CNIC-01638/18
CNNC-0003

Beam Dynamics Design and Error Study of the 5 MeV RFQ

LUO Zihua FU Shinian WANG Linlin
Institute of High Energy Physics, The Chinese Academy of Sciences, Beijing, 100039
GUAN Xialing
China Nuclear Data Center, CIAE, Beijing, 102413
GUO Zhiyu
Beijing University, IHIP, Beijing, 100078

Abstract: An RFQ, which will be operated at 352 MHz frequency and 6% duty factor and will accelerate 50 mA proton beam from 80 keV to 5 MeV, has been proposed as an injector of the verification facility of Accelerator Driven System (ADS) for Radioactive Clear Nuclear Power System in China. The RFQ general layout and beam dynamics simulation and error study are described.

Key words: Beam dynamics, RFQ, Simulation, Error

INTRODUCTION

In November 2000 it was considered to construct an RFQ as an injector of the verification facility of ADS in China. Then we started to do the conceptual design of the RFQ. According to the design requirements, the RFQ will be operated at 352 MHz frequency and 6% duty factor. The RFQ will accelerate 50 mA of peak proton beam current from 80 keV to 5 MeV and deliver it to the DTL, which keeps the same frequency of the RFQ. The RFQ transverse acceptance is sufficient to accelerate beams up to 50 mA output current with a normalized emittance less than 0.2 πmm • mrad (r. m. s.) and with a transmission efficiency of greater than 95%. The RFQ power consumption needed is near 900 kW. The design requirements of our RFQ are listed in Table 1.

Table 1 Design requirements of our RFQ

Particle	H+
Energy input/output	80 keV/5 MeV
Peak beam current	50 mA
Tran. norm. emittance, r. m. s.	0.2 πmm • mrad
Duty factor	6%
Frequency	352 MHz
Beam transmission	>95%
Peak RF power consumption	<900 kW

1 BEAM DYNAMICS DESIGN

According to the beam dynamics design, our RFQ is divided into four sections: the radial matcher, the shaper, the gentle buncher and the accelerator. The first six cells is the radial matching section, where the proton beam is gradually matched to the time dependent transverse focusing system. The next 93 cells is the shaper section where the bunching process is initiated with a slow decrease of stable phase from −90 to −83.1 degree and with a slow increase of modulation parameter m from 1 to 1.1038. The next 139 cells is the gentle buncher section, where the stable phase is decreased to −38 degree, the parameter m is increased to 1.794, the proton beam is brought to 514 keV and fully bunched. At the end of the gentle buncher section, where the beam has achieved its minimum bunch length, space charge forces on the beam are at a maximum and the aperture (a=2.05 mm) is at a minimum. The final 173 cells is the accelerator section. In order to shorten the RFQ length and to get more accelerating efficiency, in this section the stable phase and parameter m are not constant. The stable phase is gradually varied from −38 degree to the end of −29 degree and the parameter m is slowly varied from 1.794 to the end of 1.943. And the proton beam is accelerated to 5 MeV at the end of RFQ. In the accelerator section, that corresponds to more than 3/4 of the total structure length. Our RFQ has a total of 411 cells and a length of 7.13 meters, corresponding to 8.3 times the wavelength in free space. In order to extend the mode distant respect to the closest quadrupole modes and to sure the operation stability, the segmented resonantly coupled four vanes structure has been chosen for our RFQ [1, 2]. The RFQ has three of coupled segments and two of coupled gaps. In our case the operating mode is more than 2 MHz distant respect to the closest quadrupole modes, and the dipole modes are outside the range of the main quadrupole band. The inter-vane voltage is kept constant of 68 kV along the structure, while the average aperture R_0 is increased so to allow a higher electrode modulation keeping the necessary aperture *a*. This choice allows to shorten about 0.6 m (see Table 3) RFQ length and to save the RF power, near 54 kW (see Table 3), without a ramp of the inter-vane voltage. The main parameters of our RFQ are shown in Fig. 1 and listed in Table 2.

