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INITIAL BEAM COMMISSIONING OF LEAF AT IMP*

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Abstract

A Low Energy intense-highly-charged ion Accelerator Facility (LEAF), which mainly includes an ECR ion source, LEBT and an 81.25 MHz RFQ, was designed to produce and accelerate heavy ions, from helium to uranium with A/Q between 2 and 7, to the energy of 0.5 MeV/u. The typical beam intensity is designed up to 2 emA CW for the uranium beam. The facility has been successfully commissioned with He^{+} (A/Q=4) and N^{2+} (A/Q=7) beams and accelerated the beams in the CW regime to the designed energy of 0.5 MeV/u. Beam properties and transmission efficiencies were measured, indicating a good consistency with simulated data. After having briefly recalled the project scope and parameters, this paper describes the beam commissioning strategy and detailed commissioning results.

INTRODUCTION

A Low Energy intense-highly-charged ion Accelerator Facility (LEAF) was launched at IMP in 2015 for researches of irradiation material, highly charged atomic physics, low energy nuclear astrophysics, *et. al*. Meanwhile, this facility can be a prototype of the frontend of HIAF project [1] which is a new national project proposed by IMP and officially approved for heavy ion related researches. LEAF is mainly composed of a superconducting ECR ion source, a LEBT line and a RFQ. The ion source, a so-called 4th generation ECR ion source with 45 GHz microwave hearting, FECR, is expected to be able to provide 2 emA U^{34+} beam. The RFQ, operating at 81.25 MHz, is a 4-vane structure cavity designed to accelerate various heavy ion beams from 14 keV/u to 0.5 MeV/u, in CW mode. The layout of LEAF is shown in Fig. 1. DC beam produced by the ECR ion sources is bunched and matched to the RFQ acceptance by an external Multi-Harmonic Buncher (MHB) located in the LEBT upstream of the RFQ. The MHB helps to produce a smaller longitudinal output emittance and reduce the length of the RFQ since the starting synchronous phase of the RFQ is set to -45 degree and therefore the RFQ should only accept the well-bunched central part of the distribution containing more than 80% of the particles. Table 1 shows the main RFQ parameters.

The RFQ was assembled in Dec. 2017 and the cavity RF conditioning finished in Feb. 2018. The conditioning in CW mode up to 75 kW (1.1 times the required maximum RF power) went smoothly, consuming only 44 hours. The whole complex installation was finished in May 2018, and the beam commissioning started soon after that. However, the 45 GHz superconducting ECR source and MHB are still under development. In the initial beam commissioning, we use a 14.5 GHz room-temperature ECR source as a proxy and DC beam injection into RFQ. The facility has been successfully commissioned with A/Q=4 ion He^{+} and A/Q=7 ion N^{2+}. This paper will present the beam commissioning details and characteristics.

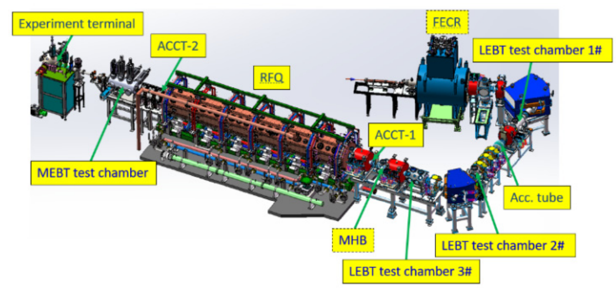

Figure 1: Layout of LEAF.

