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# OFFLINE TESTING OF THE CARIBU EBIS CHARGE BREEDER*

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*Abstract*

In 2015 an electron beam ion source (EBIS) will be installed at the ATLAS facility to charge breed radioactive beams from the Californium Rare Isotope Breeder Upgrade (CARIBU). Currently an ECR ion source is used to charge breed CARIBU beams. The EBIS will provide beams with much less contamination and higher breeding efficiencies. In preparation for its installation at ATLAS the EBIS has been successfully commissioned offline. The EBIS was configured in the offline facility to closely mimic the conditions expected in the ATLAS installation, so commissioning results should be representative of its performance with CARIBU. The EBIS breeding efficiency was tested with pulses of $^{133}Cs^{1+}$ from a surface ionization source, and for multiple operational modes relative breeding efficiencies greater than 25% could be achieved. After transmission losses the total efficiency of the system was 15-20%. The contaminants were expectedly very low for a UHV system with nominal pressures of ~1 – 3 x $10^{-10}$ Torr.

## INTRODUCTION

Acceleration in the ATLAS facility requires an A/q ≤ 7, so the ions produced by the CARIBU $^{252}Ca$ source in the mass range 80 – 160 amu with 1+ and 2+ charge states require charge breeding [1]. Presently an electron cyclotron resonance ion source (ECRIS) breeds the radioactive ion beams (RIB) from CARIBU. The combination of capture, breeding, and transport efficiencies of the ECR for CARIBU RIBs is typically 8-15%, but extracted beams can contain significant contamination which can be problematic for experiments with low intensity radioactive ions.

Later this year an electron beam ion source (EBIS) charge breeder will replace the ECRIS. Based on the performance achieved during offline testing and reported here, the EBIS will increase the intensity and reduce the contamination of RIBs accelerated in ATLAS.

## OFFLINE CONFIGURATION AND OPERATING CONDITIONS

To take advantage of the higher breeding efficiencies an EBIS can reach when operated in a pulsed mode, ions from CARIBU will be cooled and bunched in a Radio Frequency Quadrupole (RFQ) prior to injection into the CARIBU EBIS. The offline configuration, shown in Figure 1, was designed to be able to closely match the injected ion beam expected in the final ATLAS installation. Instead of RIBs from CARIBU, pulses of stable $^{133}Cs^{1+}$ were created from a DC beam by pulsing the voltage of a deflector near the surface ionization source. Injected ion bunches were trapped, bred, extracted, and finally analysed with a 70° dipole magnet. Ion intensities were measured with standard Faraday cups and a Tektronix 3032B oscilloscope. Peak heights from the oscilloscope traces were recorded, and could be converted from voltage to charge with the measured capacitance of the cable and cup.

During commissioning two main operating modes were established. The EBIS was first operated in mode 1, for this was the initial commissioning configuration. Mode 1 was generally lower power; using a lower trap magnetic field, lower electron beam current, and lower trap current density. When it was clear better performance would be needed, the mode 2 configuration was established. The operating parameters for both modes are listed in Table 1.

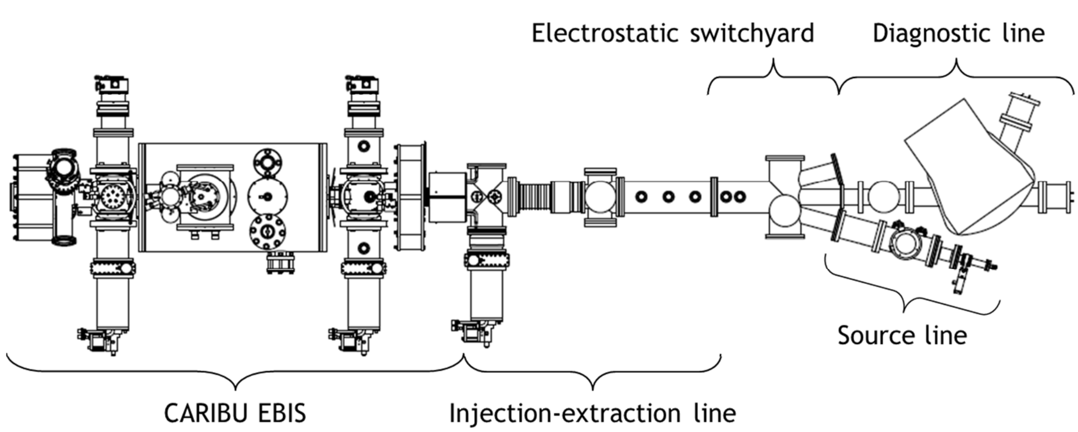


Figure 1: Offline EBIS configuration.