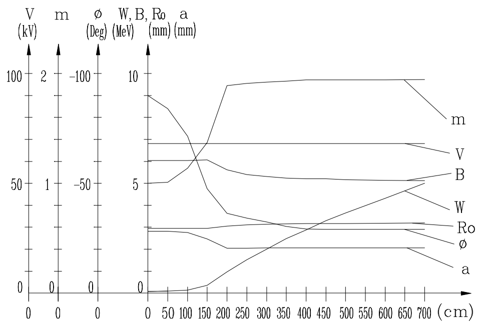


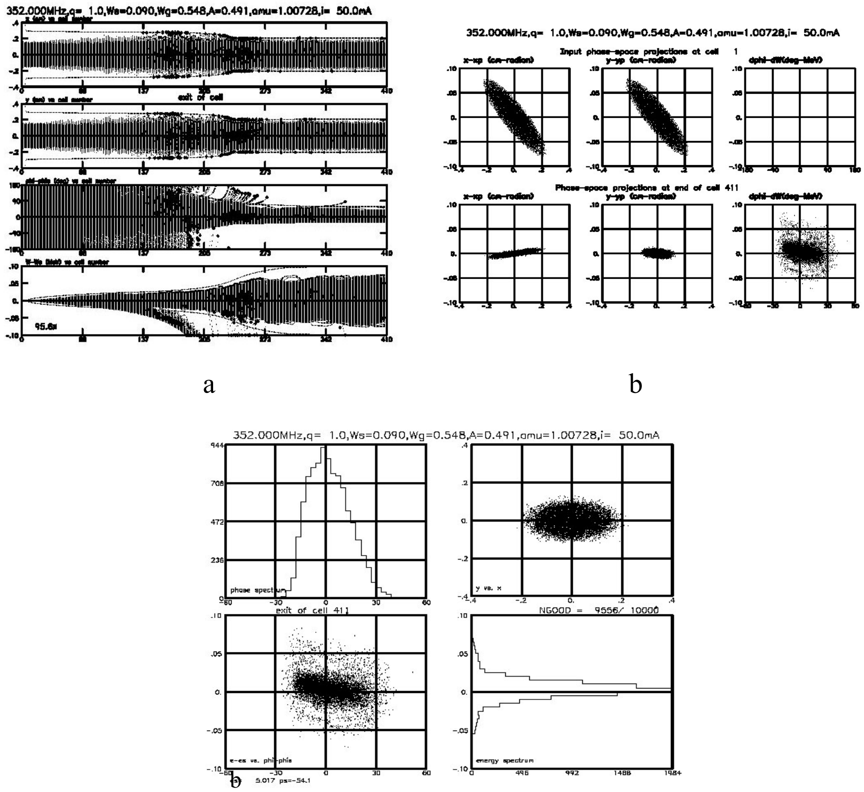
Fig. 1 Main parameters of RFQ versus length

Table 2 Main parameters of our RFQ

Inter-vane voltage	68 kV
Tran. focusing parameter B	6.08～5.116
Modulation parameter m	1～1.943
Stable phase	−90～ −29 Deg.
Beam transmission	> 95%
Max. surface field	< 33 MV/m
Dissipated power (SF*1.3)	0.627 MW
Peak beam loading power	0.246 MW
Total peak RF power	0.873 MW

Table 2 (Continued)

Average aperture	2.93～3.19 mm
Minimal aperture	2.05 mm
RFQ length	713 cm
Number of coupled segment	3
Number of coupled gap	2



c

Fig. 2 Beam simulation of the RFQ for 50 mA current

(a) shows the PARMTEQM simulation of the RFQ using 10000 macro particles. From top to bottom are: x, y, phase and energy coordinates versus cell number. Bold black points indicate the lost particles in RFQ. (b) shows the phase-space projections at input of cell 1 and output of cell 411. (c) shows the beam profile and phase spectrum at output of cell 411

The beam simulation of the RFQ had been performed by codes of PARMTEQM and LIDOS.RFQ. The beam transmissions are 95.6% and 97.7% by PARMTEQM (with 10000 macro particles) and LIDOS.RFQ (with 50000 macro particles) respectively. The simulation results are rather similar. Fig. 2 shows the beam simulation results by PARMTEQM.

