FINAL CRADA REPORT

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CRADA Title: Optimization of Electron-Cyclotron-Resonance Charge-Breeder Ions

CRADA Start/End Date:

Argonne Dollars: $215,000
Participant Dollars: $465,000

Argonne PI: Richard Pardo

Industrial Partner:
FAR-TECH, Inc.
10350 Science Center Drive
Bldg #14, Suite 150
San Diego, CA 92121-1129

DOE Program Manager: Manouchehr Farkhondeh

Summary of Major Accomplishments:

Measurements of 1+ beam properties and associated performance of ECR Charge Breeder source determined by total efficiency measurement and charge state distributions from the ECR Charge Breeder. These results were communicated to Far-Tech personnel who used them to benchmark the newly developed programs that model ion capture and charge breeding in the ECR Charge Breeder Source.

Summary of Technology Transfer Benefits to Industry:

Providing the basic data described above and in the discussion below to Far-Tech allowed them to improve and refine their calculational tools for ECR ion sources. These new tools will be offered for sale to industry and will also provide important guidance to other research labs developing Charge Breeding ion sources for radioactive beam physics research.

Other Information/Results: (Papers, Inventions, Software, etc.)

Far-tech, Inc received the above referenced CRADA Grant from the Department of Energy, Office of Nuclear Physics in order to develop a suite of codes that would be useful in designing Charge-Breeder ECR Ion Sources and in modeling their performance. Far-Tech sought out the participation of personnel in the Physics Division of ANL to assist them in this project by providing performance data for the Charge-Breeder ECR source that is a part of the CARIBU project.

Specifically ANL agreed to characterize the beam properties of the 1+ ion source that provided seed ions to the Charge-Breeding ECR source and to also provide information on the performance of the Charge-Breeder source (hereafter called ECRCB) under varying conditions and injected beam properties. In order to achieve these goals, the Charge Breeder ECR source had to be completed and operated (as part of the CARIBU project) and additional equipment, especially an emittance measuring system, had to be constructed to characterize the 1+ ion source.

These activities have been carried out and the results of our measurements were communicated privately to Far-tech over the past two years. Far-tech has then used those results to compare the output of the codes they have developed over that same period of time. Both groups have also now reported those results publically in a number of publications at accelerator conferences and ion source conferences and workshops in the past two years. The most recent publication from our group summarizes the results of the measurements made at ANL. That publication is attached to this report as Appendix A. All data presented in this paper and additional information, not part of this report was provided to Far-Tech.

Results with the ECR charge breeder for the ^{252}Cf fission source project (CARIBU) at ATLAS [a)]

[1] R. Vondrasek,[b)] S. Kondrashev, R. Pardo, R. Scott, and G.P. Zinkann

[1]*Physics Division, Argonne National Laboratory, Argonne, IL 60439, U.S.A*

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(Dates appearing here are provided by the Editorial Office)

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. Thus far the charge breeder has been tested with stable beams of rubidium and cesium achieving charge breeding efficiencies of 9.7% into $^{85}Rb^{17+}$ and 2.9% into $^{133}Cs^{20+}$.

[2] I. INTRODUCTION

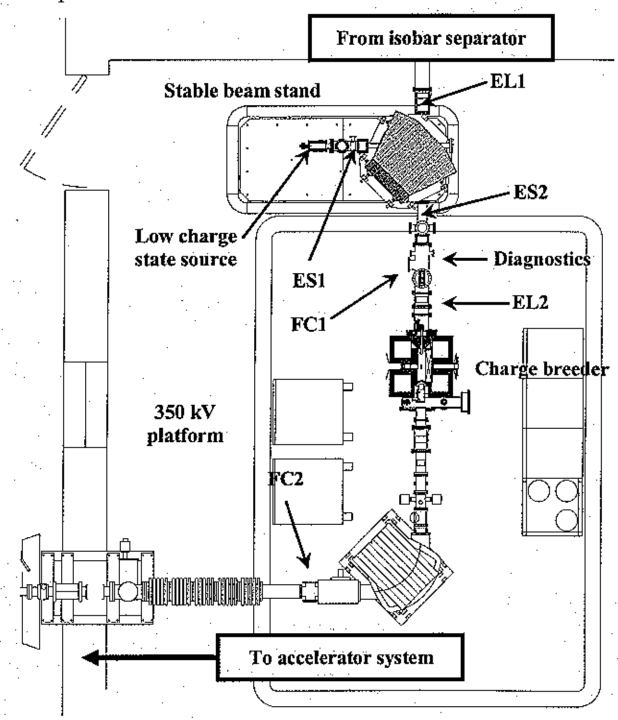
[3] The Californium Rare Ion Breeder Upgrade (CARIBU)[1] will utilize fragments from fission of ^{252}Cf to provide nuclei which will be thermalized in a helium gas-catcher, mass separated and injected into an ECR charge breeder (ECRCB) to raise their charge state for subsequent acceleration in the ATLAS superconducting linear accelerator.

