BEAM DYNAMICS DESIGN OF A 325 MHz RFQ*

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Abstract

The beam dynamic design of a 325 MHz Radio Frequency Quadrupole (RFQ) is presented in this paper. This 4-vane RFQ will accelerate pulsed proton beam from 30 keV to 3 MeV with repetition frequency of 1 MHz. A 1 MHz chopper and a 5 MHz buncher are arranged in the Low-Energy-Beam-Transport (LEBT) to produce the injected beam. The beam length at the RFQ entrance is about 3 ns, and the energy-spread is about 10%. The code of PARMTEQM is used to simulate RFQ structure. The design should realize high transmission for very high intensity beam meanwhile low emittance growth and relatively short length should be kept.

INTRODUCTION

Recently a 300 MeV proton accelerator is discussed and planned to produce fast neutron for nuclear physics experiments at China Institute of Atomic Energy. The accelerator is composed of 3 MeV RFQ, 75 MeV DTL, 300 MeV CCL and Accumulating Ring. The experiment can provide the needed nuclear data for the equilibrium Th-U cycle reactor. The generated fast neutron will be less than 1 ns pulse length, which demands only one bunch with 1 MHz repetition frequency. So we design a micro pulsed branch which includes the ion source, Low-Energy-Beam-Transport (LEBT) and RFQ. In order to obtain the micro pulse, we need to bunch the beam into 3 ns length and the energy-spread will be about 10%. Then the RFQ should be designed carefully as it is difficult to obtain the micro bunch. Figure 1 shows the sketch of the CIAE project.

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 ion beams with high transmission (>90%) and minimum beam emittance growth [1]. Many accelerators with frequency more than 300 MHz have been designed and produced internationally. Such as the project of LEDA [2], the frequency of this RFQ is 350 MHz and it accelerates the 100 mA proton beam to 6.7 MeV. The CPHS [3] project requires a 325 MHz RFQ to accelerate the proton beam to 3 MeV. In this RFQ, the intervane voltage is increased with the longitudinal position to reduce the length of the cavity. The Italian research program TRASCO [4] has designed a 352.2 MHZ RFQ which aims to accelerate proton from 80 keV to 5 MeV.

Those high frequency RFQ Linacs provide lots of valuable design experiences to the design of this RFQ. However, in many traditional RFQ, there is no energy-spread at the entrance of the cavity. But, as there is a pre-buncher system in the LEBT in this project, the high entrance energy-spread has to be considered. While the designed beam current goes up to 75 mA, the space charge effects will affect the stability of the beam. The initial beam dynamics design was proposed to fit the project requirements.

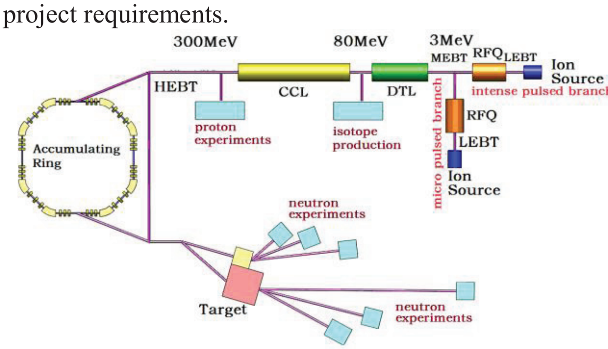

Figure 1: The sketch of the CIAE project.

RFQ BEAM DYNAMICS

The basic parameters of this RFQ are listed in Table 1. The dynamic simulation of this RFQ was carried out by the code of PARMTEQM [5], which was developed at Los Alamos National Laboratory (LANL) and widely applied to the design of many RFQs. According to the code, the whole RFQ beam dynamics design is divided into four sections: radial matching (RM), shaper (SH), gentle buncher (GB) and acceleration section (ACC).

Table 1: Basic Parameters

Parameters	Value	Unit
Particle	Proton	
Type	4-vane	
Input Energy	30	keV
Output Energy	3.0	MeV
Transverse Emittance (RMS)	0.2	π mm mrad
Peak Beam Current	75	mA
Beam Duty Factor	5	%

Low-Energy-Beam-Transport

The LEBT consists of three main parts: a 1 MHz chopper, two solenoids and a 5 MHz buncher. The chopper cuts the continuous beam to a 50 nanoseconds pulse. The pulsed beam is then transmitted to the buncher. And the buncher will bunch the length of the beam to 3 nanoseconds before it enters the cavity. The layout of the

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LEBT and the pulse time structure are shown in Fig. 2 and Fig. 3, respectively.

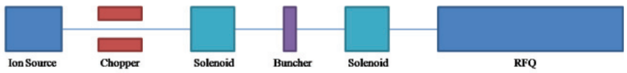

Figure 2: The layout of the LEBT.

