COMMISSIONING EXPERIENCE WITH CARIBU

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Abstract

The Californium Rare Ion Breeder Upgrade (CARIBU) of the ATLAS superconducting linac facility aims at providing low-energy and reaccelerated neutron-rich radioactive beams to address key nuclear physics and astrophysics questions. These beams are obtained from fission fragments of a Cf-252 source, thermalized and collected into a low-energy particle beam by a helium gas catcher, mass analyzed by an isobar separator, and charge bred with an ECR ion source to higher charge states for acceleration in ATLAS. The facility has ramped up operation from an initial 2.5 mCi source to the present 55 mCi source. A 500 mCi source has been produced at Oak Ridge National Laboratory and is expected to be ready for installation in mid-2012. Low-energy mass separated radioactive beams have been extracted, charge bred with a 10% efficiency, reaccelerated to 6 MeV/u, and delivered to GAMMASPHERE for beta decay studies. The Canadian Penning Trap (CPT) mass spectrometer has been relocated to the CARIBU low-energy beam line. Mass measurements on over 60 neutron-rich nuclei have already been performed and additional measurements are underway. In addition, a new tape station for beta decay studies has just been commissioned.

THE CARIBU FACILITY

Science is driving the development of ever more capable radioactive beam facilities. While present day facilities (REX-ISOLDE, TRIUMF, TRIAC, ANL) can deliver particle intensities in the 10^4 to 10^8 pps range, future facilities (FRIB, HIE ISOLDE, SPES, SPIRAL2, EURISOL) will deliver beams in the 10^{10} to 10^{13} pps regime. However, these are large costly projects which have a long timeline from conception to full operation. In the United States, the Facility for Rare Ion Beams (FRIB) [1] will be the flagship radioactive beam facility producing a wide array of beams via in flight fragmentation, but the facility is not expected to be fully functional until 2021. In the interim, the CARIBU facility [2] (Fig. 1) will provide beams of radioactive nuclei albeit with a more limited reach and intensity but also at a substantially reduced cost and project footprint. CARIBU will utilize fission fragments from ^{252}Cf to provide nuclei which will be thermalized in a helium gas-catcher, mass separated and injected into an ECR charge breeder (ECRCB) to raise their charge state for subsequent acceleration in the ATLAS superconducting linear accelerator. The facility also encompasses a low-energy experimental area for mass measurements and decay studies.

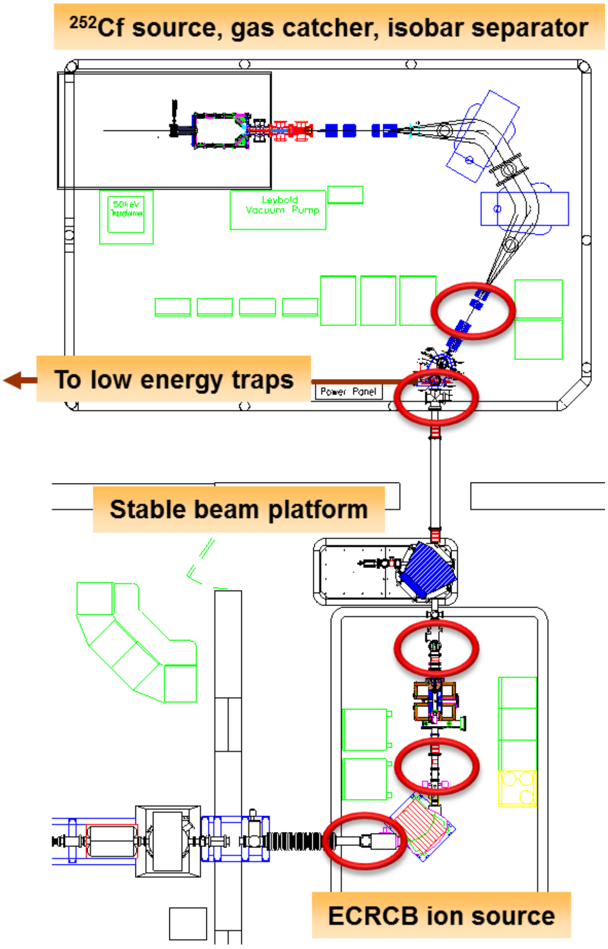


Figure 1: Overview of CARIBU facility and ECR charge breeder. The locations of surface barrier detectors used for radioactive beam tuning are marked with red ovals.