Table 1. Basic Design Specifications of LEAF-RFQ

Duty cycle	100%
Operating frequency	81.25 MHz
Resonant cavity	4-vane
Input particle energy	14 keV/u
Output particle energy	500 keV/u
Max. Vane voltage	70 kV (U^{34+})
CW RF power	67 kW (U^{34+})
Peak field at electrode surface	1.67 Kilpatrick units
Length of the RFQ vane	~596.4 cm

BEAM COMMISSIONING

Diagnostics

Diagnostic devices were installed in both LEBT and MEBT lines to validate the facility performances and measure the following beam characteristics:

- ✧ LEBT Test Chamber 1# (LTC 1#):
  - ➢ Intensity with Faraday cup (FC).
  - ➢ Transverse emittance with Allison scanners.
  - ➢ Beam transverse profile with fluorescent target.
- ✧ LEBT Test Chamber 2# (LTC 2#):
  - ➢ Intensity with Faraday cup.
  - ➢ Beam transverse profile with fluorescent target.
- ✧ LEBT Test Chamber 3# (LTC 3#):
  - ➢ Intensity with FC.
  - ➢ Transverse emittance with Allison scanners.
  - ➢ Beam transverse profile with fluorescent target.

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- ✧ Beam intensity with ACCT-1 and ACCT-2 before and after RFQ respectively.
- ✧ MEBT Test Chamber (MTC):
  - ➢ Intensity with FC.
  - ➢ X and Y transverse emittance with slit+slit+FC.
  - ➢ Beam transverse profile with slit+FC.
  - ➢ Longitudinal profile with a Fast Faraday Cup (FFC) whose time resolution can be 80 ps due to bandwidth limitation (12.5 GHz).
  - ➢ Energy with a Time of Flight (TOF) monitor based on two Beam Position Monitors (BPM) with a distance of 1068.9 mm between them.
  - ➢ Energy spread with a scattered particle monitor (unavailable) [2].

Source Results

Since 45 GHz FECR is still under development a 14.5 GHz room-temperature permanent magnetic ECR ion source LAPECR1U was employed for the commissioning of LEAF. Up to 5 emA He^{+}, 1.5 emA He^{2+}, 1.7 emA N^{2+} and 0.16 emA N^{5+} have been extracted from the source. In the initial commissioning the slits at the end of charge selection were throttled to confine the beam emittance. Figure 2 shows the measured beam emittance in the LTC 1# for a 90 eμA He^{+} beam at energy of 20 keV/q. The rms emittances in both directions are 0.05 π.mm.mrad.

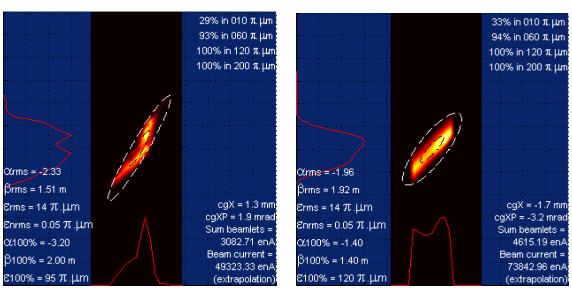

Figure 2: LEBT test chamber 1# emittance measurement for 90 eμA He^{+} beam, throttled slits.

Beam Transmission in LEBT Line

By having the beam parameters after charge selection, beam transmission simulation in the LEBT line was performed. Figure 3 gives the simulated result from LTC 1# to 3#. By adjusting the field gradients of the quadrupoles an approximately axisymmetric beam was obtained. We set the currents of the quadrupoles according to the simulation and measured the emittance in LTC 3#. The results are shown in Fig. 4. Beam current measurement indicates a 100% transmission in LEBT.

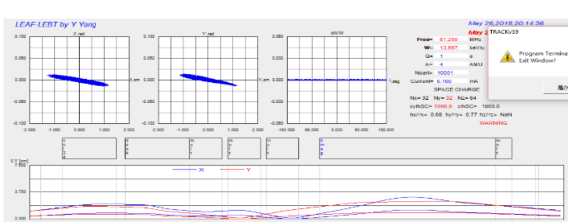
Figure 3: Beam transmission simulation in the LEBT line.

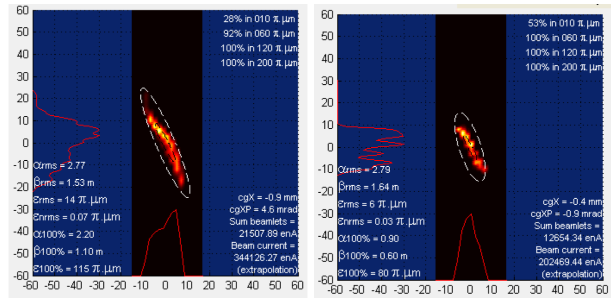

Figure 4: LTC 3# emittance measurement.

