# INITIAL RESULTS OF THE ECR CHARGE BREEDER FOR THE $^{252}$Cf FISSION SOURCE PROJECT (CARIBU) AT ATLAS*

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*Abstract*

The construction of the Californium Rare Ion Breeder Upgrade (CARIBU), a new radioactive beam facility for the Argonne Tandem Linac Accelerator System (ATLAS), is nearing completion. The facility will use fission fragments from a 1 Ci $^{252}$Cf source, thermalized and collected into a low-energy particle beam by a helium gas catcher. In order to reaccelerate these beams, the existing ATLAS ECR1 ion source was redesigned to function as an ECR charge breeder. The helium gas catcher system and the charge breeder are located on separate high voltage platforms. An additional high voltage platform was constructed to accommodate a low charge state stable beam source for charge breeding development work. Thus far the charge breeder has been tested with stable beams of rubidium and cesium achieving charge breeding efficiencies of 5.2% into $^{85}$Rb$^{17+}$ and 2.9% into $^{133}$Cs$^{20+}$.

## INTRODUCTION

The Californium Rare Ion Breeder Upgrade (CARIBU) [1] will utilize fragments from fission of $^{252}$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 1Ci $^{252}$Cf source will be mounted in a heavily shielded cask assembly attached to a helium gas catcher/RFQ ion guide which will thermalize the fission fragments. After a 50 kV acceleration, the fission fragments will be delivered to an isobar separator with a mass resolution of 1:20000. The entire system will be on a high voltage platform located in a new building addition allowing isolation from the rest of the ATLAS facility.

After analysis by the isobar separator, the mass analyzed beam will be delivered to the ECRCB through an electrostatic beam transport system. The ECRCB is based on the redesign of an existing ATLAS stable-beam 10.5 GHz ECR source (ECR1) [2] and is mounted on a separate 350 kV high voltage platform to provide the necessary velocity to match the velocity profile of the first resonator of the Positive Ion Injector (PII) linac. A small high voltage platform was constructed next to the existing ECRCB platform to house a stable beam source. The source provides stable low charge state beams to the ECRCB for system configuration, accelerator tuning, and development work. The overview of the charge breeder system is shown in Fig. 1.

*Work supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.
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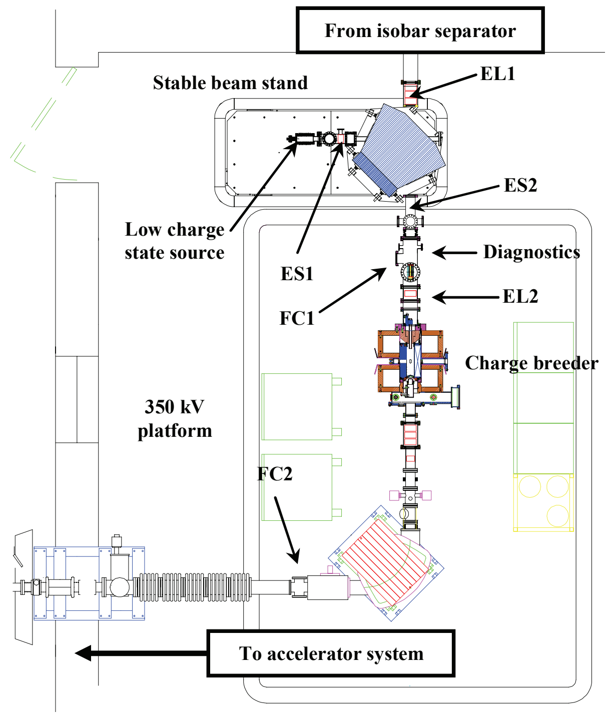


Figure 1: Floor plan of the charge breeder system showing the stable beam stand and surface ionization source, the electrostatic steerers (ES1 and ES2), the einzel lenses (EL1 and EL2), the Faraday cups (FC1 and FC2), the diagnostics location (emittance), and the ECR charge breeder.