Californium Source

A ^{252}Cf fission source is used to produce the neutron-rich nuclei with a fission fragment distribution peaked in regions of interest that are not well populated by uranium fission. With a 2.6 year half-life and a 3.1% fission branch, ^{252}Cf has a relatively long source lifetime and thus minimizes the need for source replacement. The source is stored in a heavily shielded cask assembly which attaches to the helium gas catcher/RFQ ion guide system. In its final configuration, CARIBU will utilize a 1Ci ^{252}Cf source, but facility commissioning took place with a 55 mCi source. This served as a test of the shielding integrity and allowed for safe equipment modifications.

Gas Catcher

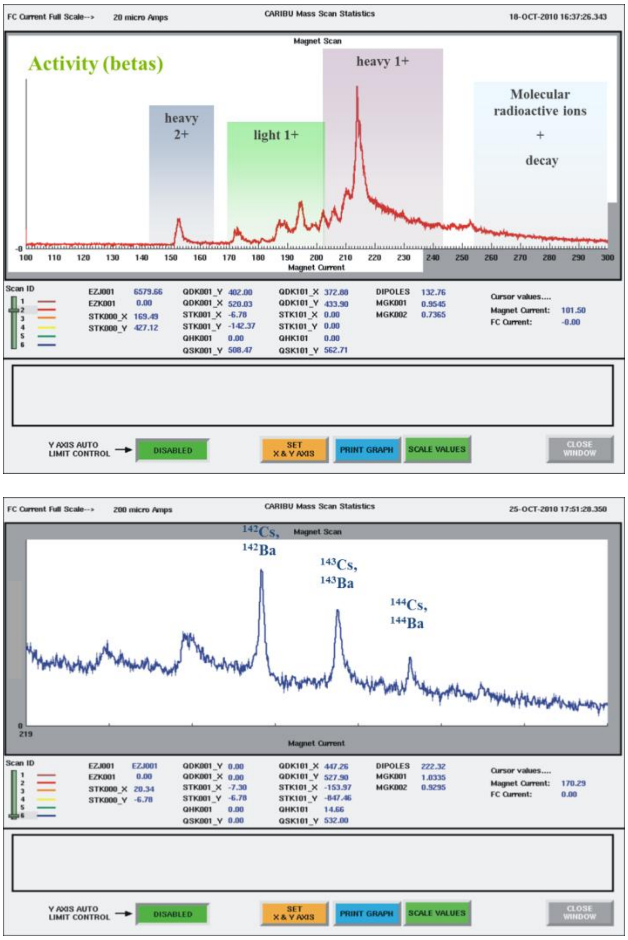
The gas catcher is a large-volume high-intensity device measuring 50 cm in diameter and 1 m in length. The UHV construction, utilizing all stainless steel and ceramic components, allows for a clean system that can be baked after source installation. The fission fragments lose the majority of their energy in a degrader foil placed over the Cf source. The fragments are then thermalized in the ultra-pure helium gas operating at a pressure of 150 mbar. A combination of RF and DC fields keep the ions off of the wall and move them towards extraction at which point the helium gas flow in the RF cone section serves to transport the ions to two differentially pumped RFQ sections. The extraction RFQ leads to a 50 kV acceleration section forming a beam containing all off the ^{252}Cf fission products but of very good quality – 1 eV energy spread and 3 π mm mrad emittance. The typical extraction time is 10 msec with an overall efficiency of 20%. Some of the expected yields for a 1 Ci source both at low energy and after acceleration are shown in Table 1.