In our RFQ design there are some features as follows:

(1) The inter-vane voltage kept constant along the structure, so it is easier to adjust the field distribution along the length.

(2) The inter-vane voltage (68 kV) is low. And the parameter m and stable phase are specially varied in the accelerator section, so a more reasonable power dissipation and length of RFQ was achieved.

(3) Due to the adopting of a long and segmented resonantly coupled structure, the operating frequency is 2 MHz distant respect to the closest quadrupole modes.

(4) The beam transmission is high (>95%) and the increment of r. m. s. emittance along the *z* is low (<10%).

2 ERROR STUDY

An error study of the 5 MeV RFQ was carried out. The calculated sensitivity to initial beam alignment, mismatch, emittance and inter-vane voltage variation is shown in Fig. 3 to Fig. 9. Fig. 3 shows the transmission versus the displacement of the input beam. Fig. 4 shows the transmission versus the beam steering errors into the RFQ. Fig. 5 shows the transmission versus vane voltage factor that means the ratio of real voltage values to design one. If the vane voltage factor is less than 0.95, the beam transmission is sharply reduced. In order to maintain the high beam transmission in RFQ, the voltage factor must be kept more than 0.95. Otherwise the beam transmission is low. Fig. 6 shows the effect on transmission if the input beam is not at the correct energy of 80 keV design value. Fig. 7 and Fig. 8 show the transmission versus the input beam emittance and current respectively. Observably, the emittance and current are lower and lower, the transmission can be get higher and higher. In order to get a good transmission, the emittance is as low as possible. Fig. 9 shows the transmission versus the tilt factor. On the basis of the simulation a tolerance of about ±2.5% per meter tilt with respect to the nominal field is required for good performance of the RFQ. From the error study we can conclude that a high beam transmission is preserved in case of different error sources.

