BEAM DYNAMIC DESIGN OF A 100 mA, 162.5 MHz HIGH-CURRENT LINAC *

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Abstract

The beam dynamic design of a 100 mA, 162.5 MHz Radio Frequency Quadrupole (RFQ) is presented in this paper. The RFQ will accelerate protons from 85 keV to 3 MeV under the operation mode of continuous-wave (CW). The code PARMTEQM is used to carry out the beam dynamics design and the transmission efficiency has been optimized and improved to more than 99%. In the design of this high-current linac, the space charge effect is analyzed as it can cause emittance growth, nonuniform particle density distribution and resonance effect. The electrode structure parameters generated by PARMTEQM also be adopted by the code of Toutatis to verify the result's veracity.

INTRODUCTION

Radio Frequency Quadrupole (RFQ) accelerators are widely used as injectors in the high-current linacs. Because of their remarkable capability of simultaneously focusing, bunching and accelerating the low-energy particles with high transmission and minimum beam emittance growth, many RFQ projects have been done in the world.

With the beam intensity increases from a low level to high, the particles' interaction, which is called space charge effect, become stronger and stronger. It will cause emittance growth, energy spread, beam halo, etc. These bad effects caused by space charge interaction will significantly reduce the beam quality and transmission efficiency. Due to the challenges exist in high-current linac, although many RFQ projects have been done worldwide, just a few projects have been ambitious to step into the range of more than 100 mA's RFQ design.

While, as high-current linear accelerator has wide application field such as neutron radiography, cancer therapy and the experiment of ion irradiation, many scientific research institutions put focus on the research of it now. To have deep research about high-current linacs, a new scientific research project was proposed by Institute of Modern Physics of Chinese Academy of Science and Peking University recently. The project aims to research about a new type RFQ with beam current up to 100 mA. This RFQ will adopt a new type of 4-vane with window structure. Deeper research work about high-current linacs will be done in this project. The basic beam dynamics design parameters of this RFQ are listed in Table 1.

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Table 1: Basic Parameters

Parameters	Value	Unit
Particle	Proton	
Type	4-vane with window	
Frequency	162.5	MHz
Peak Beam Current	100	mA
Output Energy	3	MeV
Input Transverse Emittance (Norm., RMS)	0.2	π·mm·mrad
Beam Duty Factor	100	%

BEAM DYNAMIC DESIGN

The dynamic simulation was carried out by the code of PARMTEQM in this project. It was developed at Los Alamos National Laboratory (LANL) and has been widely applied to the design of many RFQs.

In this project, the beam intensity reaches 100 mA. Learning from the dynamic design and the practical running results of the ≥100 mA RFQ projects such as LEDA [1], IPHI [2], JAERI BTA[3], FRANZ [4] in the world we can see that the phenomenon of accelerator's instability and low transmission is very common in high-current linac. To ensure the RFQ's high beam transmission efficiency and the stability of the operation, the dynamic parameters were optimized carefully and modulate slowly during the beam dynamic design of this project.

Design Strategy

The strong space charge effect will affect the beam transport in the low energy part prominently. Therefore the input energy should not be too low. Whereas, too high input energy will make the manufacture of ion source too difficult. And as this project requires the RFQ work in CW mode, the inter-vane voltage cann't be set too high or too low either. To keep enough radial focusing and longitudinal accelerating strength, and to reduce the power consumption and RF sparking risk, the voltage value should be set reasonably. Compared with other high-current RFQ project in the world, the input energy and inter-vane voltage of this RFQ was chosen as 85 keV and 80kV respectively.

The Four-Section Procedure [5] beam dynamics design method, developed by LANL, has been adopted and proved by various RFQ projects in the world. This method divides the whole RFQ into four sections: radial matching (RM), shaper (SH), gentle buncher (GB) and acceleration section (ACC). Formula (1) describes the radial focusing strength B, where q is the charge state of ions, χ is the focusing parameter, V_0 is the inter-vane voltage, λ is the rf wavelength, ε_0 is the particle rest energy, γ is the relativistic factor, a is the aperture of the RFQ. In this Four-Section Procedure design method, B is always kept constant from the RM section to the ACC section. However, in the high current accelerator the beam should be bunched very fast to balance the changing space charge force, so the radial focusing strength should increase with the space-charge force from RM section to GB section until the transverse defocusing force is weakened, and afterwards it should go down accordingly in the ACC section to keep the whole beam development under a transverse/longitudinal force balance [6]. Besides, at the high energy segment, a smaller value of B will be helpful to improve the cavity's accelerating gradient and this could effectively reduce the length of the RFQ [7]. In this project, we kept the parameter B vary accompanied the improvement of beam energy. Meanwhile the value of synchronous phase and modulation was retuned to get preferable transmission. The design parameters of this RFQ are listed in Table 2.

