

COMMISSIONING PROGRESS OF LEAF AT IMP

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Abstract

A Low Energy intense-highly-charged ion Accelerator Facility (LEAF), which is mainly consist of an 45 GHz superconducting ECR ion source, LEBT and an 81.25 MHz 4-vane 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 project was launched in 2015 and has been successfully commissioned with He⁺ (A/Q=4), N²⁺ (A/Q=7) beam and accelerated the beams in the CW regime to the designed energy of 0.5 MeV/u. Beam commissioning results of He⁺ beam have been reported previously. This paper presents the details of N²⁺ commissioning and beam studies.

INTRODUCTION

LEAF (Low Energy intense-highly-charged ion Accelerator Facility, see Fig. 1) [1] has been successfully commissioned with A/Q=4 ion He⁺ and A/Q=7 ion N²⁺. Since the designed heaviest ion is Uranium with charge state of 34, N²⁺ could be a substitute of U³⁴⁺ to evaluate the accelerator performance due to the same rigidities. Studies of the facility were carried out by beam commissioning with different intensities. Beam characteristics from ECR were measured and discussed. Beam phase space re-construction was developed to study the evolution process of the beam from source to RFQ, contributing to LEBT tuning and particle cutting with collimators.

SOURCE RESULTS

A 14.5 GHz room-temperature permanent magnetic ECR ion source was fabricated and employed for the commissioning of LEAF. The source performance meets intensity requirements for commissioning. The source demonstrated ~5 emA of He⁺ beam, 1.5 emA of He²⁺ beam, 1.7 emA of N²⁺ beam and 0.16 emA of N⁵⁺ beam. Beam emittances were measured for N²⁺ beam with several intensities. As shown in Fig.2, beam emittance increase with the intensity. The main reason should be attributed to the plasma meniscus change, related with source tuning. Aberrations from the magnets and space charge effects also contribute to the beam emittance degradation [2,3]. Figure 3 demonstrates the measured

phase space distributions of N²⁺ beam with intensities of ~0.14 emA and ~1.52 emA, respectively. It is seen that by increasing the beam intensity the phase spaces are seriously distorted, resulting to emittance growth.

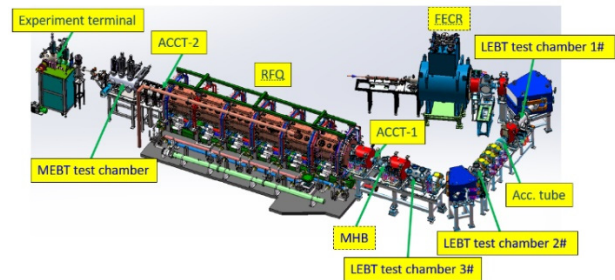


Figure 1: Layout of LEAF.

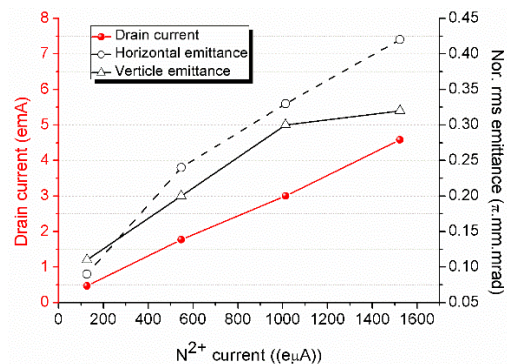


Figure 2: N²⁺ beam emittance versus beam current.

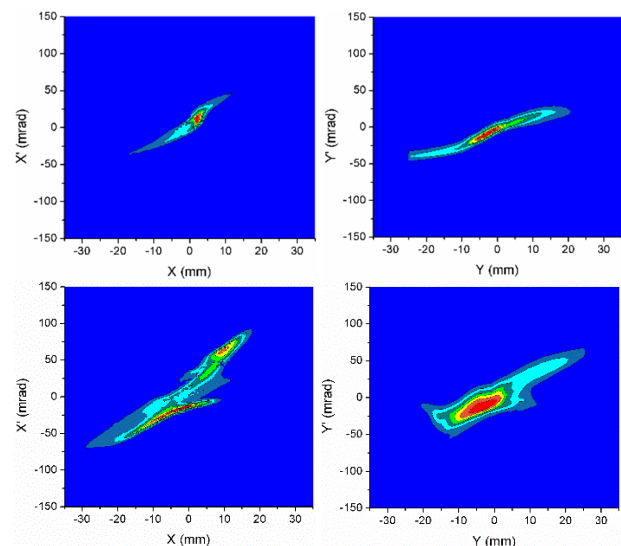


Figure 3: Measured beam phase space distributions for ~0.14 emA (up) and ~1.52 emA (down) N²⁺ beams.

