DESIGN AND SIMULATION OF A HIGH INTENSITY HEAVY ION RFQ ACCELERATOR INJECTOR*

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Abstract

An 81.25 MHz continuous wave (CW) radio frequency quadrupole (RFQ) accelerator has been developed for Low Energy Accelerator Facility (LEAF) at the Institute of Modern Physics (IMP), the Chinese Academy of Science (CAS). In the CW operating mode, the proposed RFQ design adopted the conventional four-vane structure. The main design goals are providing the high shunt impendence with low power losses. In the electromagnetic (EM) design, the π-mode stabilizing loops (PISLs) were optimized to produce a good mode separation. The tuners were also designed and optimized to tune frequency and field flatness of the operating mode. The vane undercuts were optimized to provide a flat field along the RFQ cavity. Additionally, a full length model with modulations was set up for the final EM simulations. In this paper, detailed EM design of the LEAF-RFQ will be presented and discussed. Meanwhile, structure error analysis is also studied.

INTRODUCTION

LEAF project was launched as a pre-research facility for high intensity Heavy Ion Accelerator Facility (HIAF) project [1, 2] at IMP. The LEAF will consist of a 2 mA U^{34+} electron cyclotron resonance ion source, a low energy beam transport line [3], a CW 81.25MHz RFQ accelerator, a medium energy beam transport and an experimental platform for nuclear physics. The layout of the LEAF project is shown in Fig. 1. The LEAF-RFQ will be adopted and used in the HIAF project.

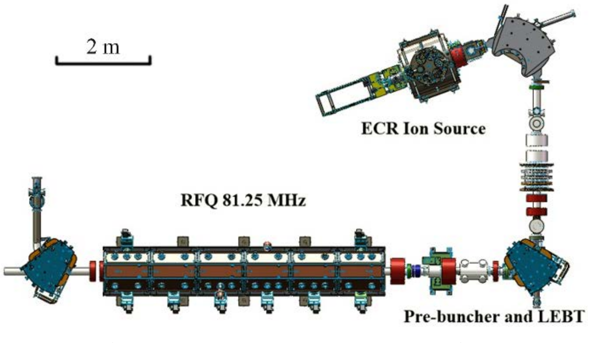

Figure 1: Layout of LEAF project.

The design goal is to design a compact type cavity with lower power loss and high operation stability. Considering that LEAF-RFQ will operate at CW mode, four-vane structure is a better choice than four-rod type [4], which is a more stable structure and has better water cooling. Dipole mode can be excited if the dipole frequency is very close to operating frequency. Therefore, a good frequency separation is always a basic task to diminish the dipole mode effect. There are several methods proposed fighting against the dipole effect, such as, the vane coupling ring [5], PISL [6] and dipole stabilizer rod [7]. PISL is a good choice because it is easy to be cooled. Meanwhile, tuners and undercuts [8] are also used for frequency tuning and field flatness.

In this paper, we focus on EM design and report detailed RF simulations using CST Microwave Studio (MWS) [9]. All parts of the resonator such as PISLs, tuners, and undercuts have been taken into account. Additionally, a complete RFQ model with vane modulations has been built and simulated.

PARAMETERS AND STRUCTURE

According to the requirements of the LEAF project, parameters of LEAF-RFQ are summarized in Table 1.

Table 1: LEAF-RFQ Main Parameters

Parameters	Value
Particle charge state	U^{34+}
Operation	CW/pulsed
Vane type	Four vane
Frequency (MHz)	81.25
Input energy (keV/u)	14
Output energy (MeV/u)	0.5
Inter-vane voltage (kV)	70
Kilpatrick factor	1.55
Peak current (emA)	2
Transmission efficiency (%)	97.2
Length of vane (mm)	5946.92
Average radius of aperture (mm)	5.805

ELECTROMAGNETIC SIMULATIONS

The LEAF-RFQ cross-section has been optimized with the CST MWS. As a result, the cross-section geometry is shown in Fig. 2. The cross-section profile is defined with nine independent variables. Their final optimized values are indicated in the Table 2. In all subsequent 3D simulations, these parameters of cross-section are fixed except H.

