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REVIEW OF SCIENTIFIC INSTRUMENTS **86**, 083311 (2015)

Fast and efficient charge breeding of the Californium rare isotope breeder upgrade electron beam ion source

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The Electron Beam Ion Source (EBIS), developed to breed Californium Rare Isotope Breeder Upgrade (CARIBU) radioactive beams at Argonne Tandem Linac Accelerator System (ATLAS), is being tested off-line. A unique property of the EBIS is a combination of short breeding times, high repetition rates, and a large acceptance. Overall, we have implemented many innovative features during the design and construction of the CARIBU EBIS as compared to the existing EBIS breeders. The off-line charge breeding tests are being performed using a surface ionization source that produces singly charged cesium ions. The main goal of the off-line commissioning is to demonstrate stable operation of the EBIS at a 10 Hz repetition rate and a breeding efficiency into single charge state higher than 15%. These goals have been successfully achieved and exceeded. We have measured (20% ± 0.7%) breeding efficiency into the single charge state of 28+ cesium ions with the breeding time of 28 ms. In general, the current CARIBU EBIS operational parameters can provide charge breeding of any ions in the full mass range of periodic table with high efficiency, short breeding times, and sufficiently low charge-to-mass ratio, 1/6.3 for the heaviest masses, for further acceleration in ATLAS. In this paper, we discuss the parameters of the EBIS and the charge breeding results in a pulsed injection mode with repetition rates up to 10 Hz. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4929464]

I. INTRODUCTION

The Californium Rare Isotope Breeder Upgrade (CARIBU) for the Argonne National Laboratory Argonne Tandem Linac Accelerator System (ATLAS) provides neutron-rich fission fragments from a 1 Curie (Ci) ^{252}Cf source.[1] The ions are thermalized and collected into a low-energy ion beam by a helium gas catcher, mass selected by an isobar separator, and charge bred to higher charge states for acceleration in ATLAS. To reach energies E/A ~ 10 MeV/u, one should inject ions with a charge-to-mass ratio (q/A) ≥ 1/7 into ATLAS. At present, the existing Electron Cyclotron Resonance (ECR) ion source is used as a charge breeder (CB).[2] Higher efficiency, shorter breeding times, and higher purity of charge-bred radioactive ion beams can be achieved by using an electron beam ion source (EBIS) as a CB instead of an ECR. Therefore, five years ago we started development and construction of the EBIS CB. The design parameters of the EBIS were reported in Ref. 3. CARIBU generates a wide range of radioactive ions with masses from 80 to 160 amu and intensities up to 10^7 ions per second. The efficiency of EBIS-CB in the pulsed injection mode will be significantly higher than in the continuous (DC) injection mode, so a Radio Frequency Quadruple Cooler-Buncher (RFQ-CB) will be used to collect ions downstream of the mass separator and create short pulses of high quality radioactive beams with the full transverse normalized emittance of ~0.003 $\pi \times$ mm $\times$ mrad.[4] To avoid ion beam intensity limitations due to space charge, the collection time for the most abundant radioactive ions will be limited to about 33 ms. During collection in the RFQ-CB, the EBIS will breed an injected ion bunch, so breeding must occur in ≤33 ms. This procedure is repeated at a frequency of 30 Hz. At present, due to lower intensity beams from CARIBU, lower repetition rates can be used in the RFQ-CB. The EBIS includes DC and pulsed power supplies. A pulsed electron beam, created by pulsing the electron gun anode with a high voltage amplifier, is used rather than a DC beam to avoid possible discharges and maintain high vacuum. Many EBIS electrodes require pulsed operation to facilitate injection, trapping, and extraction of the ion bunch. The power supplies, timing, and control systems for the CARIBU EBIS were described in Ref. 5.

The breeding of radioactive ions prior the injection into the Linac is already in use at ISOLDE (CERN),[6] ISAC (TRIUMF),[7] and at NSCL.[8] The EBIS CB project for CARIBU is utilizing state-of-the-art EBIS technology recently developed at Brookhaven National Laboratory[9] as an injector for stable ion beams. During the design and construction of the CARIBU EBIS, we implemented many innovative modifications with respect to the existing charge breeders of radioactive beams and the BNL EBIS. Many additional novel design features of the CARIBU EBIS CB are described in Sec. II and more details are given in our previous publications.[10,11] Off-line commissioning of sub-systems and first charge breeding measurements were already reported.[12,13] This paper discusses results of charge breeding experiments with the external singly charged cesium source. Due to the limited space, we report only major accomplishments related to the availability of the CARIBU EBIS as a new scientific tool for fast breeding of radioactive beams with high efficiency. Results of optimization

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of both the electron and ion beam characteristics as a function of various EBIS, ion source, and beam transport parameters will be reported in future publications.

II. DESIGN FEATURES OF THE CARIBU EBIS

The parameters of the electron gun, potential distribution in the ion trap region, electron collector, and injection/extraction beam lines were substantially modified compared to the BNL EBIS CB to obtain a short breeding time, the highest acceptance, and breeding efficiency of low intensity rare isotope beams.

A. E-gun and drift tube structure

The CARIBU EBIS was designed to operate at higher repetition rate and higher electron beam duty cycle than the BNL EBIS. However, the electron beam current density inside the superconducting solenoid is similar to that in the BNL EBIS, allowing fast charge breeding of radioactive ion beams. These improvements were achieved by choosing a 4.2 mm diameter single crystal IrCe cathode which is capable to provide up to ~2 A electron beam current with high perveance. This electron gun allows us fast breeding (<30 ms) with reasonably high breeding efficiency into the most abundant charge state, >25%. We have also developed a low-current e-gun to utilize ionization process involving the so-called shell closures effect[14] which is a straightforward and effective method to narrow the charge state distribution and improve efficiency of the breeding process. A low-energy electron beam (~2 keV) will be used for the "shell closures" operation mode of the EBIS for breeding of ions with moderate charge states (z/A ~ 1/5). An accurate adjustment of the electron beam energy will be done to be just below the ionization energy of atomic shell closures in order to collect most of the ions in the corresponding charge state. Such an approach has been experimentally proven for very high charge states,[14] but not for the moderate charge states required for the CARIBU radioactive beams. To avoid a formation of the virtual cathode for ~2 keV electron beam, a small diameter, 0.8 mm, single crystal IrCe cathode was designed and built to generate 0.2 A electron beam. For the operation of the CARIBU EBIS in shell closures' breeding mode, only electron gun will be replaced, no other parts of the CARIBU EBIS need to be modified. This paper discusses the results obtained with the 4.2 mm diameter cathode while breeding with low-current cathode will be implemented in future as operational schedule permits.

