

ERROR ANALYSIS AND RF OPTIMIZATION OF A COMPACT RFQ*

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Abstract

A 162.5 MHz, 7.2 MeV 4-rod radio frequency quadrupoles (RFQ) dynamics design has been finished for injector of a carbon ion cancer therapy facility which is promoted by the Institution of Modern Physics (IMP) of the Chinese Academy of Science (CAS). A detailed error analysis was performed after the optimization process. Field flatness error is analysed for determining a RF optimization target. The RF structure is designed based on a new type dynamics design. Electric field of the RF structure is optimized in order to supporting the dynamics design. The error analysis and detailed field flatness optimization of this compact RFQ have been presented and discussed in this paper.

INTRODUCTION

Hadron therapy offers superior dose conformity in the treatment of deep-seated tumours compared with conventional X-ray therapy due to its Bragg-peak feature of energy deposition in organs [1]. So many accelerator facility dedicated to cancer therapies have been constructed in these years. One of them is Heavy Ion Medical Machine in Lanzhou (HIMM), which has been designed and constructed by IMP (Institute of Modern Physics). A linac is designed to replace cyclotron as the accelerator injector in the next generation HIMM, which consists of an ECR ion source, a 162.5 MHz RFQ, a compact Interdigital H-mode Drift-Tube-Linac (IH-DTL), and beam transport lines. The layout is shown in Fig. 1.

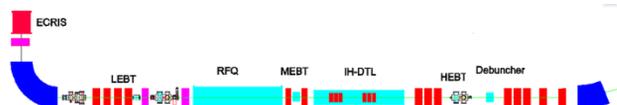


Figure 1: Layout of the linac injector of cancer therapy facility.

A RFQ operated under 162.5MHz as important part of this linac has been designed. It accelerate $^{12}\text{C}^{4+}$ beam from 8keV/u to 600keV/u with 0.1% duty factor. Unlike most research facilities, this RFQ need not running with high current and high duty factor. The optimization of designing this type RFQ is focus on compact structure, high stability and low cost. Based on a traditional setup, a new compact fast-bunching design is introduced to optimize. The whole dynamics design process is supported by PARMTEQM [2]. This method is used to create a more compact structure by ignoring the space-charge effect [3]. Finally, RFQ structure length is shorten from the standard design value 272cm to

230 cm, while effectively regulating the particle loss and emittance growth. The final parameters is shown in the Table 1. And main parameters as a function of position z . is shown in Fig. 2.

Table 1: Main Dynamics Parameters for RFQ

Parameter	Value
Frequency (MHz)	162.5
Beam current (euA)	200
Input energy (keV/u)	8
Output energy (keV/u)	601.45
Duty factor	0.1%
Kilpatrick factor	1.83
Minimum aperture (a)(cm)	0.3
Input trans. emit. ($\pi \cdot \text{mm} \cdot \text{mrad}$)	0.200
Output trans. emit. ($\pi \cdot \text{mm} \cdot \text{mrad}$)	0.199
Output longitudinal emit. ($\pi \cdot \text{MeV} \cdot \text{deg}$)	0.242
Length of the vane (cm)	230.14
Transmission efficiency	99.3%

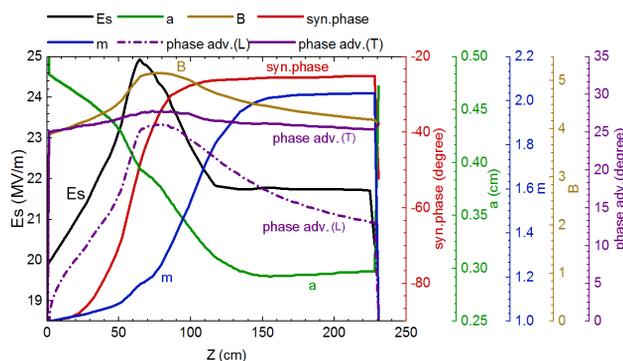


Figure 2: The RFQ beam dynamics parameters as a function of position z .

It can be seen from Fig. 2 that the bunch process is completed in a short time in this design, which shorten overall structure length. Based on the dynamics design, the error is analysed from two aspects: 1. Input beam errors; 2. Errors of field flatness distribution along inter-vane. The dynamic design of RFQ is tested by the tolerance of mismatched beam. And optimization objective of RF design is carried out by the error analysis of field flatness. The RF design has been optimized to meet the requirement of field flatness.

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ERROR ANALYSIS

Input Beam Errors

The beam injected into RFQ is affected by the stability of ion source and power supply of LEBT transmission line [3]. The beam parameters are usually different from the ideal condition given in the design. The RFQ's compatibility to the undesired beam is researched as a comprehensive consideration of the RFQ front-end device.