Isobar Separator

The fission fragments are delivered to a compact isobar separator with a design mass resolution of 1:20,000. Matching sections at the entrance and exit form a vertical ribbon beam for mass selection, and all optics are electrostatic so that the beamline tune is mass independent. To date, the best achieved resolution has been 1:10,000 in part due to difficulties with the field control of the magnets. There are several surface barrier detectors installed in the beam transport line for diagnostics. These are used to monitor the radioactive isotope intensity via beta decay. For beam identification, the magnets are ramped in the traditional manner while observing the beta activity as shown in Fig. 2. The spectrum is divided into several regions representing the heavy 2+ fission products, the light and heavy 1+ products, and the molecular components with an underlying decay tail from the long-lived activity. Higher resolution scans are performed on regions of interest allowing definitive beam identification as shown in the lower panel of Fig. 2.

Table 1: Isotope yields at low energy and after acceleration in the ATLAS linac assuming a 1 Ci source.

Isotope	Half-life (s)	Low-energy Beam Yield (s^{-1})	High-energy Beam Yield (s^{-1})
^{104}Zr	1.2	6.0 x 10^{5}	2.1 x 10^{4}
^{143}Ba	14.3	1.2 x 10^{7}	4.3 x 10^{5}
^{145}Ba	4.0	5.5 x 10^{6}	2.0 x 10^{5}
^{130}Sn	222	9.8 x 10^{5}	3.6 x 10^{4}
^{132}Sn	40	3.7 x 10^{5}	1.4 x 10^{4}
^{110}Mo	2.8	6.2 x 10^{4}	2.3 x 10^{3}
^{111}Mo	0.5	3.3 x 10^{3}	1.2 x 10^{2}



EZJ001 6579.66
EZK001 0.00
STK000_X 169.49
STK000_Y 427.12
QDK001_Y 402.00
QDK001_X 520.03
STK001_X -6.78
STK001_Y -142.37
QHK001 0.00
QSK001_Y 508.47
QDK101_X 372.88
QDK101_Y 433.90
STK101_X 0.00
STK101_Y 0.00
QHK101 0.00
QSK101_Y 562.71
DIPOLES 132.76
MGK001 0.9545
MGK002 0.7365
Cursor values....
Magnet Current: 101.50
FC Current: -0.00

EZJ001 EZJ001
EZK001 0.00
STK000_X 20.34
STK000_Y -6.78
QDK001_Y 0.00
QDK001_X 0.00
STK001_X -7.30
STK001_Y -6.78
QHK001 0.00
QSK001_Y 0.00
QDK101_X 447.26
QDK101_Y 527.90
STK101_X -153.97
STK101_Y -847.46
QHK101 14.66
QSK101_Y 532.00
DIPOLES 222.32
MGK001 1.0335
MGK002 0.9295
Cursor values....
Magnet Current: 170.29
FC Current: 0.00

Figure 2: Scans of the isobar separator magnets showing the beta activity of the radioactive fission products. The coarse upper scan delineates the various regions of interest, while the fine lower scan displays positive beam separation and identification.

LOW-ENERGY EXPERIMENTS

CARIBU provides a wealth of neutron-rich nuclei available for study. For many of these nuclei, not even their fundamental properties, such as mass and half-life, are known. To measure these properties, it is not necessary to accelerate the neutron-rich nuclei produced by CARIBU. Instead, the beams from CARIBU are delivered to a low-energy experimental area after they are further cooled and bunched with an RFQ along a low-energy beamline, ejected at rates of ~10 Hz, and transformed by an 'elevator' from the ~50 kV beam extracted from the gas catcher to a ~2-10 kV beam.