An electron gun, beam transport system, and collector were designed for a 2 A 25 kW DC electron beam. An electron beam inside the EBIS has three different perveance values in different areas: the e-gun, the drift tube structure, and the collector. In our case, the most challenging task is transporting the electron beam through the drift tube structure where the electron beam energy should be low enough to provide high efficiency for the ion charge breeding. The perveance inside the drift tube structure defines the maximum current of the EBIS-CB for a given electron beam energy. An electron beam current that can be transported without space charge compensation through a conducting tube with radius r_t in vacuum is limited by the Bursian current, which can be written in practical units as[15]

$$I_B = 25.4 \times 10^{-6} \frac{U_t^{3/2}}{1 + 2\ln(r_t/r_b)} = P(r_b, r_t) \times U_t^{3/2}, \quad (1)$$

where r_b is the radius of the electron beam, U_t is the potential difference between the tube and cathode (U_t is in volts), I_B is the electron beam current in amperes, and P is the perveance of the electron beam. The electron beam current density in Equation (1) is assumed to be homogeneous. The higher the perveance is the higher current can be transported at lower energies. As one can see from Equation (1), the maximum perveance of the electron beam inside the drift tube structure is achieved when the ratio of the electron beam radius to the drift tube radius is close to 1. In reality, the drift tube radius should be significantly larger than the electron beam radius to provide the electron beam transport along the EBIS axis with negligible beam losses. Other advantages of larger diameter drift tubes are better pumping of the internal drift tube volume and lower probability of parasitic RF field generation. As a reasonable compromise, we have selected 10 mm drift tube radius for the CARIBU EBIS.

At present, the CARIBU EBIS operates with an electron beam current up to 1.6 A, which is a factor of 2 higher than any other operational EBIS-based charge breeders for radioactive beams. The high current electron beam transmission is achieved with relatively low electron beam energy in the trap, 6.5 keV.

Special attention was paid to the design of the vacuum system to enable high purity charge-bred radioactive ion beams. The ion trap includes 11 drift tubes installed on a pipe scaffold which is coated by non-evaporable getter (NEG) using the technology recently developed at CERN.[16] All drift tubes have longitudinal slots to facilitate efficient pumping of the ion trap volume as shown in Fig. 1. The location and orientation of the slots have been selected to avoid possible discharges in the presence of a high magnetic field and RF instabilities induced by the high current electron beam. In the environment of high stray magnetic fields, both turbo- and cryopumps require appropriate magnetic shielding for reliable operation. We designed the vacuum pump shielding to minimize the effect of the magnetic field distortion along the electron beam path. In addition, eight dipole steering coils in the horizontal and vertical planes have been implemented into the EBIS system.

Complete assembling of 11 drift tubes was performed inside a class 100 clean room to avoid contamination of the surfaces with oils and particulates. No fine adjustment was foreseen in the design of drift tube structure, so the alignment relies on the manufacturing accuracy of all elements. After the assembly was completed, the alignment was verified using a FaroArm Platinum series 3D scanner with an accuracy of ±25 μm. The alignment of drift tubes from 1 to 9 was found to be within ±100 μm in the vertical direction and within ±200 μm in the horizontal direction. Drift tubes are numbered starting from the output of the e-gun anode downstream to the collector entrance. Alignment of the e-gun and collector was within ±100 μm to the rest of drift tube structure. Finally, the whole EBIS assembly from e-gun to collector was aligned to

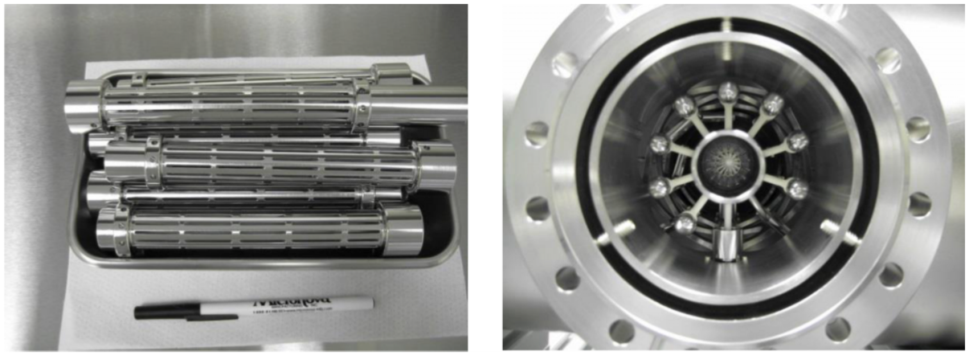

FIG. 1. Set of individual drift tubes prior the installation (left) and a view (from the e-gun side) of the scaffold with installed drift tubes (right).

the magnetic axis of a 6 T superconducting solenoid within ±50 μm.

B. Ion injection and extraction (I-E) lines

The I-E ion beam transport line includes two Einzel lens assemblies, two steerers, and an acceleration tube, as was discussed in Ref. 10. Initial beam dynamic studies revealed that the beam is not axially symmetric due to the not axisymmetric grounded vacuum chambers. The aperture diameter of the Einzel lens, its gap, and the physical size of vacuum chambers were optimized to balance the linear region of the focusing fields at the reduced effect of the vacuum chambers on the beam quality. Three X-Y electrostatic steerer configurations (parallel quartered, diagonally quartered, and two sets of diagonally halved) have been studied in terms of the beam emittance growth. Voltages were applied to the electrodes until a deflection of 13 mrad was achieved in both X and Y planes for each assembly. Two sets of diagonally halved steerer were selected as they provided lowest emittance growth. Our results are consisted with Ref. 17, which reported low beam aberrations when the diagonally halved cylinder is used to create dipole electric field as compared to the parallel sectioned configurations.

Numerical simulations and breeding efficiency measurements at BNL's test EBIS revealed that the 30° electrostatic switchyard for the injection and extraction of ions can introduce significant distortions on singly charged beams being injected into the EBIS. The CARIBU EBIS switchyard employs a single electrostatic deflector to direct the injected ion beam from the source line to the I-E line and to guide the extracted beam from the I-E line to the diagnostic line. A diagonally halved cylindrical deflector was chosen over other deflector configurations because this design can maintain the ion beam quality better than others, as discussed with respect to the steerer assemblies. A schematic of the switchyard is shown in Fig. 2. In the final configuration, the source beam line will be used for injection of the radioactive beams from the CARIBU and the spare beam line port will be used for injection of singly charged cesium beam. The deflector midplane was shifted from the intersection of the 15° source beamline axis and the 0° I-E beamline axis by 0.96 cm as seen in Fig. 2. The value of this offset was determined by programmatically minimizing the deflection and the shift of the injected ion beam from the 0° axis in the EM Studio.[18] This offset will ensure the injected beam can ideally be deflected exactly on axis. The overall length of the deflector was chosen to keep the necessary applied voltages less than ±10 kV, the magnitude for commonly available and moderately priced high voltage amplifiers.

