ONGOING STUDIES OF THE SUSI ECR ION SOURCE AND LOW ENERGY BEAM TRANSPORT LINE AT THE MSU NSCL*

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Abstract

Heavy ion accelerator laboratories for nuclear science and rare isotope research require a wide array of high intensity heavy ion beams. Due to their versatility and robustness, Electron Cyclotron Resonance (ECR) ion sources are the choice injectors for the majority of these facilities worldwide. Steady improvements in the performance of ECR ion sources have been successful in providing intense primary beams for facilities such as the National Superconducting Cyclotron Laboratory (NSCL). However, next generation heavy ion beam laboratories, such as the Facility for Rare Isotope Beam (FRIB), require intensities that are approaching the limits of current possibility with state of the art ion source technology. In this proceedings, we present the ongoing low energy beam transport characterization efforts of a superconducting ECR ion source injector system at the MSU NSCL.

INTRODUCTION

The Coupled Cyclotron Facility (CCF) at the NSCL [1] utilizes two superconducting cyclotrons to accelerate primary ion beams up to 160 MeV/u corresponding to beam power deposition on production target of up to 1 kW for rare isotope production. The parallel operation of the two ECR ion source injector systems allow for the delivery of primary beams, from helium up to uranium, to the CCF while permitting development on the other source. The Advanced Room TEMperture Ion Source (ARTEMIS) [2] operating at 14.5 GHz uses normal conducting solenoids for axial confinement and permanent magnet hexapoles for radial confinement, whereas the Superconducting Source for Ions (SuSI) [2] operating at 18 GHz from a klystron and 24 GHz from a gyrotron uses superconducting solenoids and hexapoles for confinement of the plasma.

The production of rare isotopes often require expensive and difficult to obtain stable isotopes as primary beams, therefore research efforts are focused on improving the understanding of heavy ion beam transport in the low energy section of injector systems to minimize systematic beam loss. In this proceedings, we will focus on the superconducting SuSI ECR ion source and its corresponding low energy beam transport line, related beam diagnostics, and beam transport simulation efforts.

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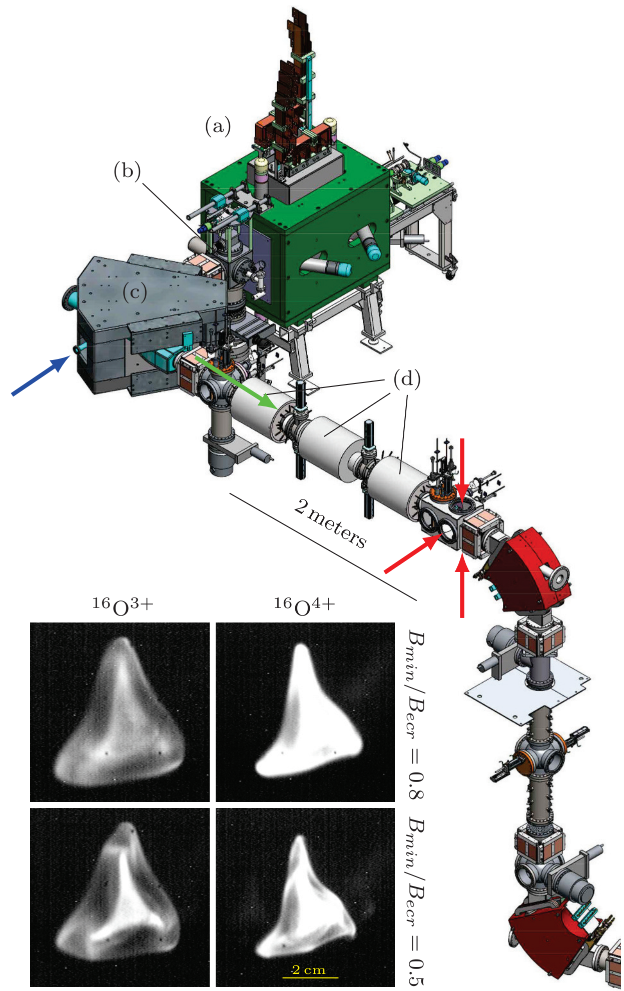

Figure 1: (color) Diagram of the SuSI ECR Ion Source Injector showing (a) the ion source, (b) extraction system, (c) *A/Q* spectrometer, (d) solenoid triplet, blue arrow indicate the location of the HPGe detector, red arrows indicates the location of emittance scanners and scintillator screen, and green arrow the direction of the beam.