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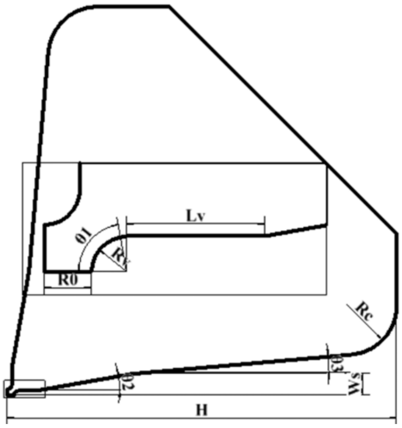

Figure 2: Geometry of LEAF-RFQ cross-section.

Table 2: Parameters of LEAF-RFQ Cross-Section

parameter	value	parameter	value
R0	5.805 mm	Ws	20 mm
Rv	4.354 mm	θ3	5°
θ1	80°	Rc	50 mm
Lv	17 mm	H	360.5 mm
θ2	10°		

In order to study the mode separation between the main quadrupole mode and neighboring dipole mode, the EM simulations of PISL period RFQ model were performed without modulations. As shown in Fig. 3, PISL period of model includes two pairs of PISLs and eight tuners.

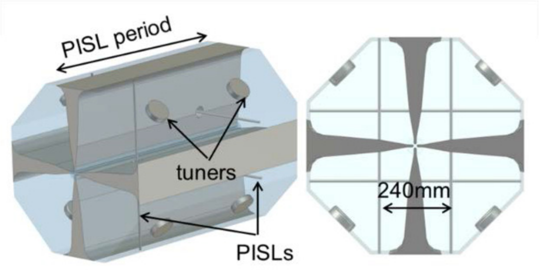

Figure 3: PISL period model of LEAF-RFQ.

Table 3: Frequency Separation Comparison

Parameters	Without PISLs	With PISLs
Frequency (MHz)	81.233	81.173
Nearest dipole mode frequency (MHz)	78.765	86.739
Q-D separation (MHz)	-2.468	5.566

After optimization, as shown in Fig. 3, the PISLs have 10 mm outer diameter and pass through 50 mm holes in the vanes. After simulations, the RF parameters are shown in Table 3. Without PISLs, the dipole mode frequency is 2.468 MHz lower than the operating frequency. However, the dipole mode frequency is 5.566 MHz higher than operating frequency with PISLs.

For frequency and field distribution tuning, the RFQ will be equipped with a total of 48 slug tuners. Figure 4 is the sketch map of tuners, which have a diameter of 100 mm and are uniformly distributed along the beam direction. According to the linear fitting shown in Fig. 5, tuning sensitivity of tuners equals 15.21 kHz/mm.

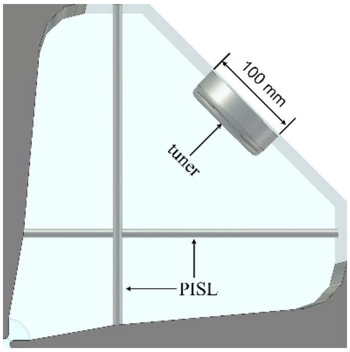

Figure 4: Sketch map of tuner.

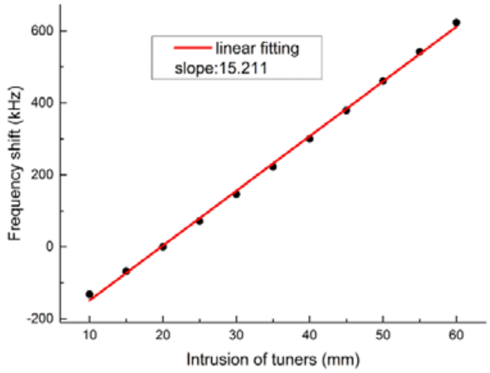

Figure 5: Tuning sensitivity for all tuners.

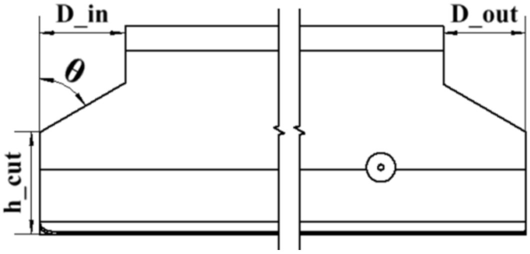

Figure 6: Sketch map of undercuts.