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Table 1: Offline Testing Operating Parameters

| Parameter | Unit | Mode 1 | Mode 2 |
|---|---|---|---|
| Trap magnetic field | T | 4 | 5 |
| Cathode magnetic field | T | 0.15 | |
| Trap electron radius | μm | 407 | 367 |
| Trap electron energy | eV | 7775 | 6495 |
| Electron beam current | A | 1 | 1.6 |
| Current density | A/cm$^2$ | 192 | 385 |
| Potential well within electron beam radius | V | 172 | 299 |

## RESULTS

Considerable effort was made to minimize the residual gas contamination from the EBIS. Besides causing problems with the extracted beam of interest being obscured, a significant density of residual gas may neutralize the trap and result in poorer extracted beam quality or reduced ionization efficiency through charge exchange. Once all leaks with rates greater than ~1x10$^{-11}$ Torr-l/s were eliminated, a base vacuum was established with turbo molecular and cryogenic pumps, and finally the SAES non-evaporable getter (NEG) pumps on the electron gun cross and in the trap vacuum chamber were activated. Figure 2 shows the resulting residual gas charge state distribution. The constituents are expectedly H, C, N, and O, and intensities are very low in the A/q region where CARIBU RIB will be created, $4 \leq A/q \leq 7$.

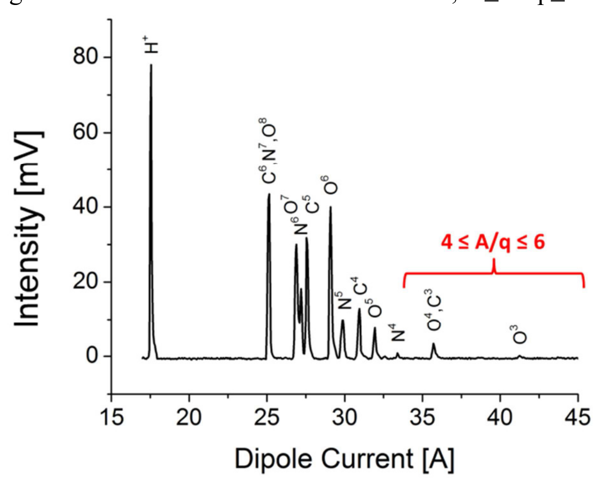


Figure 2: Charge state distribution of residual gas constituents for a 30 ms breeding time measured during mode 2 operation. The region of expected CARIBU beam breeding is highlighted.

The charge state evolution was studied extensively to establish a set of conditions optimized for CARIBU integration. The basic goal was to achieve the highest breeding efficiency for an acceptable mass-to-charge ratio ($A/q \leq 7$) in a breeding time ≤ ~33 ms. This breeding time corresponds to the highest expected EBIS operating frequency, ~30 Hz, determined by the operating frequency of the RFQ cooler buncher. The minimum acceptable charge state for $^{133}$Cs is q=20, but as q=20 became the most abundant for breeding times between 5 and 15 ms the distribution broadened and intensities of the most abundant q's dropped, Figure 3. A sharp intensity increase in the most abundant charge state from a low of 13% to a high of 25% was observed as the breeding times were increased from 15 to 70 ms. Simulation results from CBSIM [2] for the same operating conditions are also included Figure 3, and the simulations also predicted a decrease in the intensity of the most abundant q between 5 and 30 ms followed by an increase in intensities at 50 ms. Mode 2 operation was similar, showing a sharp increase in relative abundances between 10 and 20 ms [3]. Mode 2 operation was able to achieve a maximum abundance of 27% for q=28 at a breeding time of 28 ms, Figure 4. While the trends between the measured and simulated values were comparable the absolute values differed notably.

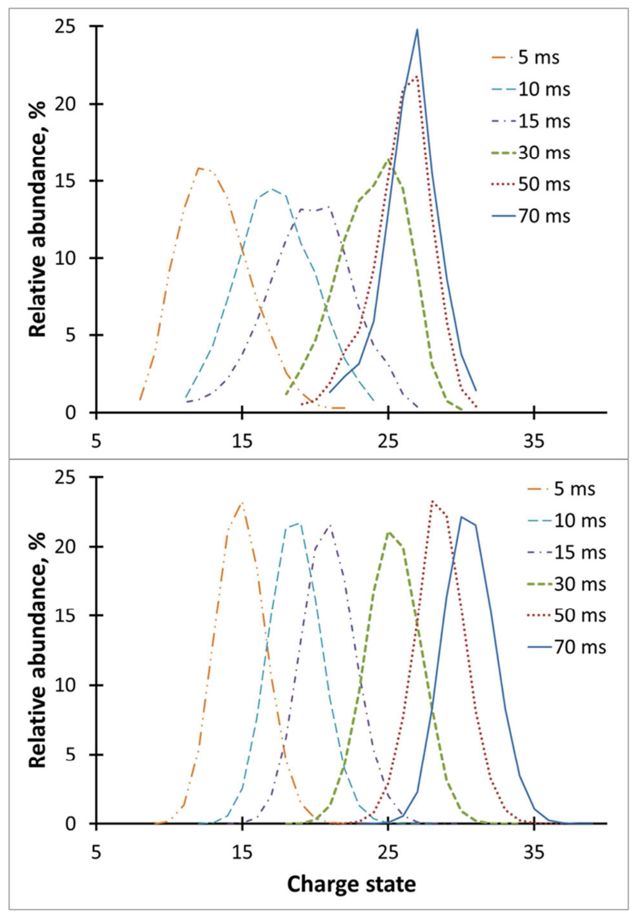


Figure 3: Measured (top) and simulated (bottom) charge state distributions for various breeding times for mode 1 operating parameters.