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BEAM COMMISSIONING

~0.1 emA of N²⁺ Beam Commission and Characteristics

The RFQ commissioning of N²⁺ beam started with ~0.1 emA. The slits in Q/A analyser of ECR were throttled to confine the emittance. Figure 4 shows the measured emittance, indicating 0.07 π .mm.mrad in horizontal and 0.05 π .mm.mrad in vertical. The beam, with energy of ~3.57 keV/u (25 kV extraction voltage of ECR), was pre-accelerated to the designed RFQ input energy of 14 keV/u by the accelerating tube and converted to an approximately axisymmetric beam by four quadrupoles in the LEBT line. Afterwards the beam was focused by two paired solenoids [2] and matched to RFQ. Beam transmission efficiency through LEBT reached 100%.

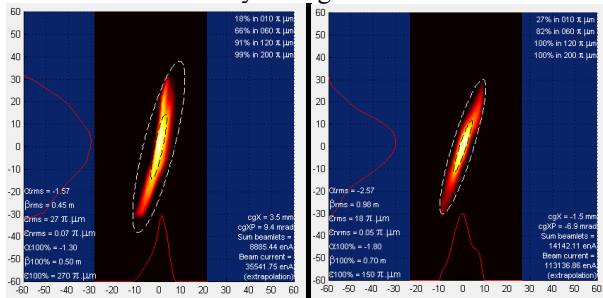


Figure 4: Emittance measurement for ~100 emA N²⁺ beam, throttled slits.

The RFQ was conditioned to 63 kW, corresponding to the vane voltage of 71.3 kV, which was slightly higher than the designed voltage of 70 kV to accelerate A/Q=7 ion beams. The measured transmission efficiency (including non-accelerated particles) was ~98%. The Multi-Harmonic-Buncher (MHB) has not been operational yet, therefore beam injected into the RFQ was a DC beam. The acceleration efficiency was of ~54.6% because the starting synchronous phase of the RFQ was set to -45 degree. The beam energy was measured with TOF monitor (two BPMs with a distance of 1.068 m between each other, see Fig. 5), satisfying the designed energy of 0.5 MeV/u.

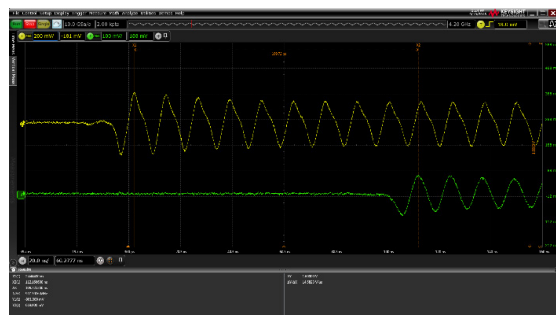


Figure 5: BPM signals (yellow: BMP-1, green: BMP-2).

Transverse emittances after RFQ were measured by using slit+slit+FC and plotted in Fig. 6. The measurements demonstrated rms emittances of 0.119 π .mm.mrad in horizontal and 0.088 π .mm.mrad in vertical. The phase

spaces were slightly distorted, which can be due to the factor that the injection beam had been aberrant. Simulations by TRACK code were also provided in Fig. 6, which indicated horizontal emittance of 0.119 π .mm.mrad and vertical emittance of 0.092 π .mm.mrad. Measurements have a good agreement with simulations. Besides, we observed that no emittance exchange between X&Y directions. That's because after ECR beam emittance measurement (at LEBT test chamber 1#, see Fig. 1) there is no element creating transverse coupling in LEBT and also no coupling in RFQ for such low-current beam.

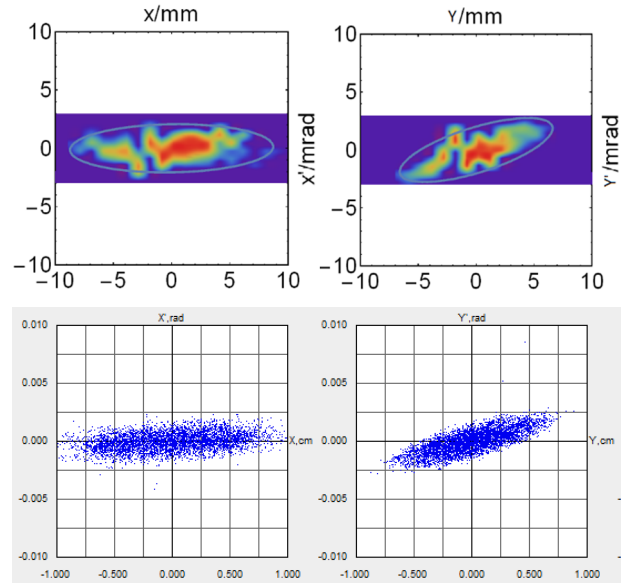


Figure 6: Measured (up) and simulated (down) beam emittance in MEBT test chamber after triplet focusing.