The first experiments using low-energy beams from CARIBU have begun. A program to measure the masses of neutron-rich nuclei has been initiated with the Canadian Penning Trap (CPT) mass spectrometer. Masses of neutron-rich nuclei not only help to disentangle the underlying nature of nuclei, but they are also essential ingredients for understanding the astrophysical r-process thought to produce more than half of the heavy elements

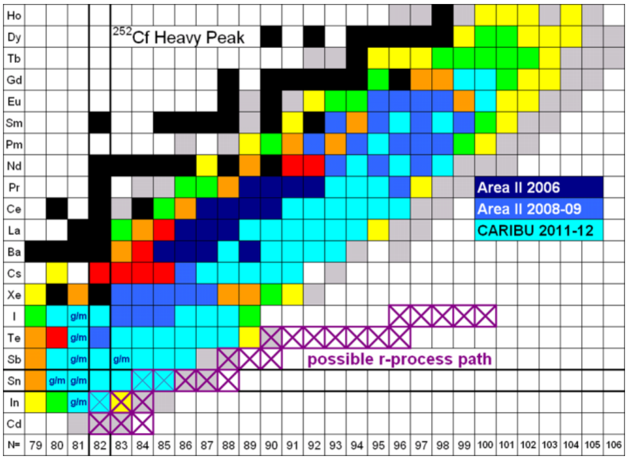


Figure 3: Masses measured during the various campaigns with the Canadian Penning Trap.

in the universe. To date, masses have been measured with the CPT for 62 nuclei along the In, Sn, Sb, Te, I, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd isotopic chains (Fig. 3) to a precision of typically 10 keV/c2. Of these, 17 masses were obtained for the very first time, and the mass precision of the other masses was vastly improved. After the 500 mCi source is installed, it is expected that more than 100 additional mass measurements of neutron-rich nuclei will be made.

A moving tape collector system, or "tape station", has been constructed and installed in the low energy experimental area of CARIBU. The system consists of an implantation chamber and tape transport/storage mechanism. Fission fragments from CARIBU are implanted on 35 mm aluminized tape and beta/gamma activity is detected using plastic scintillators and high purity germanium detectors. Once a counting cycle is completed, the activity can be transported on the tape away from the detectors to a shielded location within a storage unit capable of holding ~350 ft of tape. The system has been commissioned by using it to measure half-lives for ^{142}Cs and ^{144}Cs. Preliminary values of 1.68(2) s and 0.99(5) s, respectively, were obtained on the first attempt with 7 hours of beam time. The quoted uncertainties are purely statistical. The system is capable of operating with a sufficiently short duty cycle to study nuclei with half-lives as short as 300 ms and has been observed to operate reliably in this mode for 16 hours.

CHARGE BREEDER

The charge breeder is a room temperature ECR ion source operating at 10-14 GHz with a design extraction voltage of 50 kV, matching that of the gas catcher. The ECRIS has an open-structure NdFeB hexapole with six radial ports. The radial ports which are each 17 x 41 mm in size act as pumping channels resulting in a plasma chamber pressure of 5 x 10^{-8} Torr. They also serve to introduce the RF and support gas into the plasma chamber. This eliminates the need for cut-outs in the injection side iron plug and results in a large peak and highly symmetric axial magnetic field where the ions enter the plasma. This scheme differs from other ECR charge breeders in existence which are closed hexapole devices with axial RF injection. For the ANL ECRCB, the low charge-state ions are introduced into the plasma through a grounded stainless steel tube mounted on a linear motion stage. The stage has a 30 mm range of travel, and thus the deceleration point of the low-charge state ions can be adjusted on-line without disturbing the source conditions [3, 4].

Breeding Efficiency

A summary of achieved charge breeding efficiencies of the ANL ECRCB compared to that of other breeders operating in the world is given in Fig. 4. The ANL charge breeding development system consists of a source for the production of stable ions (either a surface ionization source or an RF discharge source), a transport system, and the ECR charge breeder (see Fig. 1). A diagnostics region includes a fully shielded Faraday cup for measuring the 1+ beam and a silicon surface barrier detector (SBD) for measuring radioactive beams via beta decay. After charge breeding, the intensity of the mass analyzed n+ ions is observed on either a Faraday cup for the stable beams or a SBD (which has an identical configuration to the 1+ SBD) near the Faraday cup for the radioactive beams. The breeding efficiency and time are determined by pulsing the incoming 1+ beam, using an electrostatic steerer voltage, and measuring the n+ response on the Faraday cup or SBD. The breeder typically operates at 36 kV potential with two RF frequencies (11.44 + 11.7 GHz) exciting the plasma. While the breeding efficiencies of the stable and radioactive species have been similar, the beamline tunes used to achieve these results are different. There is some evidence that the beam extracted from the ECRCB differs in its trajectory depending upon the source of the feed material – neutral gas injection versus 1+ injection. This is quite unexpected for a plasma driven device given the long ion confinement time, and this phenomenon is being investigated.