RFQ Commissioning and Beam Characteristics

Before entering the RFQ the beam was chopped by an electrostatic chopper that is installed in LTC 3#, so that the transmission efficiency of RFQ could be measured by two ACCTs situated on both sides of the RFQ. According to the current readings of ACCTs, as shown in Fig. 5, the measured transmission efficiency was ~98.5%. The accelerated particles could pass through the MEBT quadrupole triplet channel and be detected by the FC in MEBT test chamber while the non-accelerated ones would be lost in the focusing channel due to the widely different rigidity from the synchronous particles. The measured acceleration efficiency was ~46.5%. The low acceleration efficiency can be due to the factor that the MHB was not operational.

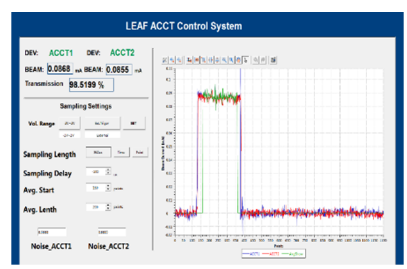

Figure 5: Current readings of two ACCTs.

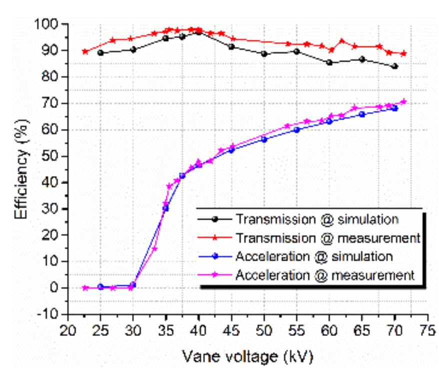

Figure 6: Measured and simulated RFQ transmission and acceleration efficiencies as a function of the vane voltage.

The RFQ transmission and acceleration efficiencies were measured as a function of the RFQ vane voltage (RF power). Figure 6 shows the measured results and the results simulated by TRACK for He^{+} beam. The figure demonstrates good agreement between the measurements and simulations. For the nominal voltage of 40 kV the transmission efficiency reaches maximum, while the

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acceleration efficency increases with the voltage. That's because the longitudinal acceptance of the RFQ is enlarged while increasing the vane voltage. However, the output longditudinal emittance is minimal with the designed voltage of 40 kV, as shown in Fig. 7.

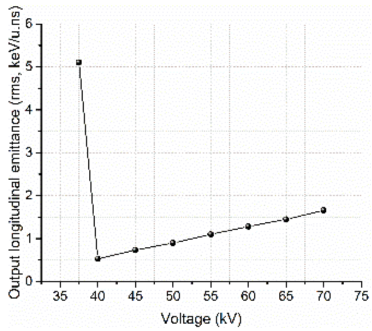

Figure 7: Simulated RFQ output longitudinal emittance as a function of the vane voltage.

The beam energy measured with TOF monitor was ~0.5 MeV/u. Figure 8 illustrates the signals detected by two BPMs. The bunch length was measured by the FFC. Figure 9 shows the measured (FFC signal) and simulated bunch length. The measured Full Width at Half Maximum (FWHM) was ~0.83 ns which is similar to the simulated number. Transverse emittances were measured based on slit+slit+FC in MEBT test chamber. Figure 10 demonstrates the measured and simulated particle distributions in the phase spaces. The measured rms emittances were 0.08 π.mm.mrad in horizontal and 0.078 π.mm.mrad in vertical, respectively. The simulated values were slightly smaller, with 0.074 π.mm.mrad in horizontal and 0.062 π.mm.mrad in vertical, since we used an idealized 4-D water-bag model in the simulation.

