DESIGN AND BEAM COMMISSIONING OF THE LEAF-RFQ

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Abstract. An 81.25 MHz continuous wave (CW) radio frequency quadrupole (RFQ) accelerator has been designed and fabricated for the Low Energy Accelerator Facility (LEAF) by the Institute of Modern Physics (IMP) of the Chinese Academy of Science (CAS). The operation frequency is 81.25 MHz and the inter-vane voltage is a constant of 70 kV. It took about 44 hours continuous conditioning to reach RF power of 75 kW which is 1.1 time of the maximum designed value, and the successful CW acceleration of 150 eµA He+ beam to the designed energy of 0.5 MeV/u was already done. The results of the low power test, the RF conditioning and the beam acceleration will be reported in this paper.

1. Introduction
The LEAF project was launched as a pre-research facility for the high intensity Heavy Ion Accelerator Facility (HIAF) project and a heavy ion irradiation facility for material research at IMP [1, 2]. The LEAF will consist of a 2 mA U34+ electron cyclotron resonance ion source, a low energy beam transport line, a CW 81.25MHz RFQ accelerator [3], a medium energy beam transport line and an experimental platform for nuclear physics. The layout of the LEAF project is shown in Fig. 1. The LEAF-RFQ shown in Fig. 2 will operate as a CW injector with the capability of accelerating all ion species from proton to uranium from 14 keV/u up to 500 keV/u. The design goal of the LEAF-RFQ is to design a cavity with high power efficiency and high operation stability. Considering the LEAF-RFQ will operate in CW mode, a four-vane structure is a better choice than four-rod type, because the four-vane structure is a more stable structure for water cooling. The PISL (Pi-mode stabilizing loop) structure is adopted to suppress the dipole effect. In addition, tuners and undercuts are used for frequency tuning and field flatness. The main parameters of the LEAF-RFQ are listed in the Table 1. In this paper, we report the designs and results of the low power test and the high-power acceleration.

2. Design and low power test
The LEAF-RFQ is an octagon normal 4-vane structure with uniform-distributed 48 tuners and 12 pairs PISLs. The RFQ is 6 m long and adopts two RF couplers. Based on our simulations

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Figure 1. Layout of the LEAF facility.

Figure 2. Side view of installed RFQ after full assembly on site.

Table 1. Main Parameters of the LEAF-RFQ.

| Parameters               | Value               |
|--------------------------|---------------------|
| A/q                      | 7                   |
| Operation                | CW/plused           |
| Frequency                | 81.25 (MHz)         |
| Input energy             | 14 (keV/u)          |
| Output energy            | 0.5 (MeV/u)         |
| Inter-vane voltage       | 70 (kV)             |
| Kilpatrick factor        | 1.55                |
| Peak current             | 2 (emA)             |
| Transmission efficiency  | 97.2 (%)            |
| Acceleration efficiency  | 81.7 (%)            |
| Length of vane           | 5946.92 (mm)        |
| Average radius of aperture | 5.805 (mm)        |

of the thermal analysis and multipacting, the RFQ could operate very stable. For fabrication, the RFQ was divided 6 segments. Each segment was connected by screws. The low power tests and the tuning of the RFQ were carried out through 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 a tuning code, 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 aluminum those. This step was to check the resonant frequency and field distribution, meanwhile, the $Q$ factor was measured.

The LEAF-RFQ low power test consists of each section test and the whole cavity test. The low power tests of single section were carried out to check the machining and brazing quality. The average frequency difference between the simulated and the measured after brazed is 10.15 kHz. The average frequency difference between the measured before brazed and after brazed is 23.35 kHz. Shown in Table 2, the low power test of the full length RFQ showed that the final quadrupole mode frequency is 81.253 MHz which meets well with the design value of 81.25 MHz, the measured $Q$ factor is 16230 which is 90.3% of the simulated value and the measured frequency separation was 5.54 MHz which is enough for safe operation. Fig. 3 shows the measured longitudinal field distributions of the quadrupole, two dipole fields in the cavity with the tuned tuners [4]. 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. Therefore, the frequency and field distribution meet the operation requirement.

### Table 2. Main Parameters of the LEAF-RFQ.

| Measured results     | Value                     |
|----------------------|---------------------------|
| Quadrupole frequency | 81.253 (MHz)              |
| $Q$ factor           | 16230 (90.3(%))           |
| $Q$ field relative error | 0.8 (%)                |
| Admixture of dipole field | 1.5 (%)            |
| Separated $\Delta f$ | 5.587 (MHz)              |

**Figure 3.** Measured $Q$ and D field of the LEAF-RFQ.

3. **RF Conditioning and Beam Commissioning**

After installing vacuum pumps, couplers, cooling routers, ARC detectors and pick-ups, and connecting with two 60 kW solid state type RF sources, the RF conditioning was started from Feb. 3rd, 2018 aiming to 75 kW (1.12 times of necessary power). The conditioning was performed carefully from several milli-Watts at CW mode, by monitoring the vacuum and reflected rf power, we achieved CW 15 kW in 2 hours and the goal of 75 kW in 44 hours. In the conditioning, the discharge did not occur and the pressure of cavity was better than $5 \times 10^{-4}$ Pa.

With installing of steering magnets and other detectors, the beam conditioning was restarted in June 1st, 2018, the beam transmission and acceleration efficiency were measured 97.21% and...
50.11%, respectively. The LEAF-RFQ was designed for all species ion acceleration, and the designed Kilpatrick factor was 1.54. The \( \text{He}^+ \) beam was adopted for first beam commissioning. The first pulse beam passed the RFQ in Feb. 3\(^{rd} \) 2018. The beam current was measured 100 \( \mu \text{A} \), and the beam energy was measured 500 keV/u which meet the designed value. The first CW \( \text{He}^+ \) beam passed the RFQ in two hours after finishing the pulse beam measurements. The current of the CW beam achieved 150 \( \mu \text{A} \).

The measured transmission agreed well with the design. The acceleration efficiency is lower than the design, the reason is that a multi-harmonic buncher (MHB) is absent from the low energy beam transport line. Shown in Fig. 4 and Fig. 5, in Sep. 5\(^{th} \), 2018, the first \( \text{N}^2^+ \) beam was successfully accelerated 110 \( \mu \text{A} \) up to the designed 500 keV/u with 97.97% transmission and 56.45% acceleration efficiency. The CW 110 \( \mu \text{A} \) \( \text{N}^2^+ \) beams passed 15 minutes.

**4. Conclusion and Future Plan**

The LEAF-RFQ had been designed and simulated, and the beam test was successfully 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. According to the high-power test, several milestone goals have been achieved, such as the successful RF conditioning of LEAF-RFQ to its maximum designed power, and the successful CW acceleration of \( \text{He}^+ \) beam and \( \text{N}^2^+ \) beam to the designed energy of 500 keV/u were already commissioned. Both the measured beam transmission and beam acceleration efficiency agreed the designs.
References
[1] Yang J, Xia J, Xiao G, Xu H, Zhao H, et al. Nucl. Instr. Meth. B, 317 (2013) 263-5.
[2] Li C, Sun LP, He Y, et al, Nucl. Instr. Meth. A 729 (2013) 426-33.
[3] Wei Ma, L. Lu, Xianbo Xu, Liepeng Sun, et al. Nucl. Instr. and Meth. in Phys. Res. A, 847 (2017) 130-135.
[4] Wei Ma, L. Lu, Ting Liu, Longbo Shi, et al., Nucl. Instr. and Meth. in Phys. Res. A, 901 (2018) 180-188.