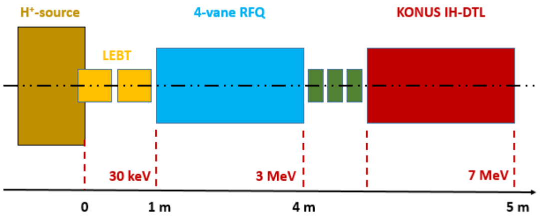

Figure 1: The specific design scheme of this injector.

RFQ DESIGN

The beam dynamics design was based on the traditional design strategy [2]. The RFQ beam dynamics design parameters are as Table 1. In order to shorten the cavity length, a fast-bunching strategy was used by replace the shaper section and slow ramping section with a fast ramping section and the input energy was set to 30 keV, which also helps reduce power consumption and extraction high voltage of proton source. At the same time, 325 MHz was chosen to reduce the R&D difficulties of RF equipment. The constant inter-vane voltage 75 kV is chosen to simplify the design and decrease the power loss by PARMTEQM v3.05 [3].

Table 1: Design Parameters of RFQ

Parameters	Value
Ion type	Proton
RF frequency (MHz)	325
Maximum duty factor (%)	0.1
Input beam energy (keV)	30.0
Output beam energy (MeV)	3.0
Peak current (mA)	20.0
Transmission efficiency (%)	98.0
Trans. Input norm. rms. Emit. (mm mrad)	0.2
Trans. Output norm. rms. Emit. (mm mrad)	0.205
Max. surface electric field lim. (MV/m)	30.6
Modulation coefficient	1.0~2.5
Vane length (cm)	301
Synchronous phase (degree)	-90 ~ -25

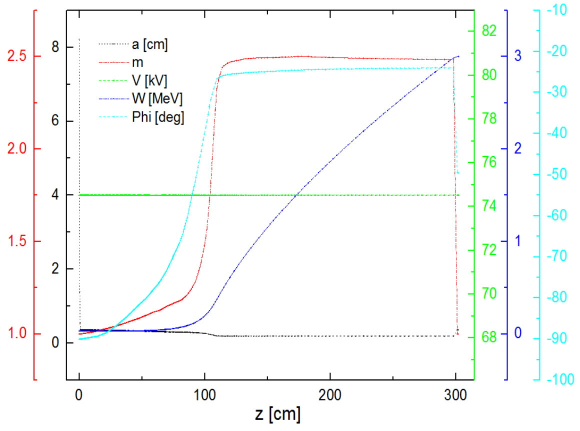

Figure 2: The physical design result of the 325 MHz RFQ.

The physical design result of the 325 MHz RFQ is shown in Table 1 and Fig. 2, in which V is the inter-vane voltage,

---

* Work supported by the Proton linear injector projector of Ministry of science and technology of China.

† puyuehu@sinap.ac.cn

a is the minimum bore radius, m is the modulation tion factor, φ_s is the synchronous phase, and W_s is the synchronous energy.

The beam dynamics simulations have been done with PARMTEQM v3.05. The input and output emittance, when the beam current is about 20 mA, is displayed in the Table 1. The output phase width is about ±20°, and the energy spread is about 1%, which meets the requirement of the acceptance of downstream DTL. The parametric resonance has been carefully avoided by adjusting the vane parameters. The phase shift in transverse and longitudinal directions is divided obviously and the curves are optimized smoothly.

DTL DESIGN

An Inter-digital H-mode drift tube linac (IH-DTL) with modified KONUS beam dynamics [4] has been chosen as a downstream accelerator. Table 2 shows the main parameter of IH-DTL.