## CHARGE BREEDER

The modifications required for the ECR1 ion source to function as a charge breeder were extensive, with the details given in [3]. In summary, the charge breeder is a room temperature ECR ion source with an open structure permanent magnet hexapole with a wall field of 0.84 T. The source is capable of accepting multiple frequencies with the RF launched through the hexapole radial slots. This scheme allows a large amount of iron to be retained on the injection side of the source resulting in a higher magnitude and symmetric axial field. The low charge state ions are introduced into the plasma through a stainless steel tube which is mounted on a linear motion stage, thus allowing the deceleration point to be adjusted on line. A new deceleration tube constructed of 1008 iron is being fabricated in order to increase the magnetic mirror ratio as well as test the theory that a better defined magnetic center field will improve the ion capture. For the isobar separator to achieve the required resolution of 1:20000, beam extraction from the gas catcher must occur at 50 kV. Hence, the high voltage isolation of the source was upgraded to allow 50 kV operation.

### *Stable Beam Source*

Stable beams for development and set up of the charge breeder are currently provided by two sources – a surface ionization source which can provide beams up to 1 eμA (Li, Na, Mg, K, Ca, Rb, Cs, Ba, and Sr) and an RF discharge source which can provide beams up to 2 eμA (O, Ne, Ar, Kr, and Xe). To date the RF discharge source has only been tested off line. The stable source is mounted on a high voltage platform adjacent to the charge breeder platform. The optics of the stable beam system were designed such that the beam coming from the stable beam source matches the optics condition of the beam coming from the isobar separator. In this way, minimal tuning should be necessary when switching over from the stable guide beam, used to set up the charge breeder and linac system, to the radioactive beam of interest.

## CHARGE BREEDING METHODOLOGY

The charge breeding efficiency is determined by measuring the ‘background’ beam (at FC2 in Fig. 1) coming from the ECR charge breeder when the system is tuned for a particular beam species but the 1+ beam is not yet being introduced into the breeder. The 1+ beam intensity is measured before the charge breeder (at FC1 in Fig. 1) and once introduced into the charge breeder, the measurement at FC2 is repeated. The efficiency is the ratio of the particle current of the charge bred n+ beam (corrected for background) and the particle current of the incoming 1+ beam. Critical to an accurate efficiency measurement is reliability of the beam current measurement system (both 1+ and n+) and the measurement of the background coming from the steady state ECR plasma.

The first charge bred beam of $^{133}Cs$ was achieved in May 2008 and resulted in an apparent breeding efficiency of 9.0% for $^{133}Cs^{20+}$. The previous best result for charge breeding of cesium was achieved by TRIUMF using a PHOENIX ECR ion source and resulted in a 2.7% efficiency into $^{133}Cs^{18+}$ [4]. The large disparity in results prompted a systematic investigation of the charge breeder system as well as the technique used to determine the breeding efficiency.

### *Beam Current Measurement*

The first path of investigation was the accuracy of the beam current measurement of the incoming 1+ beam. The calibration of the picoammeter used to measure the beam currents was checked and found to be accurate. A small Faraday cup (Fig. 2), with 300 V suppression and ground rings, was constructed and inserted into the upstream end of the transfer tube (insulated from tube with a thin walled Vespel sleeve). This method allowed a direct comparison of the two Faraday cup readings under the same running conditions and also served as a check of the acceptance of the transfer tube since its diameter (Φ 19 mm) is smaller than that of the ‘standard’ Faraday cup (Φ25 mm).

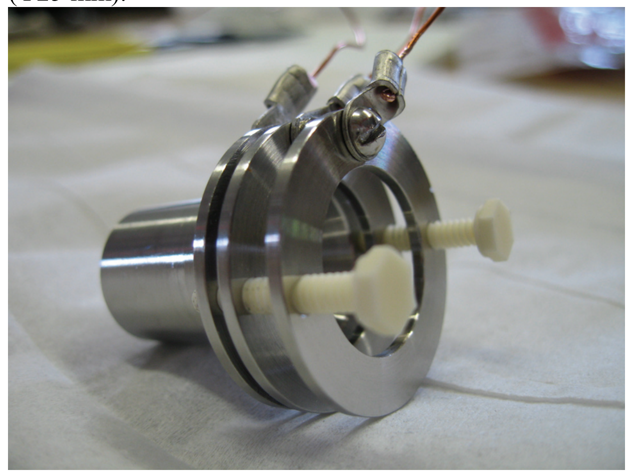

Figure 2: Small Faraday cup which was inserted into the transfer tube. The cup has an isolated ground ring, suppressor ring at -300 V, and isolated collector. The cup acceptance (Φ 19 mm) matches that of the transfer tube.