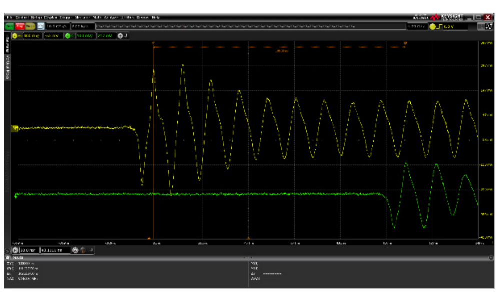

Figure 8: BPM signals (yellow: BMP-1, green: BPM-2).

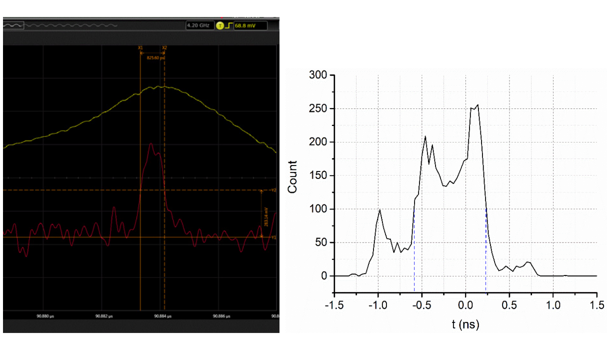

Figure 9: FFC signal (left, red line) and simulated (right) bunch length.

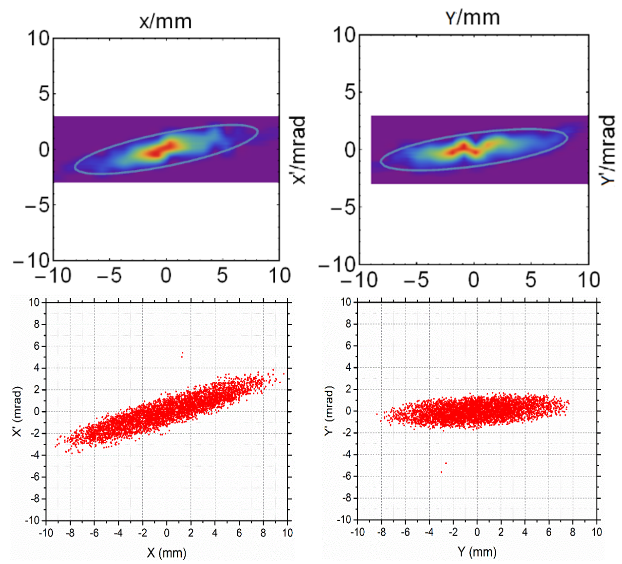

Figure 10: Measured (up) and simulated (down) beam emittance in MEBT test chamber after triplet focusing.

The RFQ transmission and acceleration efficiencies versus input beam energy were also measured and simulated. The results were plotted in Figure 11. Both measurements and simulations show the acceleration efficiency is maximal with input energy of 14.75 keV/u. The reason can be explained with the RFQ londitudinal acceptance as shown in Figure 12. More particles can be accepted by the RFQ for input energy of 14.75 keV/u than that for 14 keV/u.

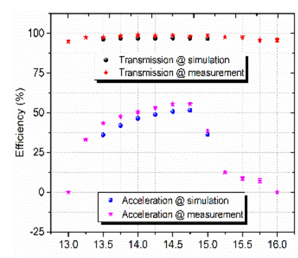

Figure 11: Measured and simulated RFQ transmission and acceleration efficiency versus the input beam energy.

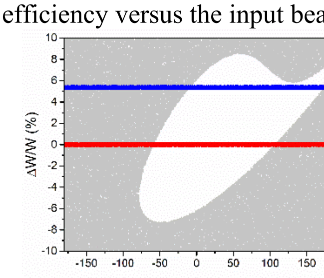

Figure 12: Simulated RFQ longitudinal acceptance and DC beam longitudinal distributions with input energy of 14 keV/u (red) and 14.75 keV/u (blue).

CONCLUSIONS

LEAF has been successfully commissioned with He^+ and N^{2+} beams. Key performance parameters demonstrated, satisfying the dynamics design. The facility has been operated at CW mode for more than one month, providing stable He^+ beam for the terminal experiments.

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