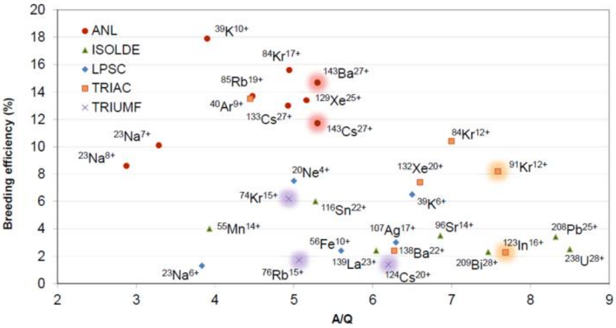


Figure 4: Summary of charge breeding results for the CARIBU program as well as other charge breeding programs. Radioactive isotopes are denoted with shading.

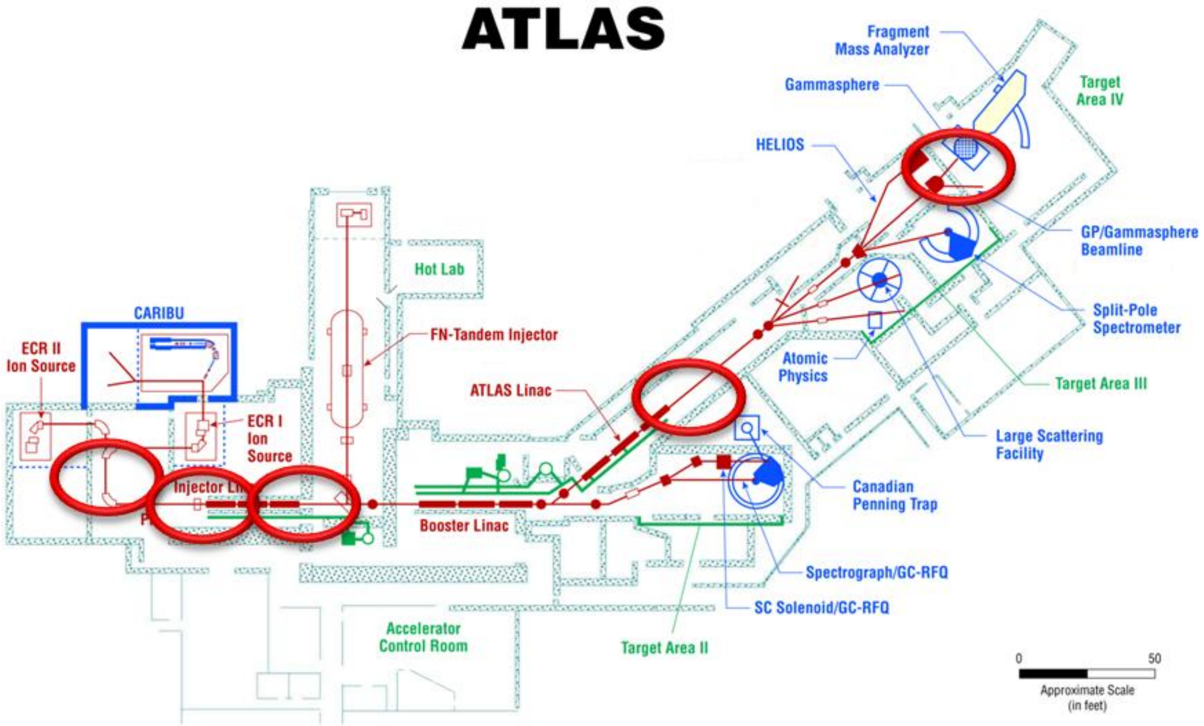


Figure 5: The ATLAS facility with CARIBU addition marked in blue. The locations of the silicon surface barrier detectors for beam tuning are marked with red ovals.