Resetting the system to the same parameters as those that produced the 9.0% breeding efficiency, it was observed that the ‘standard’ Faraday cup measured 34 enA while the ‘transfer tube’ Faraday cup measured 125 enA. The tantalum charge collector from the ‘standard’ Faraday cup was removed and testing with a multimeter showed that portions of the charge collector surface were covered with an insulating layer. With a beam energy of only 10 keV, the 1+ ions were unable to penetrate this layer, thus resulting in an erroneous beam current measurement. The charge collector was replaced with a new one fabricated from stainless steel. The series of measurements with the cesium beam were repeated and the two cup readings were found to be in agreement.

### *Background Measurement*

The n+ background level is determined by measuring the beam intensity with the transport system tuned for the ion species of interest without injecting the 1+ beam into the charge breeder. The measurement is repeated after the 1+ beam is introduced into the breeder and the difference in beam intensities represents the charge bred beam ‘n+’.

The initial technique used to stop introduction of the 1+ beam was to insert FC1. To check the validity of this technique, observations were made of the spectrum from the ECR source with the 1+ beam stopped with FC1, stopped with the electrostatic steerer just after the surface ionization source (ES1), and finally with the surface source turned off. Fig. 3 shows the disparity in background levels for these various techniques using a rubidium beam (saturating ES1 and turning off the surface source were equivalent in their effect).

A direct comparison of the techniques demonstrates the effect. With $^{133}Cs^{20+}$ under the same conditions, the calculated charge breeding efficiency using the FC1 technique was 6.5%, using the ES1 saturation technique resulted in an efficiency of 2.6%. The ultimate source of

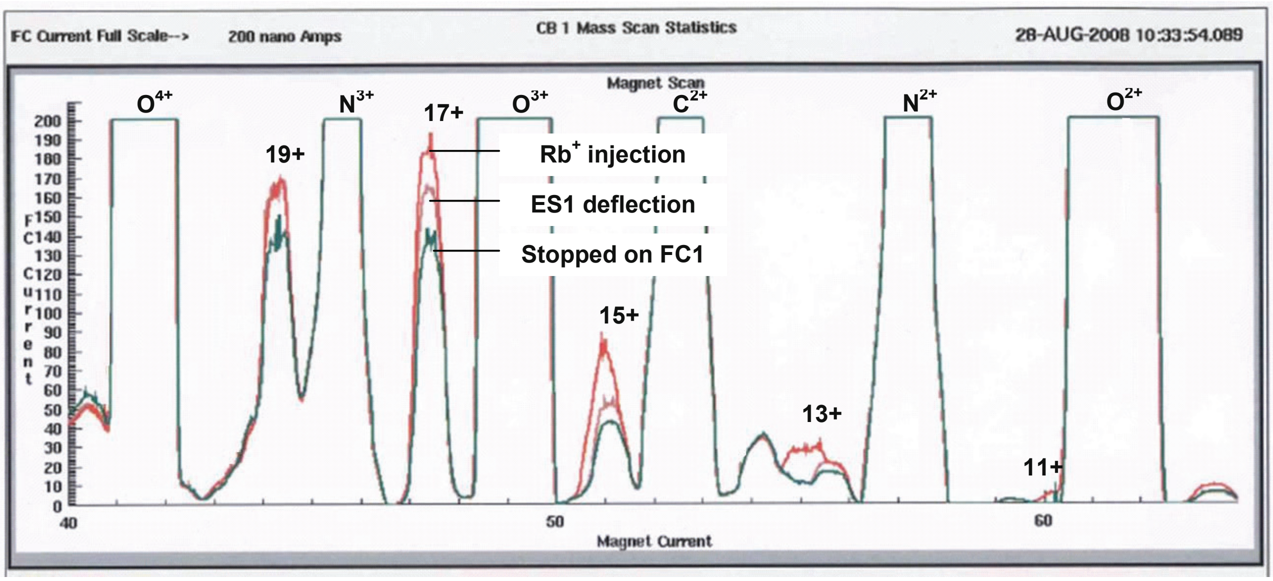


Figure 3: The top trace is with $Rb^{+}$ injection. The middle trace is with $Rb^{+}$ stopped using the electrostatic steerer (ES1) just after the 1+ source but before the analyzing magnet (saturating the steerer generates the same background spectrum as shutting off the 1+ source). The bottom trace is with the $Rb^{+}$ stopped using the Faraday cup (FC1). The rigidity of $^{85}Rb^{15+}$ is similar to that of $^{40}Ar^{7+}$ and the rigidity of $^{85}Rb^{17+}$ corresponds to that of $^{40}Ar^{8+}$.