BEAM LINE MEASUREMENTS

The relevant portion of the SuSI injector system, shown in Fig. 1, consists of the ECR ion source held at high voltage up to 30 kV, triode extraction system, an Einzel lens, solenoids, steerers, and collimation apertures and slits. The diagnostics on the beam line include Faraday cups for beam current measurements, a high-resolution *A/Q* spectrometer for ion species separation, an Allison scanner [3] for beam

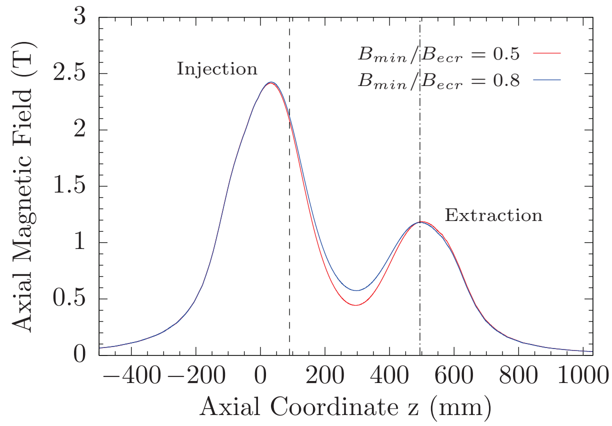

Figure 2: Axial magnetic field profile as a function of distance in the SuSI ECR ion source for B_{min}/B_{ecr} = 0.5 and 0.8 where the dashed line denote to the injection location and dash-dotted line the extraction location.

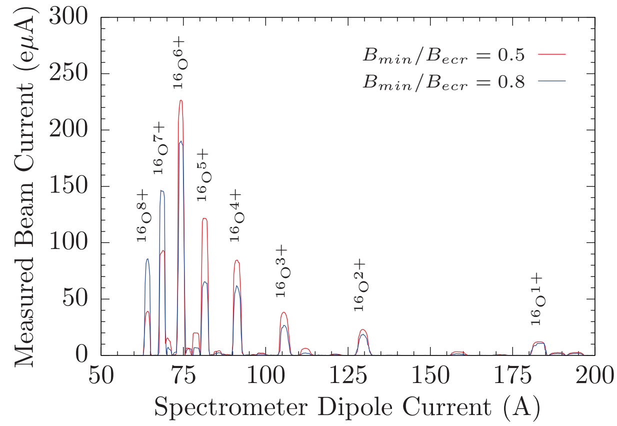

Figure 3: Beam current measured on a faraday cup as a function of the spectrometer dipole current forming a charge state distribution of oxygen for B_{min}/B_{ecr} = 0.5 and 0.8.

emittance measurements, a scintillator screen for transverse beam profile, and a High-Purity Germanium (HPGe) x-ray detector with its associated collimation system for plasma Bremsstrahlung measurements.

The SuSI ECR ion source conditioned for one week prior to the measurements to reduce residual contaminants from the plasma chamber walls. For the measurements, the ion source operated at 18 GHz with an input RF power of 1 kW from a klystron, the source was biased to 20 kV with -250 V for electron suppression, and Einzel lens focusing at 20 kV. A neutral gas pressure of 30-40 nTorr of helium, oxygen, and argon gas were maintained in the plasma for separate experiments while varying the magnetic field configuration that is characterized by the ratio of the magnetic field minimum, B_{min}, to the ECR magnetic field corresponding to the operating frequency of 18 GHz, B_{ecr}. Figure 3 shows a charge state distribution (CSD) of beams of SuSI running with oxygen for the two magnetic field configurations. It is observed that B_{min}/B_{ecr} = 0.5 enhances lower charge states whereas B_{min}/B_{ecr} = 0.8 enhances higher. The CSD, beam profile, beam emittance, and plasma Bremsstrahlung emissions [4] were carefully measured for each source conditions to generate a complete characterization catalog guiding ongoing low energy beam simulation research.