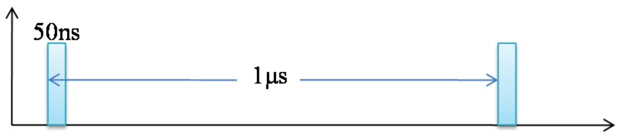

Figure 3: The pulsed time structure.

Focusing Strength B

In the RFQ, B is the radial focusing strength expressed in formula (1), where q is the charge state of ions, χ is the focusing parameter, V_0 is the intervane 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.

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

In the conventional design, B is kept constant from the RM section to the ACC section. However, this design method doesn't fit for the high-current RFQ as the four sections are divided so obvious that many particles will be lost at place of demarcation. In this design, to avoid the mismatch between beam emittance and RFQ acceptance, we keep the parameter B gently be varied versus cell number to get preferable transmission. In fact, it's unnecessary to keep B as constant because of a variational value will be much more appropriate for a RFQ cavity with the increasing particle velocity. And 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 cavity.

Modulation Parameter m

Because of the existed energy-spread at the entrance of the RFQ, we should not only consider beam transverse matching but also longitudinal matching. To achieve high transmission, the longitudinal matching is more important at the entrance. For this reason, the beginning part of the RFQ cavity should have a modulation to bunch particles and slow down the emittance growth both transverse and longitudinal. In this design, the entrance energy-spread was set to 10% of the incident particle energy, m should be larger than 1.1 at the first 10 cm of the cavity.

The design parameters of this RFQ are listed in Table 2 and the design result of the various parameters of this RFQ is shown in Fig. 4.

As shown in Fig. 4, m increases quickly in the first 20 cm of the RFQ. We can also see that B increases sharply at the beginning, after that it passes a part of smoothly increase and finally the value of B starts to decrease until it reaches the end of the RFQ.

Table 2: Design Parameters

Parameters	Value	Unit
Transverse Emittance (RMS)	0.2	π mm mrad
Longitudinal Emittance (RMS)	0.1759	MeV deg
Intervane Voltage	77.3	kV
Synchronous Phase	-90--27	Deg.
Particle Number	5000	
Modulation	1-1.98	
Minimal Aperture	0.211	cm
Length	3.54	m
Transmission	90.5	%

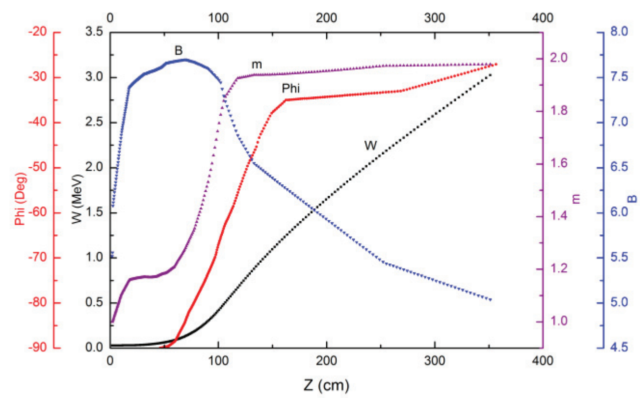

Figure 4: Various design parameters versus longitudinal position.

Kilpatrick Field

The Kilpatrick field is commonly used to describe the design field for accelerating cavities. According to Kilpatrick's theory [6], the breakdown peak surface field E_k is a function of frequency expressed in formula (2). Here the units for f and E_k are MHz and MV/cm, respectively.

$$f = 1.643 E_k^{\,2} e^{-\frac{8.5}{E_k}} \qquad (2)$$

From the formula mentioned above we get that for a given frequency the peak surface field is definite. For CW operation, $1.8E_k$ is a very reasonable value which has been proved by the Los Alamos National Laboratory. As the beam duty factor of this project is 5%, we set the peak surface field up to 1.95 E_k.

INPUT Line

In the code of PARMTEQM, the INPUT line defines properties of some particles in the input beam and it's divided into many Types. In the conventional design we always use Type 6. However, Type 6 can only allow us to input phase and energy-spread but not longitual twiss parameters. In this project, as there is a pre-buncher system before the RFQ cavity in the LEBT, we want to

ISBN 978-3-95450-122-9

set the parameters α, β and ε directly rather than phase and energy-spread. To solve this problem we decided to choose Type 8 as the INPUT line command which could realize the function that we wanted.

The format of Type 6 and Type 8 are as follows.