the discrepancy was traced to outgassing in the 1+ injection line which was not present when FC1 was inserted. With FC1 removed from the line, the n+ beam coming out of the injection side of the ECR source would generate outgassing in the upstream 908 analyzing magnet. The gas would diffuse into the ECR plasma, be ionized and raise the background level. The rigidity of $^{133}Cs^{20+}$ corresponds to that of $^{40}Ar^{6+}$. Similar results were obtained with $^{133}Cs^{23+}$ corresponding to $^{40}Ar^{7+}$.

## CHARGE BREEDING RESULTS

After resolving the problems discussed above, a series of studies of the effect of various parameters on charge breeding was undertaken.

### *Cesium Results*

$^{133}Cs$ charge breeding tests were performed using oxygen support gas and an RF power level of 250 W at 10.44 GHz. Optimizing on $^{133}Cs^{20+}$ resulted in a breeding efficiency of 2.4%. The $Cs^{+}$ beam current was 62 enA. This test was also conducted using helium as the base plasma resulting in a decreased breeding efficiency of 1.8%. At the time of these tests, the alumina insulators on the surface ionization source were beginning to break down due to surface contamination. Thus, the optics of the source could not be fully optimized, resulting in a poorly matched beam condition. It is believed that this limited the achieved breeding efficiency.

### *Rubidium Results*

The surface ionization source was disassembled and cleaned, and the rubidium sample was installed at this time to test the rubidium breeding efficiency. The source was run on oxygen support gas with 270 W at 10.44 GHz and optimized on $^{85}Rb^{15+}$ resulting in a breeding efficiency of 3.8%.

After the initial series of tests, the charge breeder remained idle and under vacuum for a seven month period while work on other aspects of the CARIBU project was undertaken. During this time the source vacuum improved resulting in an operating pressure of $7.5 \cdot 10^{-8}$ Torr with plasma. The charge breeding results with rubidium improved as well, with a shift in the peak of the charge state distribution from 15+ to 17+ and a factor of 2 improvement in the charge breeding efficiency for 17+ and above. The full results are shown in Table 1.

Table 1: Charge breeding results for rubidium and cesium with single and two frequency heating

| Species | Single Frequency Efficiency (%) | Two Frequency Efficiency (%) |
|---|---|---|
| $^{133}Cs^{16+}$ | 0.9 | 1.4 |
| $^{133}Cs^{18+}$ | 1.0 | 1.5 |
| $^{133}Cs^{20+}$ | 2.4 | 2.9 |
| $^{133}Cs^{23+}$ | 0.5 | 1.1 |
| $^{85}Rb^{13+}$ | 0.8 | - |
| $^{85}Rb^{15+}$ | 3.8 | - |
| $^{85}Rb^{17+}$ | 5.2 | - |
| $^{85}Rb^{19+}$ | 3.2 | - |
| $^{85}Rb^{20+}$ | 2.9 | - |