BEAM TUNING

The ATLAS facility has had a robust Accelerator Mass Spectrometry (AMS) program for several decades, and the experience gained in that time has been adapted for use with the CARIBU radioactive beams. First a stable beam with very similar A/Q to the radioactive beam of interest is identified. Typically an isotope of krypton or xenon fulfils this role, and that beam is produced via neutral gas injection into the ECRCB. The accelerator is tuned with this beam, optimizing transmission to target. The tune is stored in a database which is then scaled to the charge-bred beam of interest. This allows rapid cycling between machine tune configurations as the entire machine can be shifted from one tune to another via computer control. After all elements have been optimized with the guide beam, all machine elements are scaled to the A/Q of interest with no tuning of the machine elements after scaling. The SBDs arrayed throughout the machine (Fig. 5) are then used for beam detection and optimization. It has been observed that the set value for the steerer immediately after extraction changes based upon the origin of the ion source feed material - neutral gas versus a 1+ injected beam - and has a direct impact on overall beam transmission. With the steerer set for optimimum transmission of the stable guide beam, the radioactive beam transmission is greatly diminished. Once the steerer value has been optimized utilizing the SBDs, the radioactive beam transmission approaches that of the stable beam. As stated earlier, this effect is still being investigated.

Beam Contaminants

The negative of an ECRCB is the stable background produced by the ion source which can be in the enA range (10^{10} pps). The background originates from the constituents of the plasma chamber wall material as well as those of the source neutral gas load and can obscure any low-flux radioactive beams and complicate the experimental set up. Methods are being investigated to minimize the background, but there are also many A/Q combinations which can yield a relatively clean energy spectrum with the current level of background. First, a program is used to identify potential conflicts based upon A/Q ratio as well as the likelihood of particular contaminants being present in the ion source. Once a potential A/Q combination has been identified, it is investigated with the beam energy acquisition system. Two energy spectra for Cs are shown in Fig. 6. The upper spectrum is the energy spectrum of the beam taken at 0º with x1000 attenuation. Large contaminants of ^{53}Cr, ^{90}Zr, and ^{126}Sn can be clearly seen as well as lower level contaminants. For this case, a beam of ^{143}Cs^{27+}, the background rate was 330 kHz, but moving to ^{143}Cs^{25+} produced a background level of 66 kHz. The lower spectrum is that of ^{144}Cs^{25+} taken at 0º with no attenuation with a background rate of 900 Hz as opposed to ^{144}Cs^{26+} which had a background rate of 10 kHz. With this system, it is possible to find A/Q combinations which make beam contaminants less troublesome.