III. EBIS LAYOUT AND OPERATIONAL PARAMETERS

About a year ago, we started extensive charge breeding experiments at the CARIBU EBIS to establish optimal operational parameters. These experiments were interrupted several times for extended periods of a month or longer for the improvement of the EBIS sub-systems. The first charge breeding results of the cesium beam were reported at a recent symposium on electron beam ion sources and traps.[19] Significant performance improvements have been achieved in the past year as is discussed throughout the content of this paper. The 3D model and general view of the EBIS at the off-line location are shown in Figs. 3 and 4, respectively. The commissioning of the EBIS sub-systems[12,13] and beam dynamics studies were discussed in earlier publications.[10] Current operational parameters of the EBIS are listed in Table I together with possible

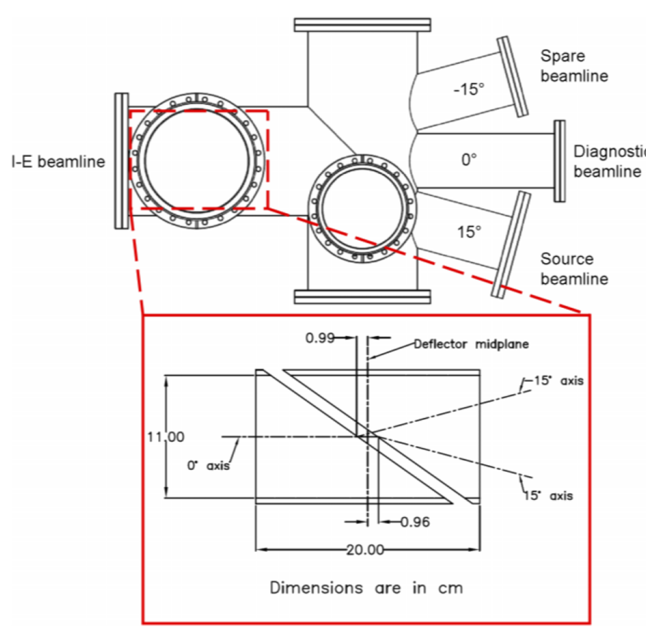

FIG. 2. The electrostatic switchyard configuration and deflector positioning necessary to inject the ion beam on the 0° beamline axis.

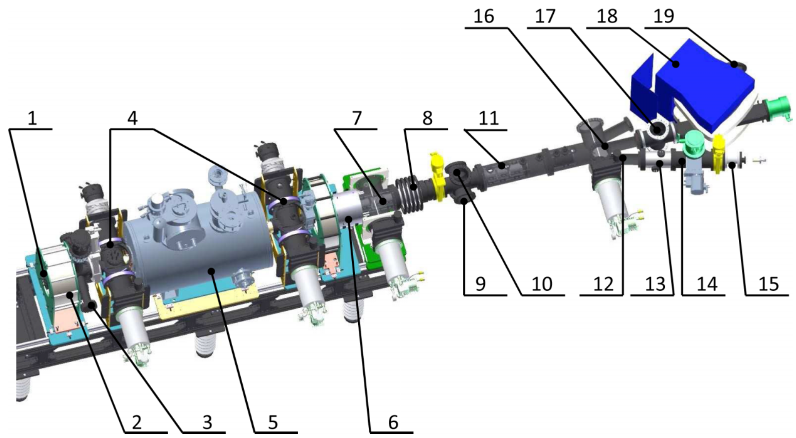

FIG. 3. 3D model of CARIBU EBIS CB in off-line installation (1—e-gun, 2—room temperature solenoid, 3—recently installed NEG pump, 4—end crosses of the ion trap chambers, 5—6 T superconducting solenoid, 6—electron collector with room temperature coil, 7—Einzel lens and steerers (EBIS potential), 8—75 kV accelerating tube, 9—Faraday cup for cesium beam (FC2), 10—pepper pot Multi-Channel Plate (MCP)-based emittance probe, 11—Einzel lens and steerers (ground potential), 12—Faraday cup for cesium beam (FC1), 13—steerers, 14—quadrupole lenses, 15—Cs^+ ion source and accelerating tube, 16—electrostatic switchyard, 17—Faraday cup for charge bred beam (FC3), 18—70° bending magnet, 19—slits and Faraday cup (FC5)).

ultimate parameters. Fig. 5 shows the potential distribution along the EBIS for the charge breeding of residual gas or an externally injected singly charged ion beam. The potential distribution is shown with respect to the EBIS platform which is biased to 20 kV with respect to the ground. The electron gun is biased to −5.75 kV and operates with a 7.5 kV anode voltage provided by a high voltage (HV) amplifier. The e-gun bias, anode voltage, cathode heater current, and the potential of the first drift tube have been optimized to extract a 1.6 A current and minimize electron beam losses along the EBIS. The e-gun bias and the trap potential together with the electron beam current define the electron beam energy in the trap. The trap potential was optimized to provide the highest extracted charge of the ionized residual gas.

For the off-line charge breeding tests of the CARIBU EBIS, we decided to use a commercial cesium ion source which is a good match with the mass range of CARIBU beams and readily available from industry.[20] Trapping/extraction of the ion pulse takes place by raising/lowering the potential of a barrier electrode using fast solid state Behlke switches.[21] The switching time is less than 0.1 μs. In most experiments, we applied ∼1 kV barrier potential with respect to the trap potential, while a ∼300 V barrier potential is sufficient for trapping. For extraction, the barrier potential is ∼−400 V with respect to the trap potential.

A. EBIS vacuum system

The EBIS vacuum system includes a set of turbopumps coupled to scroll pumps, cryopumps, and NEG surfaces. The details of the EBIS vacuum system were described in Ref. 12. Efficient vacuum separation of the trap region from the e-gun and collector is provided. We incorporated all-metal vacuum valves from both sides of the trap region to facilitate easy replacement of e-guns. In February 2015, a NEG pump was installed near the e-gun (position 3 in Fig. 3). Recently we have decided to repeat the activation of getter strips and sputtered getter surfaces in the trap region by *in-situ* baking up to 450 °C. After completion of baking and several weeks of pumping, the ion gauge readings were 1.3×10^{-10} Torr at e-gun chamber

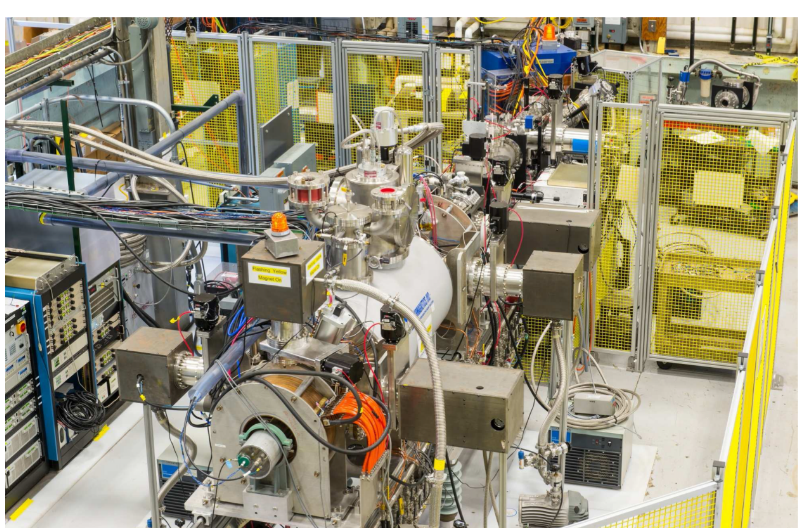

FIG. 4. General view of the EBIS in off-line installation.

