ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL011

LOW POWER TEST AND TUNING OF THE LEAF RFQ*

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Abstract

A continuous wave (CW) four-vane radio frequency quadrupole (RFQ) accelerator is under construction for the Low Energy Accelerator Facility (LEAF) at Institute of Modern Physics (IMP). The 5.96 m RFQ will operate with the capability of accelerating all ion species from proton to uranium from 14 keV/u up to 500 keV/u. In this paper, the low power test and tuning results of the RFQ accelerator, including the test of the separate sections and the whole cavity, will be presented. After the final tuning, the relative error of the quadrupole field is within 2% and the admixture of the dipole modes are below 4% of the quadrupole mode.

INTRODUCTION

Since invented by I. M. Kapchinskii and V. A. Teplyakov in 1970 [1], the Radio Frequency Quadrupole (RFQ) accelerator always plays an extremely important role in proton and heavy ion acceleration. The Low Energy Accelerator Facility (LEAF) project, shown in Fig. 1, was launched as tools for irradiation material research, highly charged atomic physics and low energy nuclear astrophysics. As a part of the facility, an 81.25 MHz four-vane continuous wave (CW) heavy ion RFQ [2] has been developed. This RFQ with a constant inter-vane 70 kV voltage could accelerate the uranium beam from 14 keV/u to 500 keV/u within 5.97 m length. It is divided into six sections. The main parameters of the RFQ are listed in Table 1.

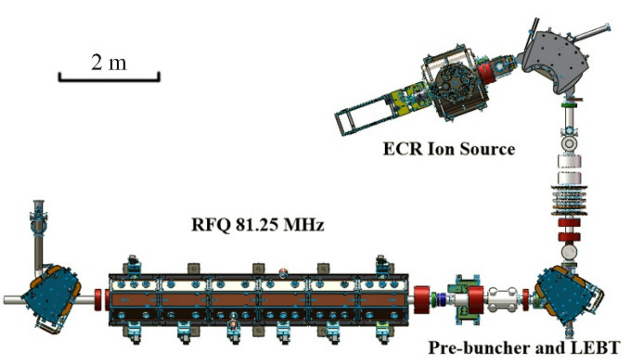

Figure 1: Layout of LEAF project.

The fabrication and low power test of the LEAF RFQ have finished. In this paper, the detailed process of the LEAF RFQ low power test and tuning will be presented.

* Work supported by NSFC of China under Grant No. 11427904 and No. 114535016,
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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

LOW POWER TEST AND TUNING THEORY

According to the Slater perturbation theorem [3], the perturbation induced by inserting a small perturbing object will shift the resonant frequency in the cavity . The local electrical field amplitude could be measured by the resonant frequency shift as the equation

$$\frac{\Delta f}{f_0} = -\frac{cV}{U} E^2 \quad (1)$$

where Δf is the frequency shift, f_0 is the resonant frequency, c is a constant, V is the volume of the perturbing object, U is the stored energy in the cavity, E is the electrical field amplitude.

The resonant frequency can be measured by the vector network analyzer (VNA). Before the perturbing object inserted into the cavity, the measured frequency is the reference frequency for calculating the frequency shift. Through this method, the local electrical field amplitude in each quadrant can be measured and marked as $\mathbf{E}_1$, $\mathbf{E}_2$, $\mathbf{E}_3$, $\mathbf{E}_4$. The quadrupole mode field amplitude is given by

$$\mathbf{E}_Q = \frac{\mathbf{E}_1 + \mathbf{E}_2 + \mathbf{E}_3 + \mathbf{E}_4}{4} \ . \quad (2)$$

The relative error of the quadrupole field is given by

$$U_Q = \frac{\mathbf{E}_Q}{mean(\mathbf{E}_Q)} - 1 \ . \quad (3)$$

The two dipole mode field amplitudes are given by

9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL011

$$\begin{cases} \mathbf{E}_{\mathrm{D13}} = \dfrac{\mathbf{E}_1 - \mathbf{E}_3}{2} \\ \mathbf{E}_{\mathrm{D24}} = \dfrac{\mathbf{E}_2 - \mathbf{E}_4}{2} \end{cases} . \tag{4}$$