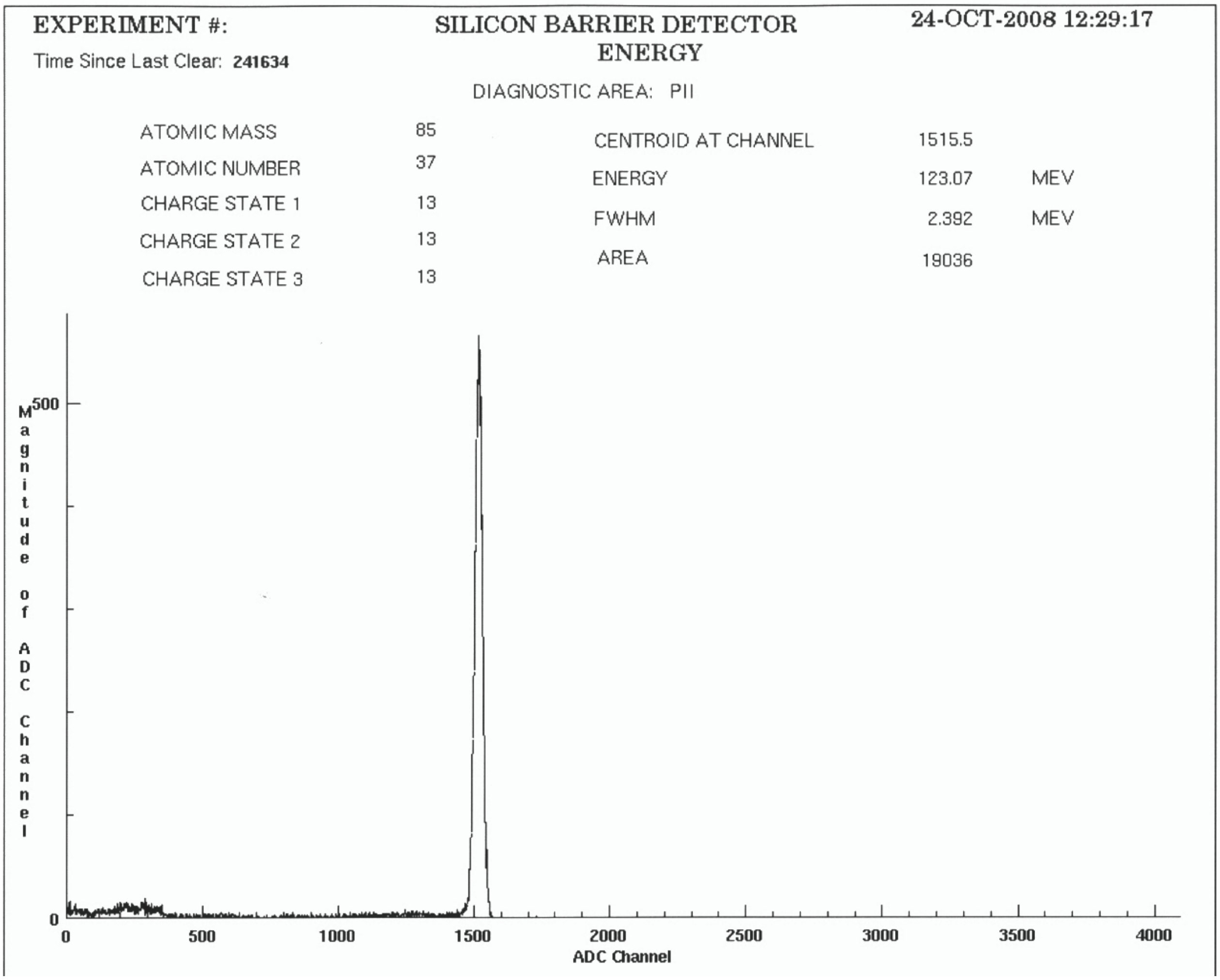


Figure 4: Energy Spectrum of charge bred $^{85}Rb^{13+}$ after acceleration through the Positive Ion Injector Linac of ATLAS showing an exit energy of 123.07 MeV(1.45 MeV/u).

### *Acceleration of Charge Bred Rubidium Beam*

As a proof of principle, a charge bred beam of $^{85}Rb^{13+}$ was accelerated off of the ECRCB high voltage platform and injected into the first section of superconducting linac (PII). A beam energy of 129 MeV was measured at the linac exit with a silicon barrier detector (Fig. 4) with an incident beam intensity of 0.62 enA.

### *Two Frequency Heating*

Multiple frequency heating was employed during the cesium tests in an effort to improve the breeding efficiency. A travelling wave tube amplifier (TWTA) was used to provide RF between 11-13 GHz in addition to the 10.44 GHz from the klystron. The total RF power was kept constant to serve as a direct comparison of the two RF injection schemes.

With the source running on an oxygen plasma and the RF divided between the two transmitters - 175 W at 10.44 GHz and 75 W at 12.27 GHz – the charge breeding efficiency for $^{133}Cs^{20+}$ increased from 2.4% to 2.9%, a modest but meaningful improvement. For $^{133}Cs^{23+}$ the efficiency increased from 0.5 to 1.1%, a doubling of efficiency at the same total RF power level.