TABLE I. EBIS parameters.

Parameter	Operational	Possible ultimate	Units
Magnetic field	5.0	6.0	T
Electron beam current, I_e	1.6	2.0	A
Cathode radius	2.1	2.1	mm
Magnetic field on cathode	0.15	0.15	T
EBIS platform bias voltage	20	50	kV
Trap length	0.5	0.7	m
Electron beam radius in the trap, $r_{e,TRAP}$[a]	364	332	μm
Electron beam density in the trap[a]	385	577	A/cm^2
Electron beam energy in the trap[a]	6495	6265	eV
Space charge potential well, $\Delta U_{e,TRAP}$[a]	299	374	V
Electron beam velocity, v_e, in the trap[a]	4.8×10^7	4.7×10^7	m/s
Normalized full acceptance[b]	0.024	0.024	$\pi\times$mm$\times$mrad
Trap capacity[a]	23	30	nC
Repetition rate	Up to 10	30	Hz
Duty cycle	Up to 40	90	%

[a]Estimated using general EBIS theory, see, for example, Ref. 22.
[b]Simulated with tracking codes.[10]

and 4.5×10^{-10} Torr near the collector with the electron beam switched off. This is a significant improvement as compared to the previous data.[19] The residual pressure depends on the electron beam current and its duty cycle. At lower electron beam currents, below 1 A, the duty cycle can be close to 100%. However, at 1.6 A, stable vacuum and stable charge breeding are observed only if the duty cycle is ≤40% at 10 Hz repetition rate. For the same electron beam current at a 1 Hz repetition rate, the duty cycle is slightly higher. Operation at higher duty cycles requires extended vacuum conditioning.

B. Cesium source

We use a commercial ion gun TB-171, model HWIG-250[20] to produce a singly charged cesium ion beam. Cesium ions are accelerated to ∼23.5 keV by the biased anode voltage and an 11-gap accelerating tube. The cesium source provides a stable DC beam. The pulsed cesium beam with the pulse length up to 55 μs is formed by an electrostatic deflector and injected into the EBIS trap with a 5 ms delay with respect to the electron beam pulse. One electrode of the deflector (chopper) is pulsed up to 5.5 kV by a HV power supply coupled to a fast

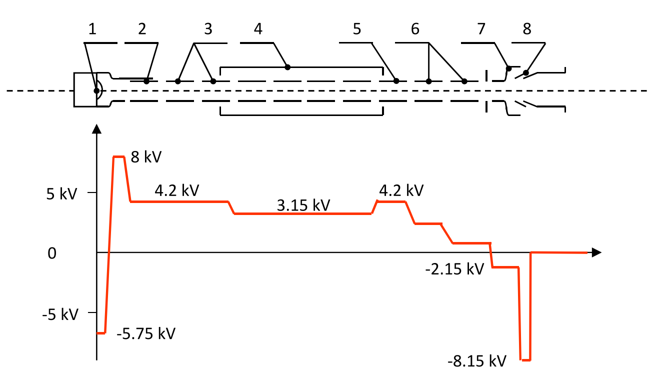

FIG. 5. Simplified schematic of the EBIS structure and potential distribution during the breeding (1—e-gun, 2—the first drift tube, 3—the second and third drift tubes, 4—trap region, 5—drift tube with the barrier potential, 6—drift tubes, 7—electron collector, 8—ion extractor).

Behlke switch. The full normalized acceptance of the EBIS was numerically defined for the wide range of parameters in our previous publication.[10] The normalized acceptance can be approximated with the expression $A_{FULL}[\text{mm}\times\text{mrad}] = \pi \times 3.8 \times 10^{-3} r_{e,TRAP}[\text{mm}]\sqrt{\Delta U_{e,TRAP}[\text{V}]}$ and equal to 0.024 π × mm × mrad for current EBIS parameters. It is significantly higher than the emittance of the radioactive beams expected from RFQ cooler-buncher which is ∼0.003 π × mm × mrad normalized. Therefore, for the purpose of EBIS efficiency measurements and application of these results to the radioactive beams, it is important to form a cesium beam with an emittance comparable to that expected from the CARIBU source. The emittance of the cesium beam is established by the appropriate focusing with a cesium source Einzel lens, an electrostatic triplet, and adjustment of an iris style aperture. The cesium beam is very sensitive to the tuning of the beam optics due to the non-linear character of the source extraction system and some off-centered beam trajectory in the transport system. In our experiments, the intensity of the cesium beam was defined both by the heater in the ion source and the collimator. About 80% of the cesium beam was intercepted by the collimator. The beam intensity did exceed $\sim 4 \times 10^7$ ions/pulse, which corresponds to 6.4 pC. A typical cesium beam image on the phosphor screen of the pepper pot emittance meter and a processed emittance shape of this beam are shown in Fig. 6. The measured rms normalized emittance of the cesium beam is ∼(0.006 ± 0.0015) π × mm × mrad. The full cesium emittance is slightly larger than the EBIS acceptance, but the current collimator configuration is unable to reduce the emittance further. In addition, some losses due to beam emittance and beam center mismatch with the EBIS acceptance may take place. All this results in a transmission efficiency of the cesium beam through the EBIS lower than 100%.

C. Ion beam diagnostics tools

Predominantly we use an oscilloscope to measure the total charge of injected and extracted ion beam pulses incident on

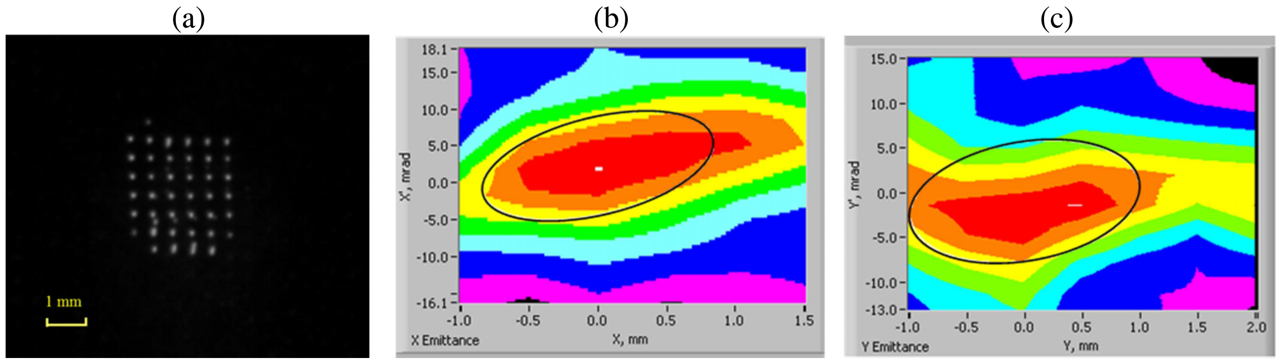

FIG. 6. A typical cesium beam image on the phosphor screen of the pepper pot emittance meter (a) and its emittance ((b) and (c)). The distance between the pepper-pot holes is 0.5 mm. The color code corresponds to a linear incremental change of the density from 0 to 10. The central red area corresponds to the density higher than 10.