The admixtures of the two dipole modes are given by

$$\begin{cases} U_{D13} = \dfrac{\mathbf{E}_{\mathrm{D13}}}{mean(\mathbf{E}_Q)} \\ U_{D24} = \dfrac{\mathbf{E}_{\mathrm{D24}}}{mean(\mathbf{E}_Q)} \end{cases} . \tag{5}$$

According to the transmission line model, the required local frequency shift by adjusting the depths of tuners is given by

$$\Delta f(\mathrm{z}) = \frac{c^2}{8\pi^2 f} \frac{V''(\mathrm{z})}{V(\mathrm{z})} , \tag{6}$$

where $\Delta f(\mathrm{z})$ is the frequency shift, f is the resonance frequency, c is the speed of light, V is the inter-vane voltage.

The depth variations of tuners are given by

$$\Delta D(\mathrm{z}) = \frac{\Delta f(\mathrm{z})}{\delta} , \tag{7}$$

where δ is the frequency sensitivity of tuner depth.

According to this algorithm, the local field could be modified to the desired distribution. However, the depths of tuners should be corrected to meet the requirement of the resonant frequency. This issue can be solved through inserting all the tuners or pulling all the tuners out as a whole. After several cycles of measuring, analyzing and adjustment, the RF parameters will satisfy the requirements.

LOW POWER TEST AND TUNING PROCESS OF THE LEAF RFQ

To get the structure error in fabrication, the inter-vane distances were measured at 32 positions along the cavity by the gauges. The designed distance and the measured distance before and after brazing are illustrated in Fig. 2. Compared to the designed inter-vane distances, the maximum errors are -36.83 μm and 43.89 μm. According to the previous analysis [2], the errors of the measuring points are all in an acceptable range.

The sketch map of the LEAF RFQ low power test system is shown in Fig. 3. The VNA feeds the signal to the cavity and extracts the signal from the cavity by the RF pick-ups. The signal data is transmitted to the Industrial Personal Computer (IPC) through the General-Purpose Interface Bus (GPIB). The IPC can analyze and process the measured data. The motion speed and direction of the perturbing object are controlled by the motor system. A teflon perturbing object, shown in the Fig. 4, will be clung to the vanes during moving. Through this method, the object could travel along a straight line. The tuners with diameter of 100 mm are uniformly distributed along the beam direction. The resonant frequency sensitivity of tuner depth is 15.21 kHz/mm.

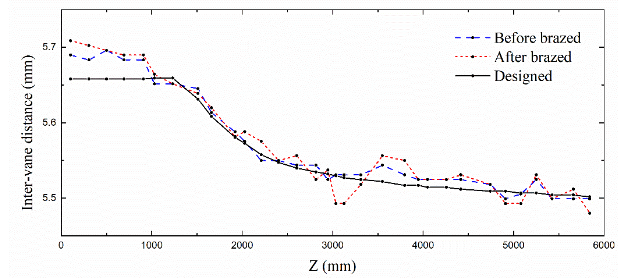

Figure 2: The designed inter-vane distances and measured inter-vane distances before and after brazing.

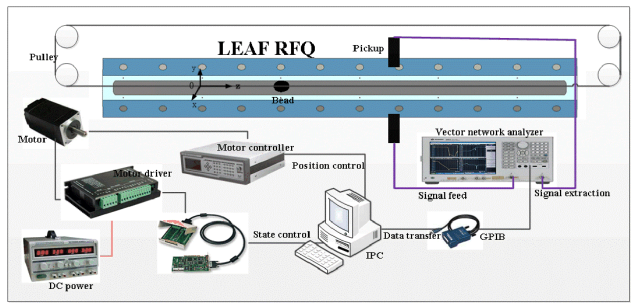

Figure 3: The sketch map of the LEAF RFQ low power test system.