$$B = q\chi V_0 \lambda^2 / (\varepsilon_0 \gamma a^2) \tag{1}$$

Table 2: Main design parameters of this H^+ RFQ

Parameters	Value	Unit
Particle Number	10000	
Input Energy	85	keV
Inter-vane Voltage	80	kV
Input Transverse Emittance (Norm., RMS)	0.2	π·mm·mrad
Synchronous Phase	-90 ~ -29	Deg.
Maximum Surface Field	17.608	MV/m
Kilpatrick Coefficient	1.295	
Modulation	1 ~ 1.967	
Minimal Aperture	0.445	cm
Maximum Radial Focusing Strength	8.322	
Length	852.94	cm
PARMTEQM Transmission	99.6	%

Equipartitioning Design

To prevent emittance growth and other sources of potential beam loss in an intense beam accelerator, the equipartitioning [8] design principle was put forward. In an equipartitioned beam bunch, which requires the beam meet the equipartitioning conditions, as the beam has equal "temperatures" between transverse and longitudinal, there is no free, unbalanced energy that could cause emittance growth via coupling mechanisms. Formula (2) describes the equipartitioning conditions, where σ_t, σ_l denotes the phase advance in transverse and longitudinal directions respectively, ε_{tn}, ε_{ln} denotes the full 100% normalized emittance of a uniform beam distribution, a, b the full beam radius, in the transverse and longitudinal direction and γ is the relativistic energy factor.

The principle of equipartitioning was considered in this beam dynamic design. From Fig. 1 we can see the parameters in the GB and the beginning of ACC sections meet the equipartitioning conditions.

$$\frac{\sigma_t}{\sigma_l} = \frac{\gamma b}{a} = \frac{\varepsilon_{ln}}{\varepsilon_{tn}} \tag{2}$$

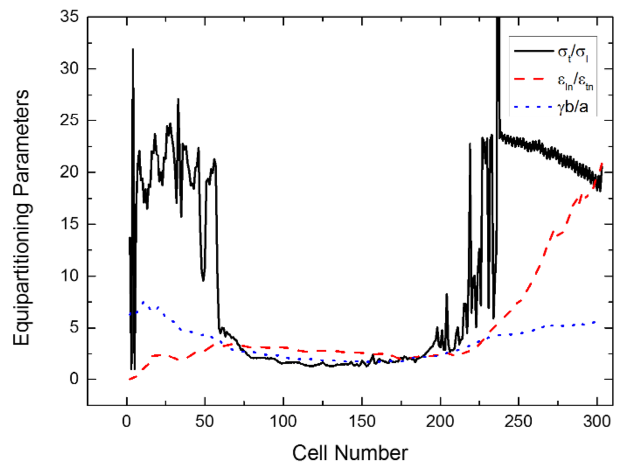

Figure 1: Equipartitioning parameters of this RFQ.

Results of Simulation

The design result of the various parameters of this RFQ is shown in Fig. 2 and the beam dynamic design result is shown in Fig. 3.

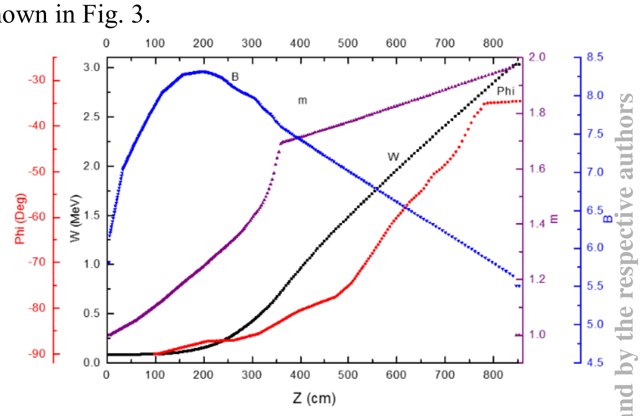

Figure 2: Various design parameters versus longitudinal position.