Faraday cups. There are 3 Faraday cups (FC1, FC2, and FC3) with 46 mm input apertures installed on air cylinders (see positions 9, 12, and 17 in Fig. 3), and a stationary cup (FC5 at position 19 in Fig. 3) installed downstream of adjustable slits after the bending magnet. FC1 and FC2 are used for the measurements of the injected cesium beam charge. Based on our previous experience with the current measurements of multi-charge ion beams, the electron suppression voltage is −300 V. The accuracy of beam charge measurements is ±1%. As is known, multi-charge beams can produce energetic Auger electrons that can escape the FC. Our measurements with ATLAS multi-charge beams show that the contribution of energetic electrons to the measurement error is less than 0.4% if a −300 V biased voltage is applied. Therefore, it is our common practice to apply −300 V to all Faraday cups used for the measurements of multi-charge ion beams. A typical FC2 signal from the pulsed cesium beam is shown in Fig. 7. The total charge is calculated as $Q_{tot} = V_{peak}C_{FC}$, where V_{peak} is the peak voltage and C_{FC} is the capacitance of the FC and signal cables. Calculation of the charge by area integration results in the same value within a ±1% error. For charge breeding efficiency measurements, we use FCs with identical capacitances to avoid error due to different decay times of the voltages during the charge accumulation over the pulse length.

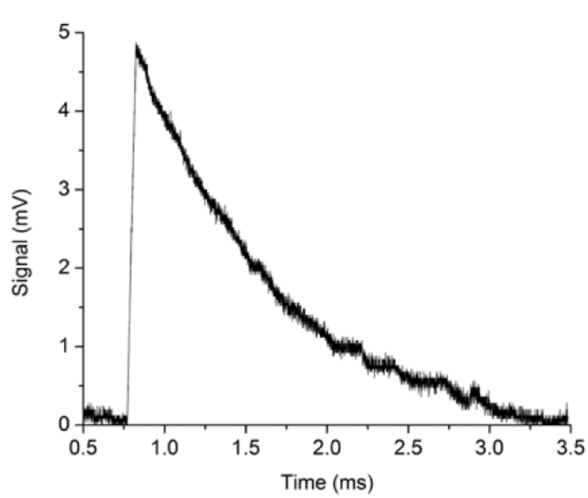

FIG. 7. Cesium beam signal reading on the FC2 prior to injection into the EBIS.

A pepper-pot emittance probe based on a Multi-Channel Plate (MCP) and a phosphor screen (position 10 in Fig. 3)[23] was used to measure the emittance of the injected cesium beam. Due to the very high sensitivity of the MCP, very low injected cesium beam intensities, ∼0.1 pC per pulse, can be analyzed by the emittance probe.

D. Electron beam commissioning

The stability of high current-high duty cycle electron beam in the EBIS is the key for breeding of ions with high efficiency. The set of electron beam diagnostics and results of the initial electron beam commissioning at 4 T magnetic field were reported in the previous publication.[12] The time structure of the electron beam was formed by applying a pulsed high voltage potential to the e-gun anode. Optimal transport of the electron beam with very low relative losses, below 10^{-4}, from the e-gun cathode to the collector was established by tuning of two sets of X and Y steering dipole coils installed on vacuum chamber crosses in both sides of the superconducting (SC) solenoid and 4 pairs of magnetic steering coils installed on the beam tube inside the SC solenoid bore. In addition, the collector solenoid field is tuned to minimize the electron beam losses. The availability of steering coils is essential for the 100% transmission of the electron beam. The tuning of the electron beam is complete when vacuum gauges do not show any pressure fluctuations. Currently we can stably operate 1.6 A electron beam at 40% duty cycle or 1.15 A electron beam at 90% duty cycle. Increasing either current or duty cycle of the electron beam requires long vacuum conditioning.

IV. RESIDUAL GAS IONIZATION

When the barrier electrode potential is raised (position 5 in Fig. 5), ionization of residual gas atoms and molecules takes place in the trap. The charge bred ions of the residual gas are extracted and analyzed using 70° bending magnet. In Sec. V of this paper, we discuss experimental data taken from FC5 for multiple pulses while the dipole current was varied. The beam charge values delivered in each pulse were generally stable, but we used averaging of the signal over several pulses when this was not the case. Fig. 8 shows spectra of the residual gas for two different confinement times for the EBIS operational

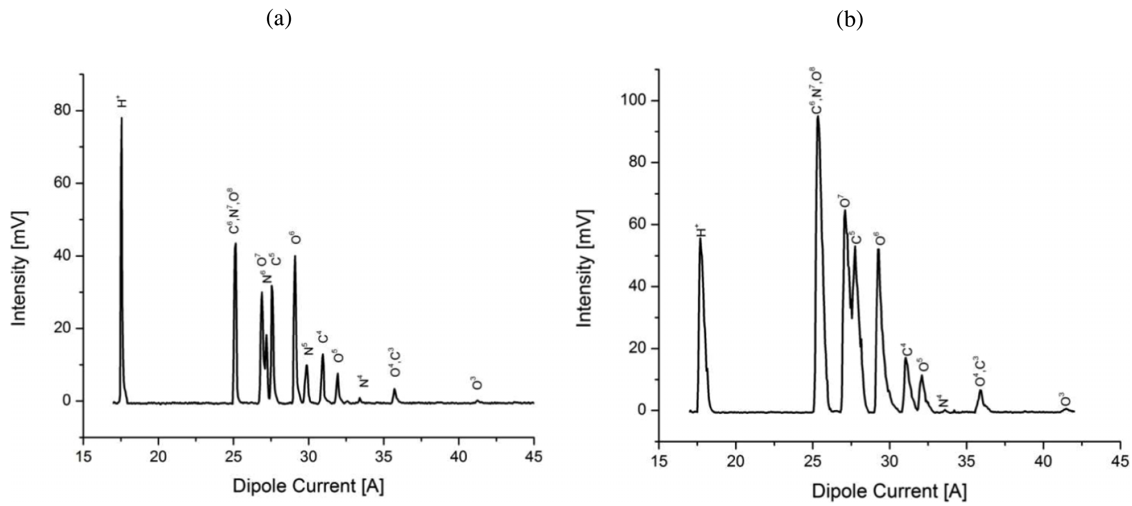

FIG. 8. Residual gas spectrum at 30 ms (a) and 65 ms (b) of confinement time. Ion pulse charge is $Q[pC] = 0.19 \times V[mV]$.