Beam bunch profile was measured by a Fast Faraday Cup (FFC) which has a time resolution of ~80 ps, as shown in Fig. 7. The measured FWHM (Full Width at Half Maximum) of the bunch length was ~1.9 ns, which was slightly larger than the simulated value of 1.5 ns (see Fig. 8).

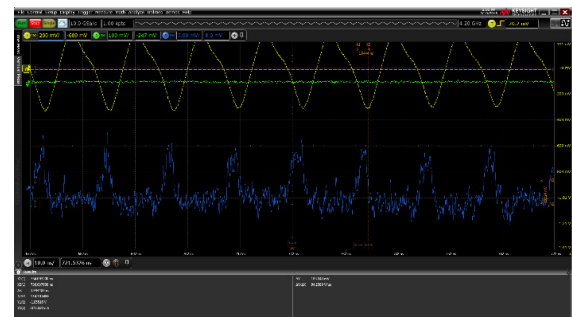


Figure 7: FFC signal.

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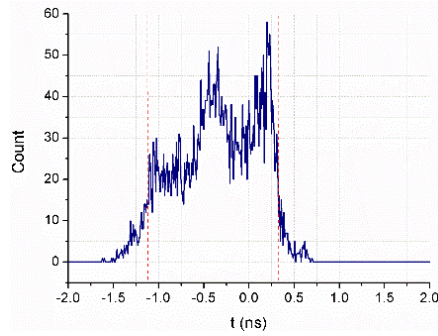


Figure 8: Simulated bunch profile.

Commission for Different-Current Beams

Further beam commissioning was to increase the beam current. The source intensity was enhanced from ~ 118 μA to 785 μA and the corresponding emittances were shown in Fig. 9. By slightly tuning the LEBT magnets to achieve maximum RFQ transmissions, the transmission efficiencies of the beam in LEBT and RFQ were measured and plotted in Fig. 10. One thing should be clear that the beam transmissions from LEBT test chamber 1# to 3# (see Fig. 1) always kept 100%, even for very high intensity as 1.7 emA. Some “tail” particles would be lost at RFQ entrance, leading to LEBT transmission efficiency (from LEBT test chamber 1# to ACCT-1) lower than 100%. The RFQ transmission decreased with the beam current. As seen from the plot, the RFQ transmission decreased to 82% while the beam intensity reached 785 μA . A collimator channel based on two sets of X&Y slits was designed and installed in LEBT test chamber 3# to remove the “tail” particles and improve the RFQ transmission so as to reduce the beam loss in RFQ. With the collimator on, $\sim 11.5\%$ (13.6%) of the particles were cut for initial 520 μA (785 μA) beam, while the RFQ transmission efficiency was improved from $\sim 88.5\%$ (82%) to $\sim 95.7\%$ (91%). Further transmission efficiency improvement requires the operation of MHB.

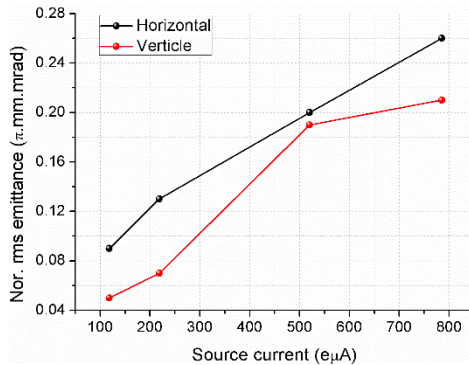


Figure 9: N^{2+} beam emittance versus beam current from source.

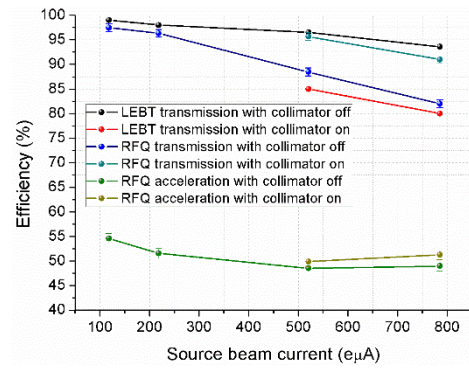


Figure 10: Transmission efficiencies in LEBT (from LEBT test chamber 1# to ACCT-1), RFQ (from ACCT-1 to ACCT-2), and acceleration efficiency of RFQ (from ACCT-1 to MEBT test chamber).