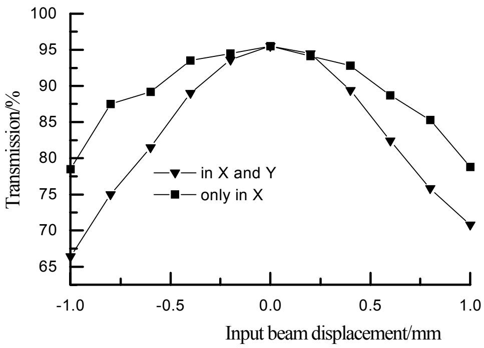


Fig. 3 Transmission vs input beam displacement

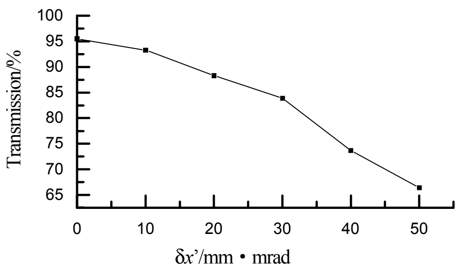


Fig. 4 Transmission vs beam angle

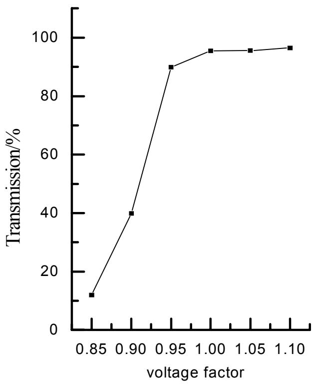


Fig. 5 Transmission vs voltage factor

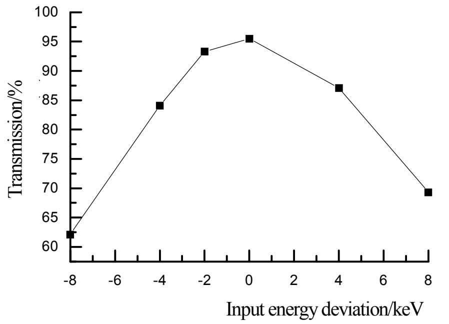


Fig. 6 Transmission vs input energy deviation

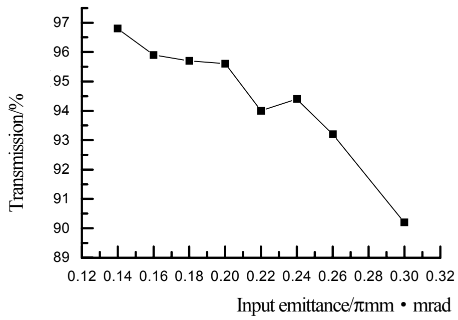


Fig. 7 Transmission vs input emittance

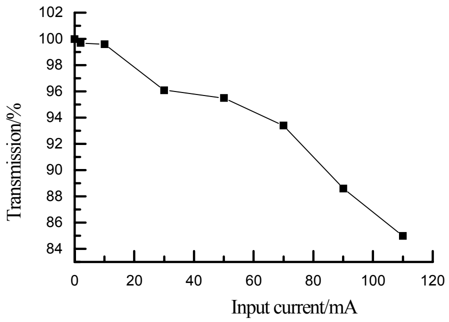


Fig. 8 Transmission vs input current

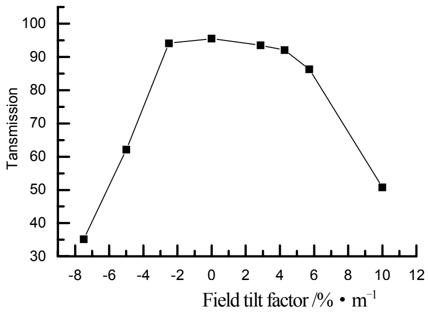


Fig. 9 Transmission vs field tilt factor

Table 3 Comparisons on the length and power for the two kinds of modulation law in the accelerator section

Modulation law in the accelerator section	Total length of RFQ/cm	Dissipated power of RFQ (SF*1.3)/kW
Kind 1 *m*=1.794 (constant)	773	681
Kind 2 *m*=1.794～1.943 (varied)	713	627
Difference	60	54

3 SUMMARY

(1) The beam dynamics design of the RFQ has been carried out, which will be operated at the 352 MHz frequency and will accelerate the 50 mA proton beam form 80 keV to 5 MeV.

(2) The beam simulation of the RFQ has been done by the codes of PARMTEQM and LIDOS.RFQ. At 50 mA the beam transmission is more than 95% and the emittance growth is less than 10%.

(3) The error study of the RFQ has also been done. The calculated sensitivity to the initial beam alignment, mismatch, emittance and inter-vane voltage variation is gotten. In order to have a high beam transmission, some values should been kept, such as

voltage factor >0.95
input energy deviation <1 keV
input beam displacement <0.2 mm
and so on.

ACKNOWLEGMENTS

The authors would like to extend their thanks to Prof. Fang Shouxian, all staff of ADS group of IHEP, CIAE and Peking University, to Dr. B.H. Choi and Dr. J.M. Han at KAERI and to Dr. A. P. Pisent and M. Comunian at INFN-LNL for the helps they given with the design.

REFERENCES

1 Young L M. Segmented Resonantly Coupled Radio Frequency Quadrupole (RFQ). I n proceedings of the 1993 Particle Accelerator Conference, (Washington D. C., May 17～20, 1993. 3136～3138

2 Young L M. An 8-meter-long Coupled Cavity RFQ Linac, in proceeding of the 1994 Linac Conference, 178～180

5 MeV RFQ 束流动力学设计模拟及误差研究

罗紫华 傅世年 王林林
中国科学院高能物理研究所， 北京，100039
关遐龄
中国原子能科学研究院，北京，102413
郭志虞
北京大学，北京，100871

摘 要： 一台出口能量 5 MeV 质子 RFQ 将作为中国洁净核能系统 ADS （Accelerator Driven System）验证装置的注入器，其工作频率 352 MHz，注入能量 80 keV，流强 50 mA。概述了这台 RFQ 的设计方法、束流动力学设计模拟及误差研究计算结果。

关键词： RFQ 束流动力学 模拟 误差