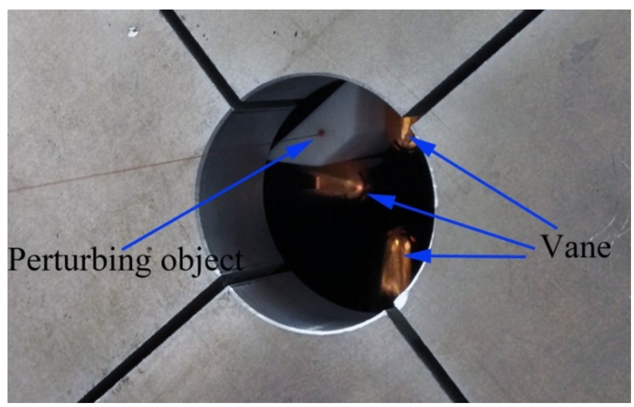

Figure 4: The teflon perturbing object used in the low power test.

The low power tests and tuning of the whole cavity were carried out in three steps. Firstly, frequencies, Q factor and fields were measured in the cavity with aluminum end-plates and aluminum tuners inserted into the cavity 26 mm, the same situation as the simulation. Secondly, through the tuning code LRFQ tuning (a code developed for LEAF RFQ tuning based on Matlab [4]), the depths of the tuners were adjusted to meet the requirements of frequency and fields. After a few iterations, a satisfactory resonant frequency and field distribution will be achieved. Lastly, the copper tuners with the final insertion and copper end-plates replaced the aluminum ones. This step was to check the resonant frequency and field distribution, meanwhile, the Q factor was measured.

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The up is the quadrupole field relative error, the middle is the admixture of dipole fields, the down is normalized field distributions.

After the tuning process, the final inserting depths of the tuners are listed in Table 2. The final quadrupole mode frequency is 81.254 MHz. The measured Q factor is 16230, which is about 90% of the simulated. The measured mode spectrum is shown in Fig. 5. Q0 mode is the operation mode, Q1 mode is the first order quadrupole mode, D10 mode and D20 mode are the dipole mode.

With aluminum end-plates and aluminum tuners with the final depths, the relative error of the quadrupole field (Q) is less than 0.5%, the admixtures of the two dipole modes (D13 and D24) are within 1.5% of the quadrupole field. According to the the final depths of the aluminum, the copper tuners were manufactured. Equipped with the copper tuners, the field distributions were measured by the same method. The relative error of Q mode is less than 0.8% and admixtures of the dipole modes are within 1%, as shown in Fig. 6.

After the tuning process, the final inserting depths of the tuners are listed in Table 2. The final quadrupole mode frequency is 81.254 MHz. The measured Q factor is 16230, which is about 90% of the simulated. The measured mode spectrum is shown in Fig. 5. Q0 mode is the operation mode, Q1 mode is the first order quadrupole mode, D10 mode and D20 mode are the dipole mode.

Table 2: The Final Inserting Depths of the Tuners

	Quadrant 1 (mm)	Quadrant 2 (mm)	Quadrant 3 (mm)	Quadrant 4 (mm)
1	29.86	29.83	29.89	29.93
2	29.95	29.94	29.99	30.00
3	30.07	30.07	30.12	30.11
4	30.19	30.20	30.25	30.23
5	30.27	30.29	30.34	30.32
6	30.31	30.33	30.37	30.35
7	30.26	30.30	30.35	30.32
8	30.17	30.22	30.26	30.21
9	30.06	30.10	30.13	30.09
10	29.96	29.99	29.98	29.95
11	29.89	29.91	29.86	29.85
12	30.05	30.04	29.89	29.90

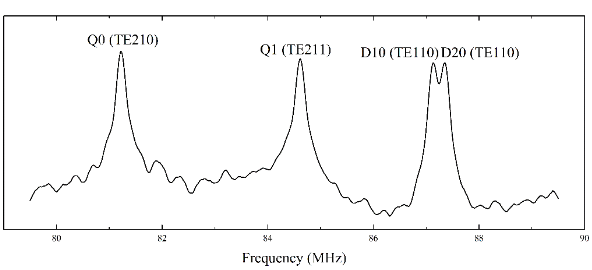

Figure 5: The measured mode spectrum in the LEAF RFQ cavity.