Emittance Measurements

The beam emittance measurements were carried out with a pair of Allison emittance scanner, one in each transverse direction. With a slit width of 0.254 mm and scanner length of 75 mm, the scanner have a phase-space area resolution of 0.8 mm mrad. Figure 4 shows the transverse-coupled beam emittance of oxygen species $^{16}O^{4+}$ for cases where B_{min}/B_{ecr} = 0.5 and 0.8. Due to the transverse coupling nature of the solenoid magnets used in the beam line [5], the Allison emittance scanner data cannot fully capture the inter-plane beam correlations that can extracted from particle tracking. A pepperpot emittance scanner can be used for full 4D beam emittance characterization at low energies.

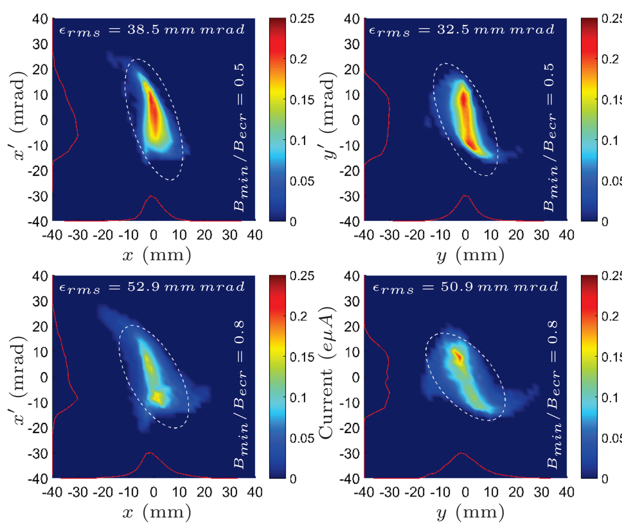

Figure 4: (color) Measured coupled beam emittance of $^{16}O^{4+}$ for B_{min}/B_{ecr} = 0.5 and 0.8 where the dashed ellipse represent ~95% of the total beam and red traces the intensity projection in each phases-space coordinate.

BEAM LINE SIMULATIONS

The low energy beam transport line simulations, built upon previous efforts by D. Winklehner, *et al.* [6], were carried out using the WARP particle-in-cell (PIC) code [7] that supports multi-species beams, non-linear space-charge effects, resolving of the plasma sheath at source extraction, and input of arbitrary 3D electromagnetic field maps for 2D-slice and 3D particle tracking.

Source Magnetic Field

The plasma etchings on the bias disc at injection were observed in the SuSI ion source, shown in Fig. 5, due to electron and ion losses. Since ions in motion in the source gyrate about the magnetic field lines, $n = 1{\times}10^5$ oxygen ions of each charge states from 1+ to 8+ were populated on the plasma loss pattern with uniform distribution in transverse positions, Boltzmann-Maxwell distribution in transverse ve-

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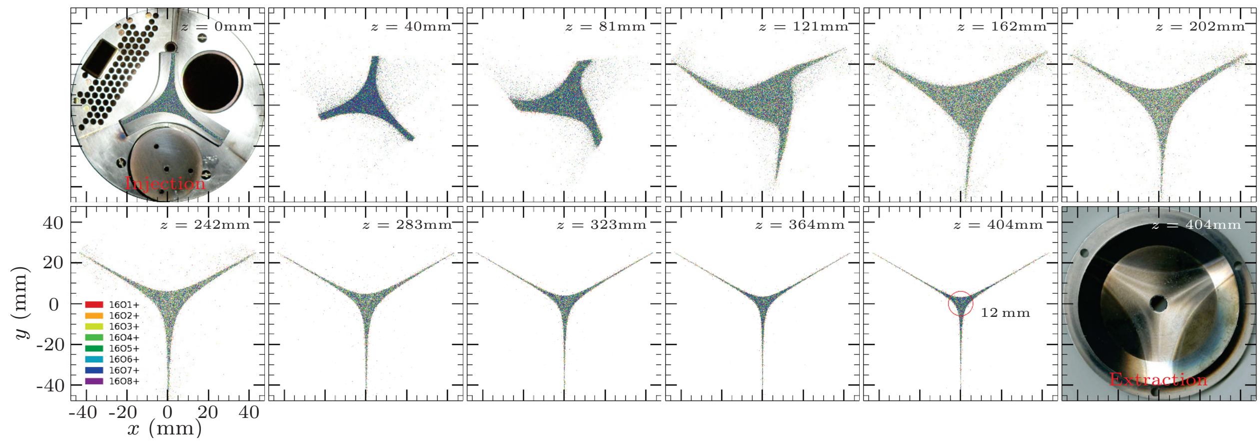