In addition to the most abundant charge state, the average charge states of the distributions were necessary to determine the overall transmission of the system. Figure 5 shows the measured and simulated average charge states vs. breeding times for both operational

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modes, and in both cases the measured average charge states were lower than predicted. The differences between the measured and simulated results may be due to improper matching of the injected ion beam or incomplete overlap of the ion and electron beams in the trap.

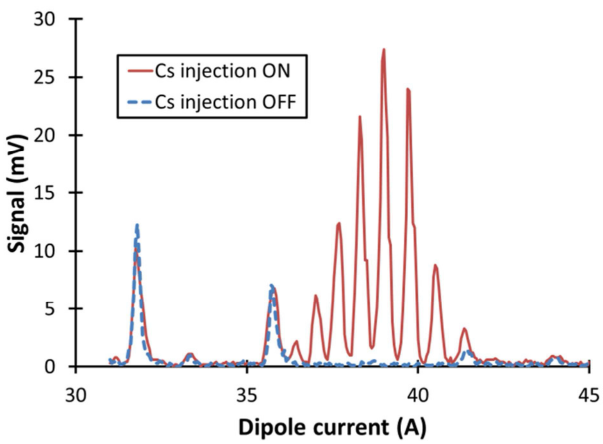


Figure 4: Charge state distribution with and without Cs injection for 28 ms breeding in mode 2 [3].

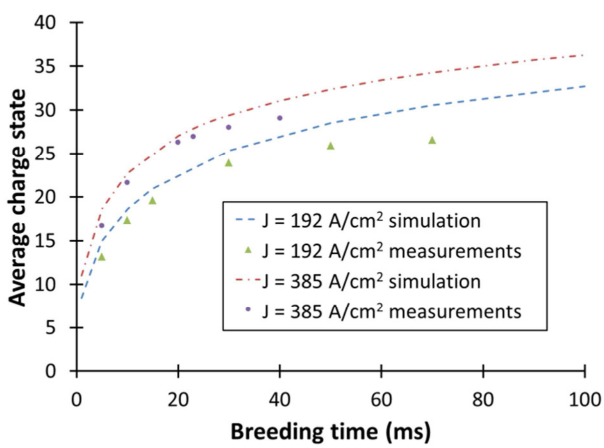


Figure 5: Measured and simulated average charge states vs. breeding time.

While the relative efficiencies achieved were promising, the total efficiency, including transport losses, is more important to understand the ultimate delivery of CARIBU RIB to an experiment. The system transmission was calculated by comparing the number of injected and extracted ions. These numbers were attained by converting the voltage signals to charge for the injected beam and the extracted charge bred Cs beam after background subtraction. The charges were then divided by the average charges states 1+ and $\overline{n}+$ (calculated from the charge state distribution) for injection and extraction, respectively, to determine the number of injected and extracted ions. Transport efficiency was typically ~70% which resulted in total system efficiencies of 18% for mode 1 and 20% obtained for mode 2 operation. The main candidate responsible for these losses is that the emittance of the injected beam [3] could not be reduced below the EBIS acceptance [4], however this issue should be minimized at CARIBU where the ideal emittance will be ~8x smaller than the maximum EBIS acceptance. The large injected beam emittance could cause a portion of the ions to be longitudinally trapped but not radially orbit completely within the electron beam. This may have contributed to the discrepancies between the measured and simulated breeding results.

## FUTURE WORK

As a sufficient operating condition was achieved using mode 2, the majority of the remaining offline testing will focus on increasing the duty cycle of the EBIS electron beam. A 90% minimum duty cycle is required for an operating frequency of 30Hz and a breeding time of 30 ms, but currently mode 2 operation is stable up to ~40% duty cycle at 10 Hz.

## SUMMARY

The CARIBU EBIS has demonstrated relative charge breeding efficiencies >25% for breeding times between 20 – 30 ms and a trap current density of 385 A/cm$^2$. These results are well within the breeding time and A/q requirements of the CARIBU RFQ cooler buncher and the ATLAS accelerator. Considering the design value of the trap current density is 50% higher than the highest used here, there is even more room for improvement. Investigations of the residual gas also showed very low background in the extracted A/q range relevant for CARIBU beams.

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