Time has not allowed similar tests to be carried out with the rubidium, but these tests are planned for the coming months. In addition, previous testing with the ECR1 ion source [5] has shown that the addition of a third frequency further enhances the source performance. The next series of tests will include this aspect of operation.

## FUTURE PLANS

### *Emittance Measurement System*

Previous groups have observed that the breeding efficiency increases when the beam emittance is reduced [6]. This same effect was observed with our tests using a set of 4-jaw slits immediately downstream of the surface ionization source as a means of controlling the beam emittance. At the time of the test, however, an emittance measurement system was not installed and change in beam emittance could not be quantified. An emittance measurement system has now been constructed and is ready for installation. The system consists of a mask which has 20 μm laser drilled holes, 0.5 x 0.5 mm

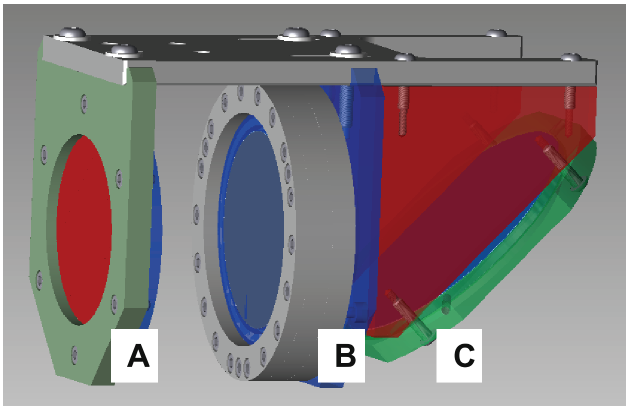


Figure 5: Schematic of the pepper pot emittance device constructed for the 1+ and charge bred beams. Item A is the mask, B is the CsI crystal and C is a mirror.

spacing, on a Φ 40 mm tantalum disk. Behind the mask is a CsI crystal (Φ 40 mm). This scintillator has been tested with a 300 enA, 10 kV beam $Cs^+$ beam to demonstrate its sensitivity at low energies and intensities. For the much weaker beam currents expected from the CARIBU system, improved sensitivity is possible using a higher lux camera, signal averaging, or the addition of a micro channel plate/phosphor assembly. The capability to add all of the above mentioned options is built into the present system.

### *Improved Vacuum*

The low charge state injection line and charge breeder have base pressures of $2.0{\cdot}10^{-8}$ Torr with no plasma present. The injection line pressure increases to $1.0{\cdot}10^{-7}$ Torr with plasma, and increases further to $3.0{\cdot}10^{-7}$ Torr when the beam extracted from the injection side of the ECR source impacts the surfaces of the analyzing magnet. As this pressure increases, the charge breeding efficiency decreases by ~30%. To combat this problem, the chamber that houses the transfer tube has been modified to accept an additional turbo pump. The analyzing magnet chamber is scheduled to be removed, cleaned, and baked out to reduce the outgassing. A set of beamline collimators will also be installed to inhibit gas flow from the low charge state line into the ECR source, an important condition when the RF discharge source is used. The turbo pump locations are such that the placement of the collimators will provide a differential pumping arrangement.

### *50 kV Operation*

For the isobar separator to achieve the required resolution of 1:20000, beam extraction from the gas catcher must occur at 50 kV. Hence, the high voltage isolation of the source was upgraded to allow 50 kV operation. To date, the source has only operated at 30 kV due to drain current issues with the high voltage power supply. However, all aspects of the ECR source were tested to 65 kV without plasma present. A new power supply has been purchased and testing to 50 kV operation will take place in the coming weeks.

### *Charge Breeding Tests*

The main issue with the injection of metallic beams is that once an incoming low charge state ion strikes the wall, that ion is lost to the plasma. In an attempt to combat this problem, a hot tantalum liner has been constructed for the ECR charge breeder. Charge breeding efficiencies with and without the liner in place will be compared to determine the effectiveness of this technique. Attention has to be paid to the hold up time of the atoms on the wall. If the hold up time becomes too great, the breeding efficiency of the shorter lived radioactive species will not be improved.

Up to now, only alkali metals from the surface ionization source have been used for charge breeding. The RF discharge source, which has been tested off line, will soon be moved on line to test the breeding efficiency with gases.

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