Figure 5: (color) Transverse beam profile of $^{16}O^{1+}$ to $^{16}O^{8+}$ with ion temperature of 3 eV evolving as a function of the axial direction within the ion source, from the bias disc to extraction aperture of 12 mm in diameter.

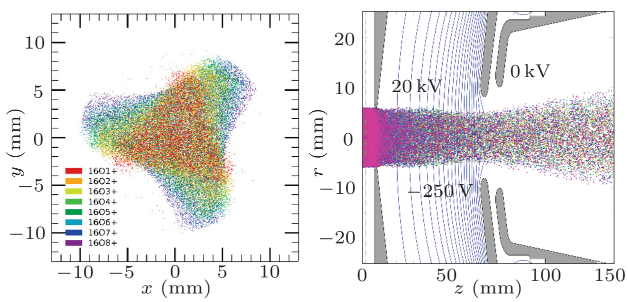

Figure 6: (color) (a) Multi-species beam of $^{16}O^{1+}$ to $^{16}O^{8+}$ after extraction where (b) the IGUN-like r-z simulations resolved the plasma sheath at the extraction aperture.

locities, and axial velocities obeying Bohm's criterion. The ions are tracked through the source with a xy-slice routine, for a given 3D magnetic field map generated by a finite-element analysis (FEA) model of the SuSI superconducting magnet coils, from the bias disc to the extraction aperture of 12 mm. The ion tracking results matches well with the plasma etchings on the plasma electrode at extraction, shown in last frame of Fig. 5. About 90% of the initial ions generated at the bias disc were lost to the plasma chamber wall and extraction aperture. Ions of each charge state surviving through the extraction aperture will form the initial beam distributions for subsequent beam extraction and plasma sheath simulations.

Extraction System

The plasma sheath at the extraction aperture was resolved by using the an IGUN-like routine in WARP to calculate the space-charge limited current in r-z coordinates for a given triode configuration of SuSI, e.g. electrode positions and applied potentials. Figure 6 shows a typical result of the extraction routine where $B_{min}/B_{ecr} = 0.8$, total beam current was $\sim$700 eμA, and current for each ion species were constrained to the measured CSD shown in Fig 3. Resolving the plasma sheath with the r-z code constitute a good approximation to the 3D treatment as evidenced by the success of IGUN [8].

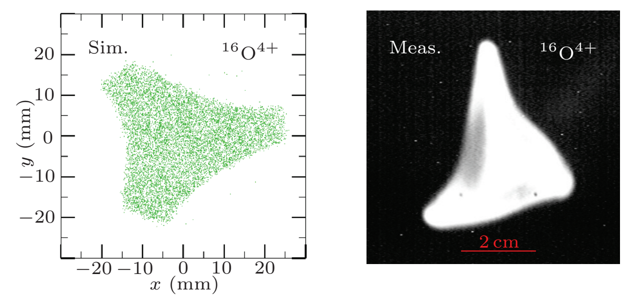

Figure 7: Comparison of simulation results to measurements for $^{16}O^{4+}$ beam with total current of 62 eμA.

Low Beam Transport Line

Following the spectrometer dipole magnet, the multi-species beam are separated and the selected charge state are tracked through a series of solenoids to a diagnostics box. Figure 7 compares the measurement to simulation for the $^{16}O^{4+}$ beam. The beam transmission of $^{16}O^{4+}$ was found to be over 98% given the acceptance of the injector system with collimation slits completely opened.

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