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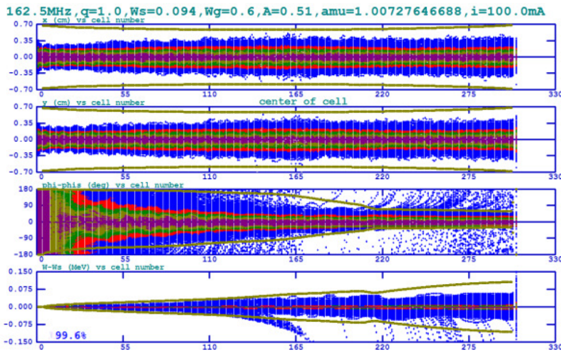

Figure 3: Beam dynamics in the RFQ for the input current of 100 mA, 10000 particles. From top to bottom are: x, y, phase, and energy coordinates versus cell number. The percentage transmission is 99.6%.

ERROR ANALYSIS

A number of error types have been considered and studied in the beam dynamic design, these errors include input Twiss parameters, input beam emittance, input beam current and input beam energy spread. The design value of beam parameters at the entrance are α=2.082, β=13.758 cm/rad, ε_t=0.2 π·mm·mrad (Norm., RMS), 85 keV input energy without energy spread and zero input phase spread. Transmission versus these parameters are shown in Fig. 4.

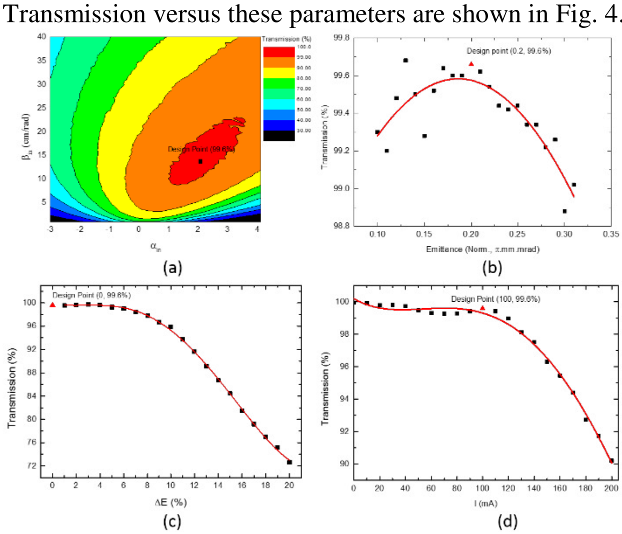

Figure 4: Transmission versus input twiss parameters (a), input beam emittance (b), input beam energy spread (c) and input beam current (d).

The code of Toutatis works depends on the generated electrode structure parameters from PARMTEQM. As Toutatis and PARMTEQM adopt different calculate methods in the beam transmission, Toutatis can be treat as the verification program for PARMTEQM. In this RFQ, Toutatis was used to verify the PARMTEQM's design parameters. Figure 5 shows the beam transmission efficiency by Toutatis is 99%. We can see both of the transmission results from Toutatis and PARMTEQM are more than 99%. This verify that the design parameters are reliable.

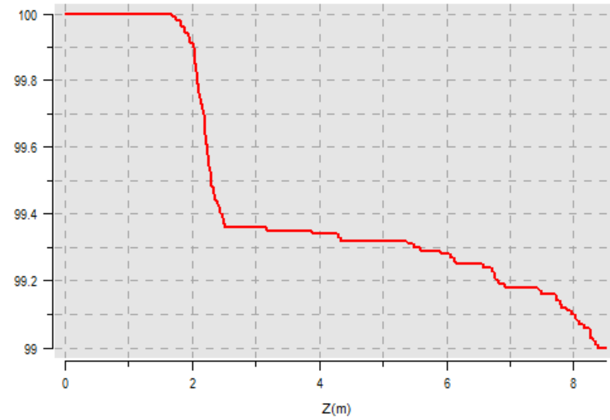

Figure 5: Transmission versus Z (m) by the code of Toutatis.

CONCLUSION

In view of this RFQ's CW operation mode and very high beam current, the design parameters are set very conservative during the beam dynamic design. To learn more about high-current linac, further work need to be done to optimize and analyze the design result.

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