parameters shown in Table I. To increase mass resolution, the beam was collimated upstream of the FC5. The residual gas contains ions of hydrogen, carbon, and oxygen. The relative contribution of nitrogen is very low. We do not see molecular ions in the spectrum. The preferable values of charge-to-mass ratios for CARIBU beams for the extraction, separation, and further acceleration in ATLAS are in the range from 1/7 to 1/4. These ratios can be achieved with breeding times from 10 to 30 ms and appear on FC5 approximately in the range of magnet currents from 36 to 47 A. By adjusting the breeding time, the most abundant charge state of a rare isotope ion beam can be located between residual gas peaks and separated from the residual gas contamination in the transport system downstream of the EBIS. We plan a detailed study of possible contaminants from the residual gas in the region between O^{3+} and O^{4+} with upgraded Faraday cups and amplifiers to measure femtocoulomb-level charges.

The capacity of the trap is calculated as $C_{TRAP} = \frac{I_e L_{TRAP}}{v_e}$ = 23 nC, where I_e is the electron beam current, v_e is the electron velocity in the trap, and L_{TRAP} is the length of the trap. For typical confinement times, ≤30 ms required for CARIBU beams, the neutralization factor is below 2%. The total extracted charge of residual gas ions does not exceed ∼7% of the total charge capacity of the trap for confinement times up to 150 ms.

V. CESIUM BREEDING EFFICIENCY MEASUREMENTS

The main goal of the off-line commissioning was to demonstrate stable operation of EBIS at a 10 Hz repetition rate and a breeding efficiency into single charge state higher than 15%. These goals have been successfully achieved and exceeded. The breeding efficiency measurements were performed according to the procedure described in detail in Ref. 24. This procedure uses measurements of total charge on FC3 with and without cesium injection. The total number of extracted cesium ions was calculated as a ratio of cesium charge on FC3 to the average charge state of the cesium beam. The latter was found from the measured cesium spectrum obtained on FC5 with 1 or 2 mm wide slits. Examples of the cesium spectra for 20 and 28 ms breeding times for the EBIS operational parameters listed in Table I are shown in Fig. 9. For

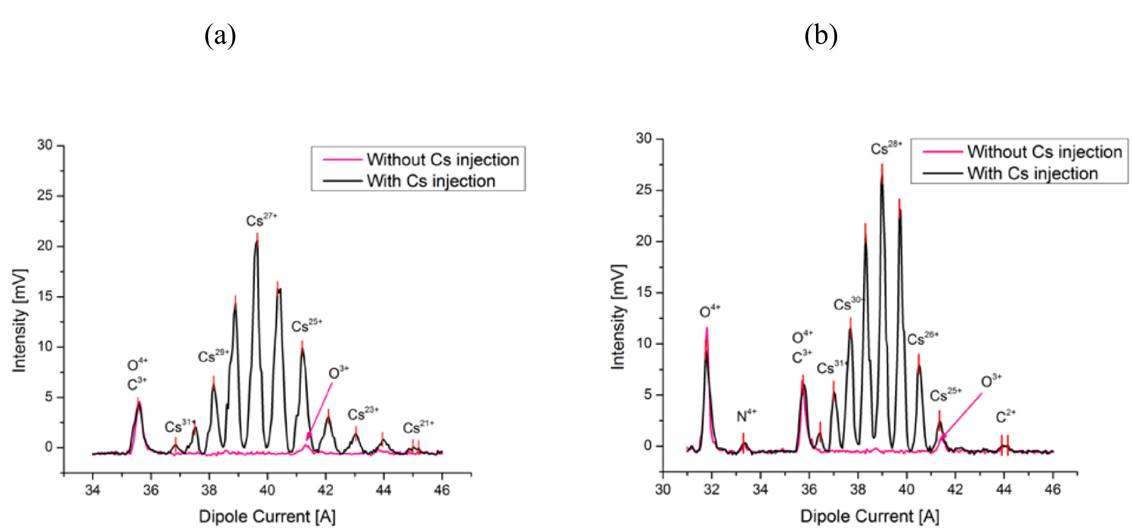

FIG. 9. Spectra of charge-bred cesium and residual gas ions for two breeding times: 20 ms (a) and 28 ms (b).

these measurements, to obtain a good resolution of different charge states, the slits upstream of the FC5 were closed to 2 mm. The average charge state, $\bar{z}$, was calculated using the expression

$$\bar{z} = \frac{\sum_{z=z_{\min}}^{z_{\max}} Q_z}{\sum_{z=z_{\min}}^{z_{\max}} \frac{Q_z}{z}}, \quad (2)$$

where Q_z is the total charge of ions at a particular charge state z, z_{min} and z_{max} are the minimum and maximum charge states correspondingly in the spectrum of charge-bred cesium ions. The total charge Q_z was calculated as an area under the Gaussian distribution obtained from the fit to the measured distribution. The relative abundance of cesium ions with different charge states is defined by the expression

$$A_z = \frac{Q_z}{z \cdot \sum_{z=z_{\min}}^{z_{\max}} \frac{Q_z}{z}} \cdot 100\%. \quad (3)$$

We noticed that the calculations of average charge state could also be done using a peak value of the signal for each charge state, Q_z^{peak}, with similar results. Breeding efficiency into the charge state with the highest abundance, $\eta_{z,\max}$, is defined as a ratio of the number of extracted ions with highest abundance to the number of injected Cs^+ ions, and it can be found from the expression $\eta_{z,\max} = \eta_{tot} \cdot A_z^{\max}$, where η_{tot} is the total transmission efficiency of cesium ions. The above mentioned method includes an error related to the measurements of the total charge of residual gas ions with and without cesium injection. Due to the interaction of cesium ions with the ions of residual gas, the total extracted charge of residual gas ions is slightly modified. From the comparison of the spectra of the residual gas ions (Fig. 8(a)) and cesium beam (Fig. 9(b)), it is clear that the ions of the residual gas are well separated with respect to the cesium spectrum. Therefore, the relative change of the total charge of the residual gas, ξ, extracted with and without cesium injection can be approximately estimated as $\xi = 2\frac{\Sigma_1-\Sigma_2}{\Sigma_1+\Sigma_2}$, where Σ_1 and Σ_2 are the integrated charges of the residual gas ions in the spectra with and without cesium injection, respectively. The calculations show that $\xi = 2.2\%$.