INPUT 6, N_A, α_x, β_x, ε_x, α_y, β_y, ε_y, $\Delta\phi$, ΔW (3)

INPUT 8, N_A, α_x, β_x, ε_x, α_y, β_y, ε_y, α_z, β_z, ε_z (4)

In the process of simulation, we used Type 6 to get the output file PARMTEQOUT.TXT firstly. As the length of the beam is 3 ns and the incident particle energy is 30 keV, the value of $\Delta\phi$ was set to 180° and ΔW was set to 3 keV in the INPUT line of Type 6. After running the command of Pari.exe and Parmteqm.exe we read the twiss parameters from the output file PARMTEQOUT.TXT. Then we took the longitunal twiss parameters as the input parameters of Type 8 to design the RFQ. By the simulation of the code LMOVE these parameters are proved reasonable. The twiss parameters are listed in Table 3.

Table 3: Twiss Parameters at Cell 0

Parameter	x	y	z
α	2.8371	2.8448	0.0695
$\hat{\beta}$	5.5947 cm/rad	5.6667 cm/rad	59083.7874 Deg./MeV
$\varepsilon_{u,\ rms}$	3.0160 cm-mrad	3.0029 cm-mrad	0.1758 MeV-Deg.
$\varepsilon_{n,\ rms}$	0.02415 cm-mrad	0.02404 cm-mrad	0.17580 MeV-Deg.

In the INPUT file the parameters α_x, α_y and α_z are dimensionless, $\hat{\beta}_x$, $\hat{\beta}_y$ and $\hat{\beta}_z$ have units of cm/radian, and the unnormalized emittance terms ε_x, ε_y and ε_z have units of cm-radian. As one has to compare emittances parameters in both transverse and longitudinal directions to make sure whether some criteria are satisfied, we should convert units before using the parameters from the output file. The conversions of the longitudinal emittance and betatron functions are expressed in formula (5) and (6).

$$\varepsilon[cm\cdot rad]=\frac{1}{\dfrac{360}{\lambda[cm]}(m_0c^2)[MeV]\gamma^2\beta}\varepsilon[Deg.\cdot MeV] \quad (5)$$

$$\hat{\beta}[cm/rad]=\frac{\lambda[cm]}{360}(m_0c^2)[MeV]\gamma^3\beta^3\hat{\beta}[Deg./MeV] \quad (6)$$

The energy-spread which exists in the beginning of the cavity will lead the shape of the longitudinal phase-space to be an elongated ellipse. During simulation we set α as a negative value to convert the entrance ellipse to a tilted ellipse so that the beam could be ensured in the state of being bunched once it was transmitted into the cavity.

The beam dynamics for the input current of 75 mA is shown in Fig. 5. The transmission rate given by the code is 90.5%. Figure 6 shows the phase-space projections at the input of the RFQ and at the output of cell 281.

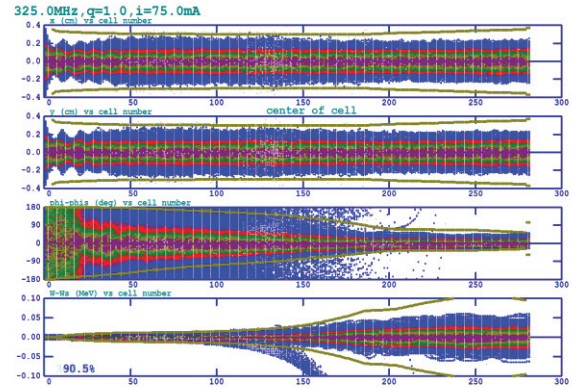

Figure 5: Beam dynamics in the RFQ for the input current of 75 mA, 5000 particles. From top to bottom are: x, y, phase, and energy coordinates versus cell number. The percentage transmission is 90.5%.

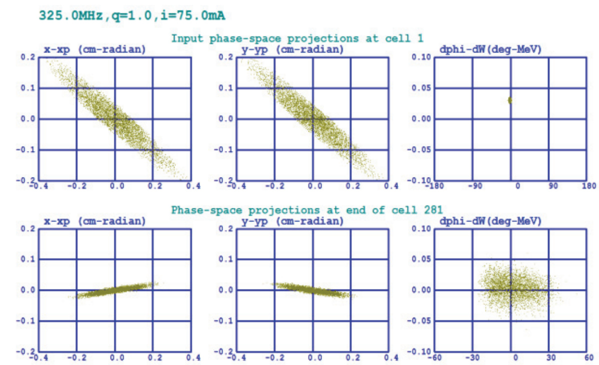

Figure 6: PARMTEQM simulation showing phase-space plots of the input beam and the beam at cell 281.

CONCLUSIONS

The transmission has been improved to 90% with the 10% of the entrance energy-spread. However, there is still much work needs to be done to optimize the beam transport. More effort should be put on the design of the LEBT in the next stage. After the dynamics design we will start the work of structure design.

ACKNOWLEDGMENT

The author thanks all the colleagues who give fruitful discussions and helpful suggestions.

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