PHASE SPACE RE-CONSTRUCTION

Ion beams from ECR source are typically distorted with aberrations due to the magnetic confinement configuration. Beam simulation by using an imaginary initial distribution, such as water-bag distribution or Gauss distribution, can't well present the evolution process of the beam. Phase space re-construction based on emittance measurement is very necessary for simulations that are close to the realistic beam transport and machine studies, especially for those high-intensity beams. A code was developed to re-construct the projection phase space distributions based on Allison scanner measurements. Beam transverse coupling was not considered because no element after ECR beam emittance measurement in LEBT could produce transverse coupling to the beam under linear conditions. As an example, Fig. 11 illustrates the measured transverse phase space distributions with Allison scanner at LEBT test chamber 1# for N^{2+} beam with current of 785 μA . The re-constructed distributions are given below.

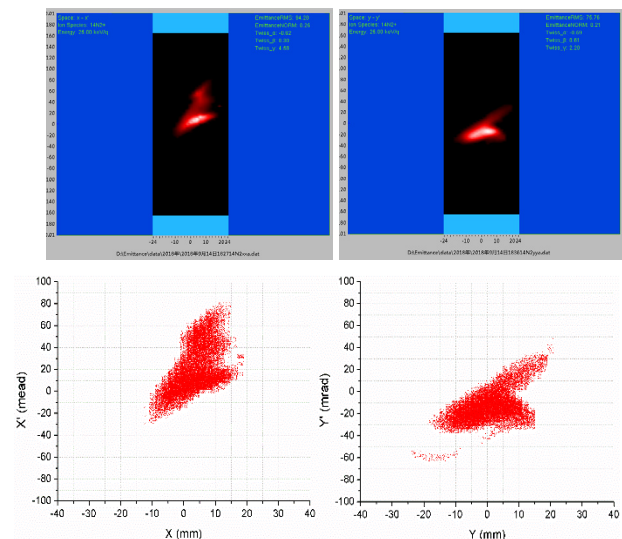


Figure 11: Measured N^{2+} beam phase space distributions with Allison scanner (up) and re-constructed distributions (down).

The artificial particle distributions were input in TRACK to perform the subsequent simulations. After LEPT transmission both measured and simulated phase space distributions at LEPT test chamber 3# were presented in Fig. 12. It is observed that the simulated distributions have very similar shapes with the measured ones, demonstrating that simulations based on phase space reconstruction could well predict the beam phase space profile at any location in LEPT, which is especially important and useful at the positions of beam collimators where particle “tails” are wanted to be cut by the slits. As shown in Fig. 12, it is possible to predict that the “tail” particles could be removed by the slits that located after the emittance measurement point.

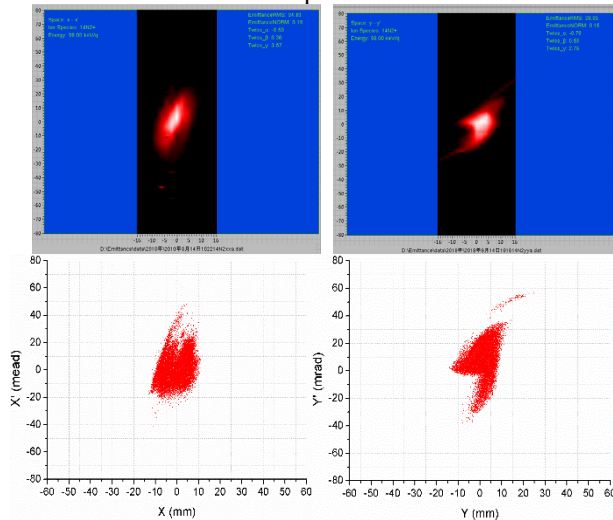


Figure 12: Measured beam phase space distributions with Allison scanner at LEPT Test chamber 3# (up) and simulated distributions based on phase space reconstruction (down).

CONCLUSIONS AND FUTURE PLANS

LEAF has been successfully commissioned with $A/Q=4$ ion He^+ and $A/Q=7$ ion N^{2+} . Key performance parameters demonstrated. MHB is now being installed and tested. Future beam commissioning will be carried out with MHB operational. Beam intensity will be increased step by step, from pulse to CW.

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