For the RFQ dynamics design, beam emittance at entrance of the RFQ is 0.2 π mm-mrad (Norm. RMS), beam current is 0.1 pA, and the energy is 8 keV/u with zero

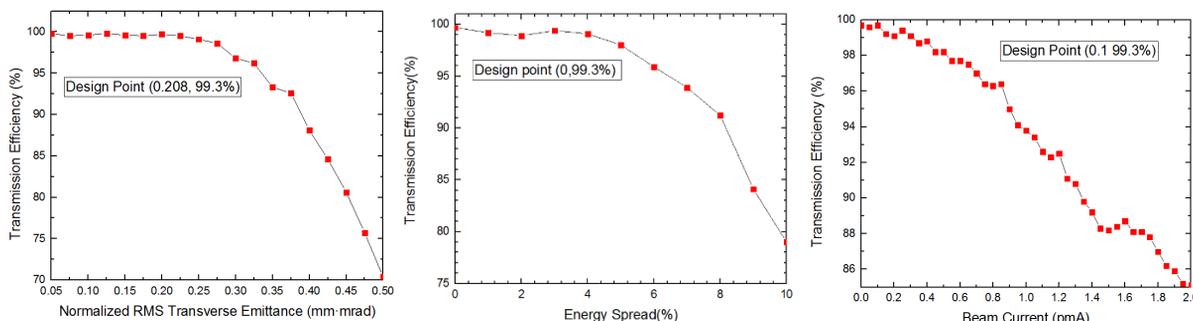


Figure 3: From left to right is transmission efficiency as a function of Norm. RMS transverse emittance, beam energy spread and beam current respectively.

Field Flatness Errors

Four-rod structure is chosen due to the compact structure and low cost. For four-rod RFQ, the optimization of field flatness is very important, which directly affect beam transmission. Field flatness error has been researched here as it is considered as the main error of RF design.

Except for the impact of a non-ideal input beam on the RFQ, there are some errors which result from fabrication, assembling, and operation. These errors are always added in the research process. They are uniformly distributed in the ranges listed in Table 2. The dR value refers to the error of the electrode pole radius, and the d refers to the error of the depth of the modulation curve. The ϕ refers to the error of the RF phase, which is determined by the precision of the RF phase control system. The ΔT and ΔL are the cavity position offsets produced during installing. All of these values are set based on prior experience learned from SSC-Linac fabrication [4].

Table 2: The Setting of the RFQ Errors

Parameter	Range
Distribution	Uniformly
dR (mm)	± 0.1
d (mm)	± 0.1
ϕ ($^\circ$)	± 1
ΔT (mm)	± 0.2
ΔL (mm)	± 0.2

Based on the fabrication, assembling errors, the field flatness error is set as 3.5%, 4% and 5% respectively for

energy spread and 360 $^\circ$ phase width. Through simulation of the PARMTEM, the input error impact is shown in the Fig. 3. During the simulation, one of the parameters such as the emittance, current or energy spread of the input beams is adjusted while the other parameters are kept constant. It could be found that 8% energy dispersion, 1 pA (4 eA) current and 0.375 π mm-mrad (Norm. RMS) emittance can be tolerated under 90% transmission efficiency respectively. The tolerances for three parameters errors are far greater than the actual requirements, because during operation, input beam errors are the superposition effect of these three errors.

researching field flatness impact. Through analysis of 1000 sets of errors, the probability distribution of the beam loss is determined using TraceWin simulations as shown in the Fig. 4. The calculated transmission efficiency is slightly higher than that of PARMTEQM, because the electric field and the beam loss criteria are different [5]. As shown in Fig. 4, the relative frequency of beam loss distribute mainly less than 5%, when the field oscillations is 3.5%. That means the beam transmission efficiency can be maintain upon 95% with 3.5% field flatness.

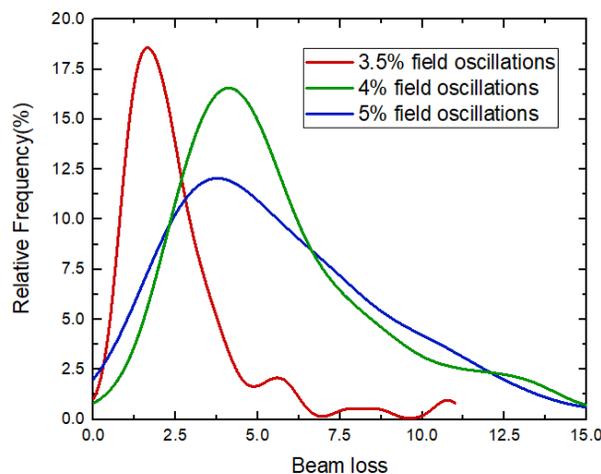


Figure 4: The relative frequency of the beam loss with different field oscillations.