In addition, we have performed direct measurements of the cesium charge in a single charge state after the bending magnet. This is possible for charge states below ~20 when the full intensity in the single charge state can be transported to the FC5 with a 10 mm slit opening. The breeding efficiency into a single charge state can be calculated directly by measuring the charge on FC5. This method results in the breeding efficiency consistent with the method described above and in Ref. 20 within ±2.5%. Overall, the systematic and measurement errors result in ±3.5% relative error of the breeding efficiency evaluations.

After several optimization rounds of cesium beam tuning, the EBIS parameters and injection-extraction potentials consistently resulted in total injection-extraction efficiencies of ~70% and can be increased to 80% with elaborate beam tuning. An example of FC3 measurements with and without injection of the cesium beam is shown in Fig. 10. These data together with the FC2 reading of the injected cesium

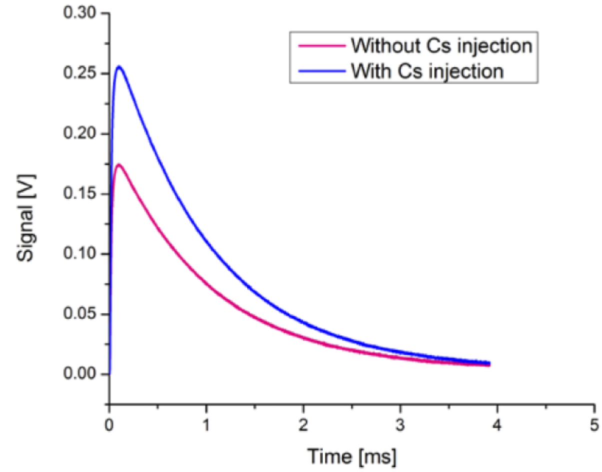

FIG. 10. FC3 signal for a single ion pulse without and with injection of cesium beam.

beam charge and average charge state calculations from the beam spectrum measurements on FC5 were used for the total breeding efficiency calculation. We found that the relative abundance of the charge state 28+ was 27% for a 28 ms breeding time as is shown in Fig. 11. Therefore, the absolute breeding efficiency of cesium ions into charge state 28+ is 20%. It is interesting to note that we observed a higher abundance of charge state 28+ as compared to the CBSIM simulations.[25] Based on these measurements, the EBIS should provide ≥20% breeding efficiency of CARIBU rare isotope beams because the expected CARIBU beam emittance is several times smaller than the cesium beam emittance. We should be able to reach an absolute breeding efficiency of ~27% when the EBIS CB is relocated and coupled to CARIBU. These experiments clearly demonstrate fast and efficient charge breeding of cesium ions. As it follows from the CBSIM simulations any ion in the full mass range of the periodic table can be charge bred with high efficiency, within short breeding times to a sufficiently high charge-to-mass ratio (≥1/6.3 for the heaviest masses) for further acceleration in ATLAS with the presently demonstrated parameters of the CARIBU EBIS.

Fig. 12 shows the average charge state of charge bred ions as a function of breeding time. The simulations with

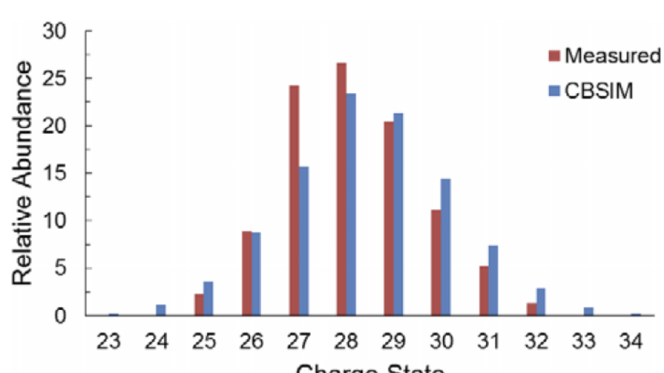

FIG. 11. Measured and calculated, using CBSIM code, relative abundances for 28 ms breeding time.

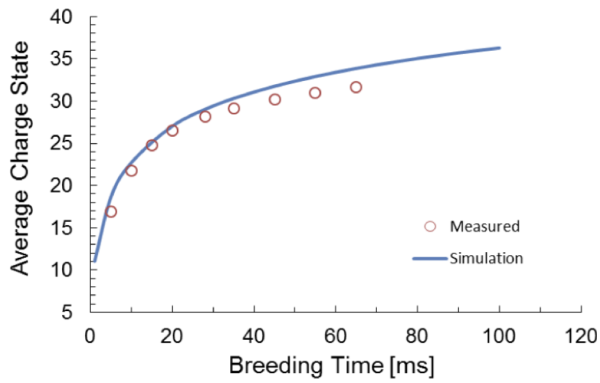

FIG. 12. Average charge state as a function of breeding time.

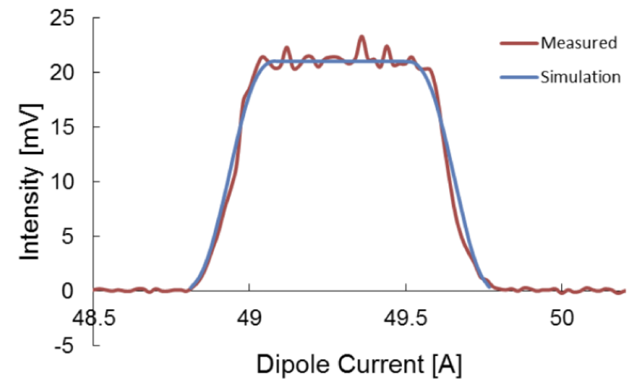

FIG. 14. Cs^{17+} beam intensity distribution as a function of magnet current. Breeding time is 5 ms.

CBSIM code[25] are also shown in this plot. The CBSIM simulations describe the experimental data well with some tendency of higher average charge states at longer breeding times as compared to the measurements.

Another practical parameter is the relative abundance of the ions in the charge state distribution. Obviously, we are looking for the highest abundance into a single charge state. Fig. 13 shows the measured and simulated highest abundance in the charge state distribution as a function of breeding time. For short breeding times, ≤15 ms, we observe lower breeding efficiency for the most abundant charge states while the average charge state is in agreement with the CBSIM simulations. Possible explanation for this is the injection of a slightly misaligned ion beam with respect to the electron beam. An explanation for higher abundance in charge states 27+ and 28+ as compared to the CBSIM simulations requires additional studies.