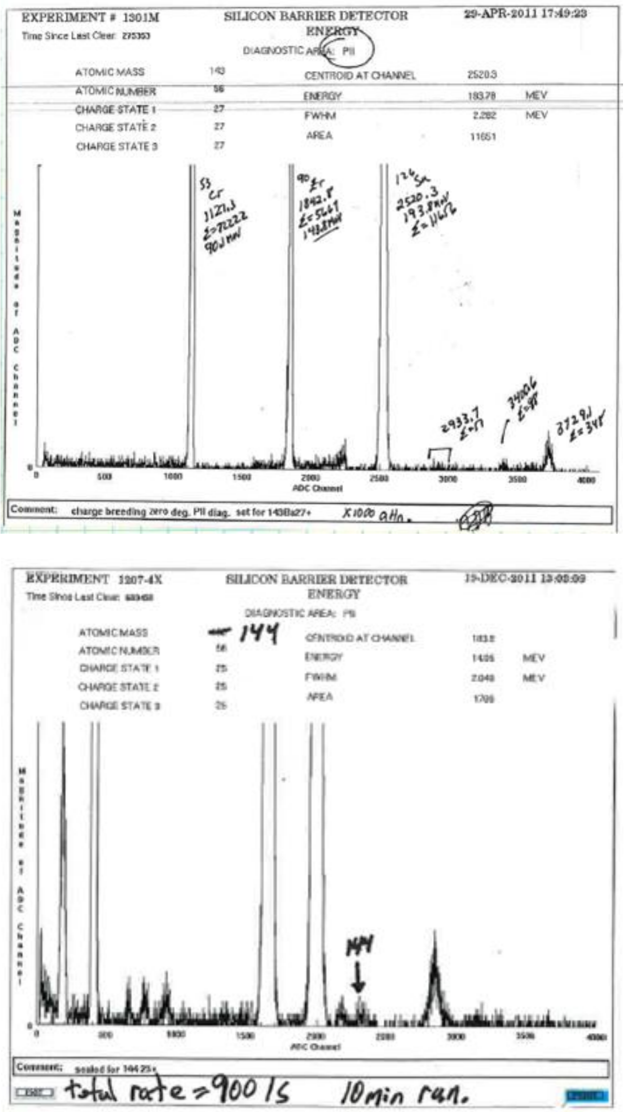


Figure 6: Energy spectra of $^{143}Cs^{27+}$ (top panel) and $^{144}Cs^{25+}$ (bottom panel) taken at 1.5 MeV/u at 0º on a silicon surface barrier detector.

COMMISSIONING

The CARIBU project commissioning goal was a beam of $^{143}Ba^{18+}$ accelerated to 6.0 MeV/u with a rate of 700 Hz. Commissioning was achieved with a beam of $^{143}Ba^{27+}$ accelerated to 6.1 MeV/u with a rate at the high energy end of 900 Hz. The ECRCB breeding efficiency was 12% with a total machine transmission from ECRCB to target of 12%.

CURRENT ACTIVITIES

The facility has ramped up operation from an initial 2.5 mCi source to the present 55 mCi source. This was done to verify the efficacy of the shielding as well as the gas catcher system operation. Recently, a 500 mCi source has been produced at Oak Ridge National Laboratory and is expected to be ready for installation in mid-2012. This will result in a factor of 10 increase in available beam intensities to the experimental program.

The isobar separator resolution continues to improve as a better understanding of the system optics is gained. The field instability of the magnets due to the power supplies not maintaining field lock is an issue which is being addressed.

In an effort to reduce the source background, the ANL ECRCB has been fitted with a high purity quartz liner. This shields the plasma chamber wall and should allow us to determine what percentage of background is due to the wall. The extraction electrode and the grounded tube have been replaced with identical components fabricated from high purity aluminum also allowing us to determine their contribution to the source background.

But even these modifications will not approach the cleanliness level possible with an electron beam ion source (EBIS). A typical EBIS will have regions with background levels $<10^6$ pps, breeding times in the 20-200 msec range, and A/Q of 2.5-4.5. These attributes are well suited to the CARIBU program, and with this in mind, an EBIS is being constructed which will replace the ERCRCB. Charge breeding tests have been carried out on the BNL TestEBIS, the device which served as the model for the ANL EBIS breeder. The BNL TestEBIS has a peak electron beam current of 10 A and a current density of 575 A/cm^2. The ANL EBIS will operate with a 2 A electron gun and 500 A/cm^2. For the test, the BNL TestEBIS electron beam parameters were adjusted down to 1.5 A and 76 A/cm^2 with a 5.3 msec breeding time resulting in a calculated transverse acceptance of 80 π mm mrad. It should also be noted that while the beam was injected with a 70 μsec bunch length through pulsing the voltage on the ion source, it did not undergo any cooling via a Penning trap. A charge breeding efficiency of 17% into Cs^{8+} was achieved with a breeding time of 5.3 msec [5]. The low charge state was chosen in order to not interfere with the residual gas background. Shifting to a higher charge state would introduce interferences, but in almost all cases a charge state can be chosen which exhibits very low residual contamination. Since the CARIBU program will not provide primary beams above 10^7 ions/s, the charge capacity of the EBIS is also not an issue.

ACKNOWLEDGMENT

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