Table 4: Tuned Undercuts Parameters

h_cut	θ	D_in	D_out
180 mm	60°	143 mm	139 mm

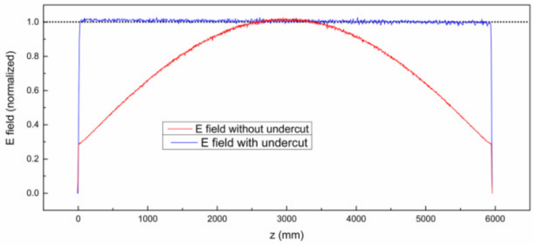

Figure 7: Normalized electric field amplitude distribution along inter-vane without undercut and with undercut.

Field flatness is very sensitive to the dimensions of undercuts. The sketch map of undercuts is shown in Fig. 6. Electric field amplitude distribution is monitored along the line in the gap between vane tips. Without undercuts, as shown in Fig. 7, the field has a bad flatness. When tuned undercuts parameters are shown in Table 4, there is a flat field distribution as shown in Fig. 7. Here are the depths of undercuts: depth for entrance (D_in) equals 143 mm and depth for exit (D_out) equals 139 mm.

The sketch map of the complete RFQ model is shown in Fig. 8. Through simulations with MWS, the final RF parameters are listed in Table 5.

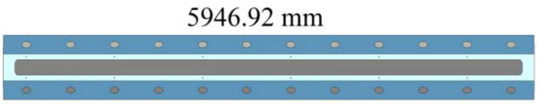

Figure 8: The sketch map of complete RFQ model.

Table 5: Final RF Parameters

Parameters	Value
Frequency（MHz）	81.261
Nearest dipole frequency (MHz)	86.827
Q factor	17963
Power loss（kW）	53.196

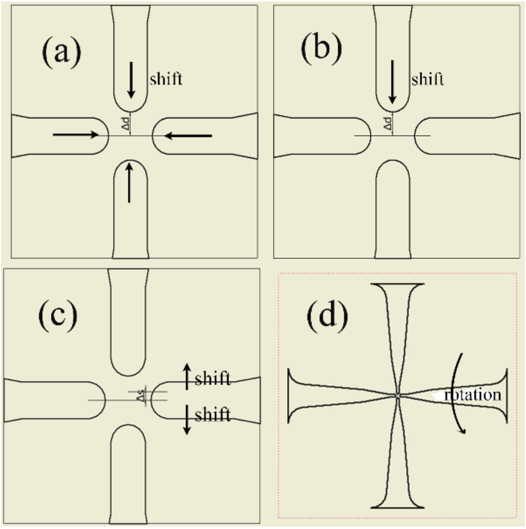

Figure 9: Main causes of structure error. (a) all vane deviation; (b) one vane deviation; (c) one vane skew; (d) one vane rotation.

STRUCTURE ERROR ANALYSIS

After machining and assembling, some errors must occur in the RFQ structure. Structure error analysis has been done to minimize the structure errors. There are many reasons leading to structure error. To simplify the simulations, some of the main causes have been taken into considerations. As shown in Fig. 9, all vanes deviation (a), one vanes deviation (b), one vane skew (c) and one vane rotation (d) were simulated for the frequency shift. Fittings were taken out to discover the law of error influence. According to these fitting equations, guidance for machining could be done for frequency control.

The fittings are summarized as follows:

a) all vanes deviation:

$$\Delta f/\Delta d = 3.58\ (\mathrm{kHz/\mu m})$$

b) one vane deviation:

$$\Delta f/\Delta d = 0.92\ (\mathrm{kHz/\mu m})$$

c) one vane skew:

$$\Delta f\ (\mathrm{MHz}) = -0.244(\Delta s(\mathrm{mm}))^2$$

d) one vane rotation:

$$\Delta f\ (\mathrm{MHz}) = -0.244(\Delta\theta(\mathrm{degree}))^2$$

CONCLUSION

LEAF-RFQ has been designed and simulated and the EM designs were performed. The RFQ is an octagon four-vane type with 48 tuners and 12 pairs PISLs. It is about 6 m long with a good mode separation and a flat field distribution between inter-vanes. A complete model of LEAF-RFQ has been built and simulated.

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