Table 2: The Main Parameters of IH-DTL

Parameters	Value
Ion type	Proton
RF frequency (MHz)	325
Maximum duty factor (%)	0.1
Input beam energy (MeV)	3.0
Output beam energy (MeV)	7.0
Peak current (mA)	20.0
Transmission efficiency (%)	100
Trans. Input norm. rms. Emit. (mm·mrad)	0.21
Trans. Output norm. rms. Emit. (mm·mrad)	0.23
Output energy spread (95%)	1.2%
Output phase width (degree)	-20~10
Cavity length (cm)	80

In order to match the beam from RFQ to DTL, a thin MEBT, composed of a quadrupole triplet, is designed between, which starting from the exit of RFQ and ending at the entrance of DTL. The whole length is about 50 cm. It is also used to adjust the beam transverse position and angle. At the same time, it reserves a certain amount of space for diagnostics and beam steering.

Generally, a KONUS-period consists of three sections with separated functions respectively, as the Fig. 3 [4-6] shows. The first section is the main acceleration section in which the beam is injected with a certain energy spread compared with a “synchronous” particle. Following the main section, some triplet transport systems are used for the transverse focusing. Afterwards, the beam is injected into a longitudinal bunching section consisting of a few gaps with a negative synchronous phase shift typically from -25° to -35°.

The LORASR code [5] was dedicated for the KONUS beam dynamics design of IH-DTL, which has been verified by many devices in the world. In this paper, the beam dynamics have been designed and simulated by LORASR code for the IH-DTL part.

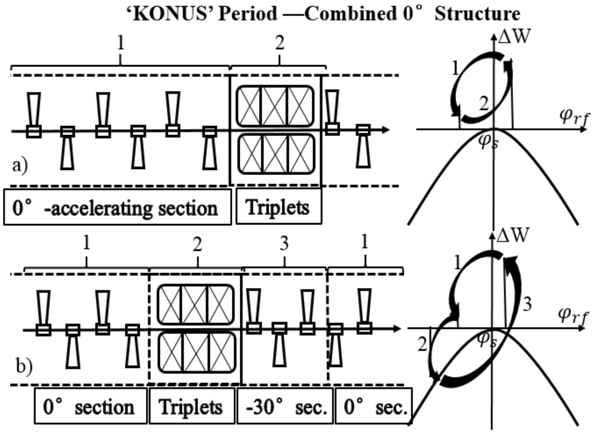

Figure 3: The KONUS period and the principle of KONUS beam dynamics.

This modified KONUS [6], shown in Fig. 4, is carried out by moving the transverse focusing elements outside the cavity, which means there are only the last two sections remaining inside the cavity.

The transverse envelope along the IH-DTL has been optimized at 20 mA beam current, and the maximum beam envelope is within ± 3 mm.

Figure 5 exhibits the longitudinal relative energy spread and phase spread as a function of position z. The transmission efficiency is 100 %. The 95 % relative energy spread is smaller than 1.5 % at the end of the DTL section, while the 95 % phase spread is about ±15°.

The rms emittance growth rates in the transverse and longitudinal planes at full beam current are only 7.8 %, 8.1 % and 3.2 %. There are about 3 cells used to bunch the coming beam from upstream, and 12 cells accelerating the proton beam up to 7 MeV. The accelerating gradient is about 4.8 MV/m.

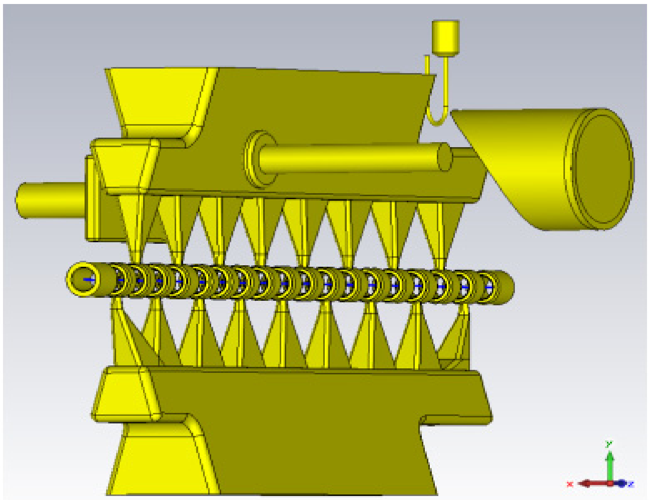

Figure 4: The scheme layout of traditional and modified KONUS IH-DTL.