RF DESIGN OPTIMIZATION

4-rod type is chosen for this RFQ, because it has advantages in flexibility for tuning and more convenient for

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maintenance [6]. An initial RF design is carried out by the CST Microwave Studio (MWS) [7], after the cavity type choosing. The field flatness as one of the important characteristics constrain the performance of RFQ. It will influence the beam quality and transmission efficiency badly. For the impact of end effect of 4-ROD RFQ, the inter-vane field along the RFQ forms a shape which the both ends is higher than the midium. The general method to improve this fluctuation of the electric field is changing the resonant frequency of the basic cell through adjusting the height of the tuner block between the stem. While local electric field will decrease with local resonant frequency decrease [8]. Theoretically, the adjustable variables increase with the blocks increase. The numbers of the blocks determines the difficulty and the limit of adjustment. And optimization of the numbers and height of blocks is a process of trial and error. For this RFQ, optimization objective of field oscillations is around 3.5%. Through field flatness error analysis, this field oscillations is enough to guarantee beam transmission. The final block position is shown in the Fig. 5. The Fig. 6 indicates the field flatness comparison between initial structure and structure with tuner block. The field flatness is judged by the formula:

$$\text{Unflatness} = \frac{E - \bar{E}}{\bar{E}}$$

where E is the electric field value in the every quadrant. \bar{E} is the average electric field in corresponding quadrant. Through optimizations, the fluctuation of the electric field is kept less than $\pm 3.5\%$, which could satisfy the operating requirement.

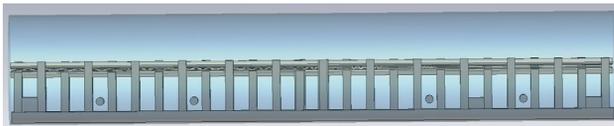


Figure 5: Setting of RFQ block (The right end of figure is beam inlet).

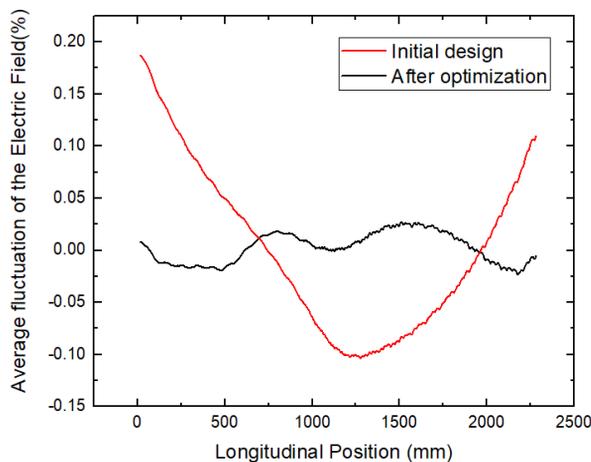


Figure 6: Average fluctuation of the electric field along the longitudinal position.

CONCLUSION

Based on the dynamics design, the input beam errors and the field flatness errors has been analysed. The feasibility of dynamics design was demonstrated by the tolerance of non-ideal input beams. And the optimization objective of the field flatness has been determined through the error analysed. Based on this optimization, the field flatness in RF design is less than 3.5%, which could guarantee beam transmission.

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REFERENCES

- [1] K. Ando, Y. Kase, International Journal of Radiation Biology 85, 2009, p.715.
- [2] K.R. Crandall, T.P. Wangler, L.M. Young, et al., RFQ Design Codes, LA-UR-96-1836.
- [3] X.H. Zhang, Y.J. Yuan, J.W. Xia, et al., Instability Research of 53.667 MHz Heavy Ion RFQ, J. Atomic Energy Science and Technology, 49(5).
- [4] G. Liu, Y.R. Lu, Y. He, et al., Design of a CW high charge state heavy ion RFQ for SSC-LINAC, Nucl. Instr. Meth. A701(3):186193, 2013.
- [5] K. Zhu, Y. R. Lu, X. J. Yin, et al. The beam commissioning of a CW high charge state heavy ion RFQ, Nucl. Instr. Meth. 2015, 794(3):113121.
- [6] T. Wangler, RF Linear Accelerators. 2008.
- [7] CST Simulation Packages <http://www.cst.com>
- [8] Simulation and experiments of rf tuning of a 201.5 MHz four-rod RFQ cavity, J. Chinese Physics C, 2011, 35(11): 1042-1046.