Emittance and energy spread of the extracted and charge selected ion beam are important parameters for the following transport and matching to ATLAS. In the off-line EBIS setup, we do not plan to measure the emittance of the extracted beam due to the lack of space for charge selection. The emittance of the extracted beam in EBIS has been measured at the BNL high-current EBIS[26] and REX-ISOLDE EBIS[22] at CERN. Emittance studies at REX-ISOLDE have shown that the emittance is a weak function of the magnetic field in non-neutralized beams, which is the case of CARIBU EBIS. Also, the emittance is a strong function of the charge-to-mass ratio: the lower this ratio the lower the emittance. On the basis of REX-ISOLDE's simulations, we have approximated the full normalized CARIBU EBIS emittance as $0.05\,\pi \times$ mm $\times$ mrad for z/A = 17/133. With an approximate transverse emittance of the extracted beam, the energy spread can be estimated by fitting simulated data to the cesium beam spectrum and beam profile after the magnet and slits. For short breeding times (lower charge states), individual charge states can be fully separated after the slits as is shown in Fig. 14. A 10 mm slit opening allowed us to select an individual charge state at full intensity. The intensity of the beam for a given charge state on FC5 was measured as the slit width was varied. The differentiation of this curve produces the horizontal beam profile as is shown in Fig. 15. By varying the beam energy spread in the TRACK simulation code,[27] we fit simulated data to the measured intensity distribution in a single charge state as is shown in Fig. 14. Also, a simulated beam profile was fit to the measured one (Fig. 15). These fits gave us a beam rms energy spread as $\sigma_E \approx 18.4$ eV per charge state z. This results in a full energy spread of $6\sigma_E = 110$ eV/z. As is well-known, the upper estimate of the full energy spread is equal to the depth of the potential well inside the electron beam.[22,28] However, in our measurements for a low breeding time of 5 ms, we observe a factor of ∼3 lower energy spread than the potential well of 299 V shown in Table I.

Currently, the CARIBU beams at ATLAS are charge bred using an ECR charge breeder. The breeding efficiency of the

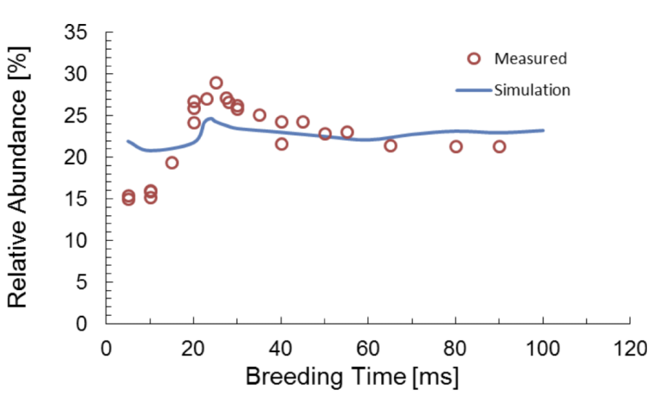

FIG. 13. Measured (dots) and simulated (solid line) highest relative abundance as a function of breeding time.

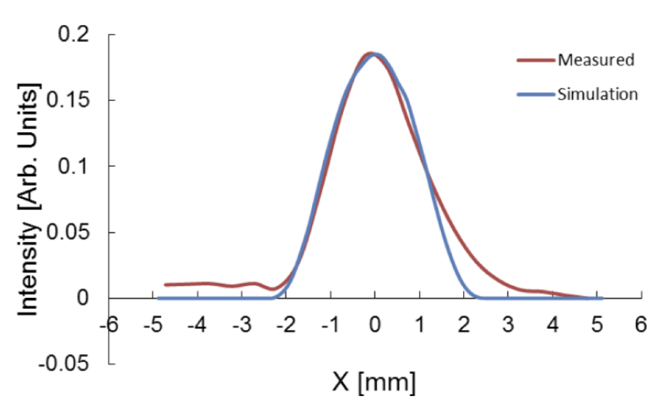

FIG. 15. Cs^{17+} beam profile downstream of the magnet. Breeding time is 5 ms.

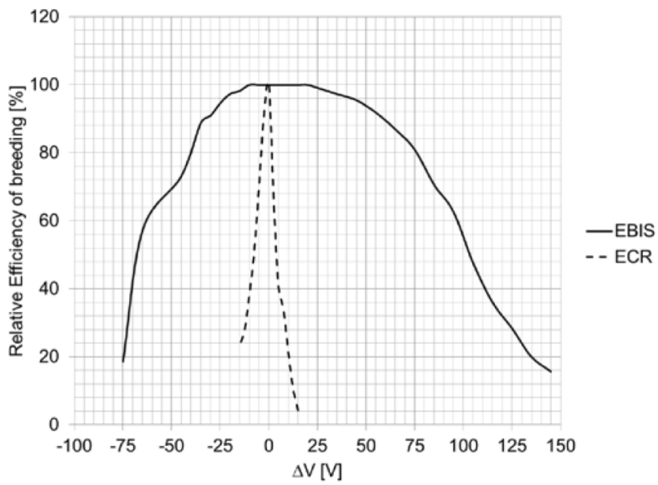

FIG. 16. The breeding efficiency of the cesium beam as a function of the bias voltage deviation from the optimal voltage.

ECR is quite sensitive to the voltage difference between the CARIBU gas catcher and ECR charge breeder.[29] To find a similar sensitivity of the EBIS to the energy of the injected beam, we have measured the cesium beam intensity on FC5 while the cesium source bias was varied. The results are shown in Fig. 16. In the range of ±15V, there is no change in breeding efficiency. Therefore, the sensitivity of the EBIS to the energy of the injection singly charged ions is several times less than in the current ECR charge breeder. This is another advantage of using the EBIS as a charge breeder instead of the ECR.

VI. CONCLUSIONS

The CARIBU EBIS CB has been successfully commissioned off-line with the external singly charged cesium ion source. The performance of the EBIS fully meets specifications to breed rare isotope beams delivered from CARIBU. The EBIS can provide charge-to-mass ratios ≥1/7 for all CARIBU beams with low breeding times in the range from 5 to 30 ms. Up to a 20% breeding efficiency into single charge state of cesium has been demonstrated. The overall transmission of cesium beam through the EBIS is 70% routinely. The transport efficiency of the charge bred cesium beam is lower than 100% primarily due to the larger emittance of the cesium beam than the EBIS acceptance. Even greater breeding efficiencies, ≥25%, are expected for the small emittance beams from CARIBU. The EBIS is ready to be relocated and integrated into ATLAS and CARIBU. Breeding of CARIBU beams at a 10 Hz repetition rate is available immediately. Tuning and conditioning of the EBIS at duty cycles higher than 50% and repetition rates up to 30 Hz is under way.

Overall success of the CARIBU EBIS commissioning is the result of implementation of many innovative design features together with application of the state-of-the-art techniques and procedures during the design and mechanical assembly. The major precursors to the successful commissioning were ultra-high vacuum, high electron beam current with relatively low energy in the trap, optimized linear focusing and steering fields in the injection and extraction region, excellent alignment of the electron and ion beam transport system components, availability of the 8 pairs of dipole steering coils for the transport of electron beam, and availability of the tracking codes for the study of ion beam optics in a wide range of parameter space. The energy spread of charge-bred ions has been determined by using original beam tracking code and fitting of the simulated ion beam distribution to the measured data.

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