With aluminum end-plates and aluminum tuners with the final depths, the relative error of the quadrupole field (Q) is less than 0.5%, the admixtures of the two dipole modes (D13 and D24) are within 1.5% of the quadrupole field. According to the the final depths of the aluminum, the copper tuners were manufactured. Equipped with the copper tuners, the field distributions were measured by the same method. The relative error of Q mode is less than 0.8% and admixtures of the dipole modes are within 1%, as shown in Fig. 6.

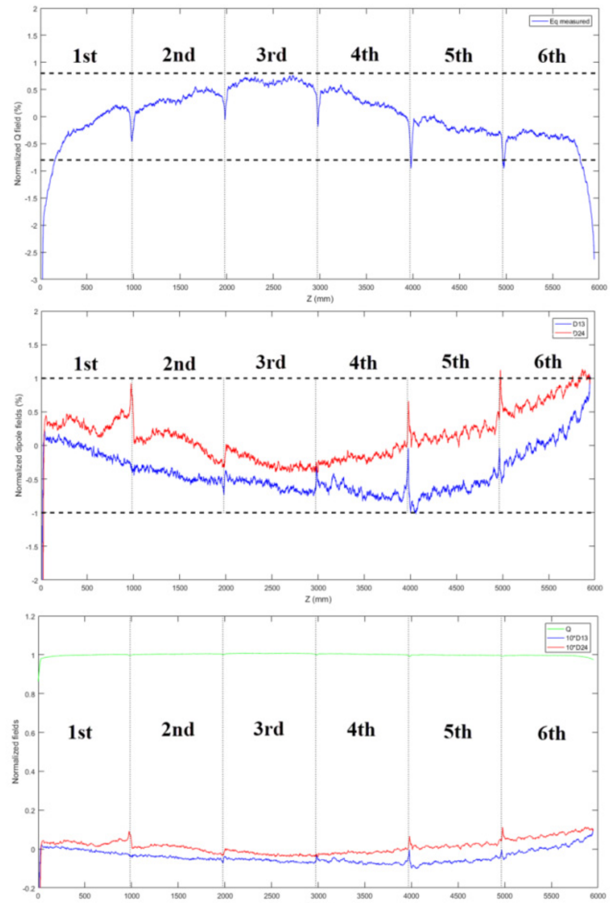

Figure 6: The longitudinal field distributions in the cavity with aluminum end-plates and copper tuners with the final depths.

From above process, the final TE210 mode frequency is very close to the operation frequency and it is could be easily tuned by adjusting the cooling water temperatures based on the previous study [5]. The field distributions meet the requirements. Therefore, the LEAF RFQ tuning with the slug tuners is accomplished.

CONCLUSION

The low power test and tuning of the LEAF radio frequency quadrupole (RFQ) have been carried out. The LEAF RFQ is the first constant-voltage continuous-wave four-vane heavy-ion RFQ. Because its cavity is long and large, the low power test is easily influenced by the gravity effect. Special perturbing object is used to ensure it move along the straight line. It is a solution for the low power test in other long accelerator cavities to remove the gravity effect. After careful adjustments of the tuner depths, the resonant frequency is very close to the opera-

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tion frequency. The relative error of the quadrupole field is less than 1% and the admixtures of the two dipole modes are within 1.5% of the quadrupole field. The results are far better than the required values. Therefore, the frequency and field distribution meet the operation requirement.

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