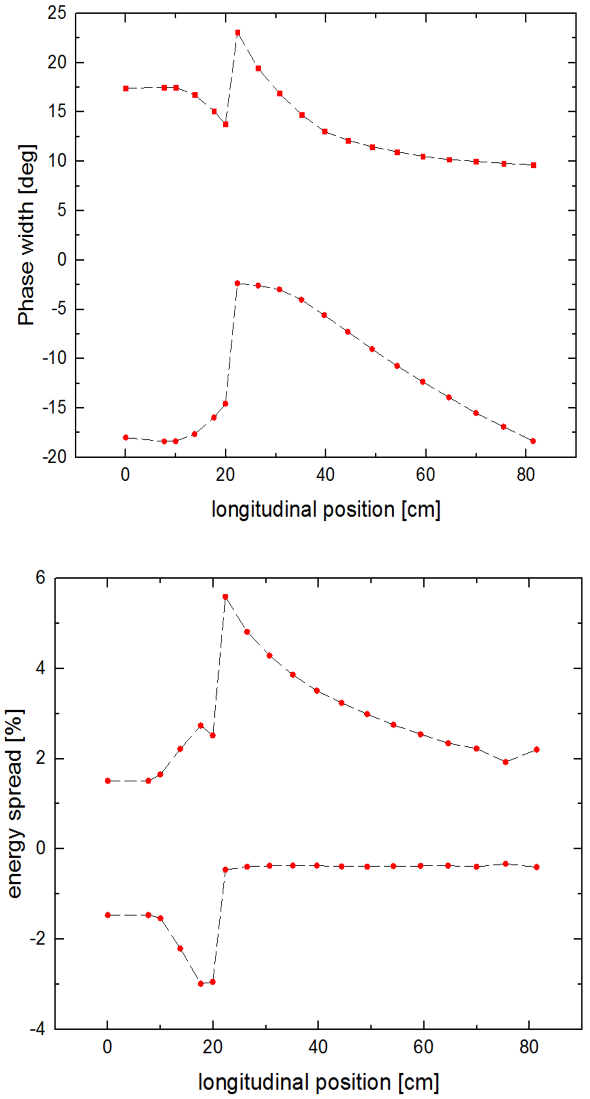

Figure 5: The longitudinal phase width (left) and relative energy spread (right) as a function of position z.

CONCLUSION

The 7 MeV room-temperature compact linac injector combines a RFQ, one thin MEBT and a modified KONUS IH-DTL without magnet inside the cavity. Based on the principles of RFQ and KONUS dynamics and the requirements of treating, the beam dynamics design results show that it has already met the needs of beam quality, structure length requirements and reduce the cost physically. The average accelerating gradient of this linac injector has reached up to 1.6 MV/m. It can accelerate 20 mA proton beam from 30 keV to 7 MeV at the length of 4 m.

REFERENCES

[1] R. Baskar, K.A. Lee, R. Yeo, *et al.,* Cancer and radiation therapy: Current advances and future directions, Int. J. Med. Sxi. 9 (3) (2012) 193-199.

[2] K.R. Crandall, T.P. Wangler, L.M. Young, *et al.*, LA-UR-96-1836, 2005.

[3] L. Young, RFQGen User Guide, Technical Report, Los Alamos Scientific Lab., NM, USA, 2016.

[4] T.P. Wangler, RF Linear accelerators [M]. Wiley. com, 2008.

[5] U. Ratzinger, *et al.,* LORASR-a computer code to calculate the longitudinal and radial beam dynamics of a drift tube accelerator, GSI Internal Report 0791.

[6] R. Tiede, U. Ratzinger, H. Podlech, *et al.* KONUS beam dynamics designs using H-mode cavities. *Hadron beam*, 2008, 1: 2013.