[4] 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 are delivered to an isobar separator with a mass resolution of 1:20,000. The entire system is on a high voltage platform located in a new building addition allowing isolation from the rest of the ATLAS facility.

[5] 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 into the superconducting Positive Ion Injector (PII) linac. A stable beam 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.

[6] II. CHARGE BREEDER

[7] 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 high magnitude and symmetric axial field. The low charge state ions are introduced into the plasma through a stainless steel tube mounted on a linear motion stage, thus allowing the deceleration point to be adjusted on line. For the isobar separator to achieve the required resolution of 1:20,000, 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.



[8]
[9] FIG. 1. Floor plan of the charge breeder system showing the stable beam stand and surface ionization source, the electrostatic steerers (ES1 & ES2), the einzel lenses (EL1 & EL2), the faraday cups (FC1 & FC2), the diagnostics location (emittance), and the ECR charge breeder.

[10]

[11]

[12] III. STABLE BEAM SOURCES

[13] Stable beams for development and set up of the charge breeder are currently provided by two sources – a surface

a) Contributed paper, published as part of the Proceedings of the 13th International Conference on Ion Sources, Gatlinburg, Tennessee, September, 2009.

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 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.

[14] IV. CHARGE BREEDING RESULTS

[15] 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 faraday cups are surpressed with -300 V and all picoammeters are calibrated.

[16] A. Cesium results

[17] The first charge bred beam of Cs-133 was achieved in May 2008 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.

[18] 1. Two frequency heating with cesium

[19] 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.

[20] 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. The results are summarized in Table I.

[21] TABLE I. Charge breeding efficiency (%) results for cesium.

Ion	Single frequency	Two frequency
$^{133}Cs^{16+}$	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

[22]

[23] B. Rubidium results

[24] 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%.

[25] 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 7.5e-8 Torr with plasma. The charge breeding results improved as well, with a shift in the peak of the charge state distribution from 15+ to 17+ and substantial increases in the breeding efficiencies.

[26] Additional tuning of the ion source produced further improvements in breeding efficiency. The RF frequency was shifted from 10.44 to 11.91 GHz and the power level was increased to 300 W. Other parameters adjusted included the solenoid coil currents, gas pressure, transfer tube position, stopping voltage, and the electrostatic focusing elements. The full results are shown in Table II.

[27] 1. Two frequency heating with rubidium

[28] Multiple frequency heating was employed during the second series of rubidium tests in an effort to improve the breeding efficiency. With the TWTA providing 300 W at 11.91 GHz, an additional 50 W of RF power was launched from the 10.44 GHz klystron. All source parameters were optimized for maximum efficiency into $^{85}Rb^{17+}$. As shown in Table II, the peak of the charge state distribution shifted slightly higher resulting in a 25% increase in breeding efficiency for the 20+ charge state. Similar improvements in charge state and efficiency were not observed when the TWTA power was increased to 350 W in single frequency mode (6.9% for 17+) or when the total RF power was held constant at 300 W in two frequency mode (5.8% for 17+).

[29] 2. Acceleration of charge bred rubidium

[30] As a proof of principle, a $^{85}Rb^{+}$ beam was injected into the ECR source, charge bred to $^{85}Rb^{13+}$, and was then accelerated off of the ECRCB high voltage platform. The beam was injected into the first section of superconducting linac (PII) with a resulting beam energy of 129 MeV as measured at the linac exit with a silicon barrier detector. The beam intensity at the linac exit was 0.62 enA. A low intensity diagnostics station is installed after the PII linac consisting of an array of high sensitivity scintillators and a high sensitivity CCD camera. Incident beam intensities as low as 1000 pps were observed on the Gd_2O_2S:Tb and Y_2O_2S:Tb scintillators in real time using single frame capture software.

[31] TABLE II. Charge breeding efficiency (%) results for rubidium showing the change due to the operating pressure as well as the best results for single and two frequency heating.

Ion	Efficiency (1.0e-7 Torr)	Efficiency (7.5e-8 Torr)	Single frequency	Two frequency
$^{85}Rb^{13+}$	1.8	-	2.4	1.3
$^{85}Rb^{15+}$	3.8	3.8	4.9	3.6
$^{85}Rb^{17+}$	0.8	5.2	9.4	9.7
$^{85}Rb^{19+}$	-	3.2	8.0	8.8
$^{85}Rb^{20+}$	-	2.9	5.6	7.0

[32]

[33] V. FUTURE PLANS

[34] A. Emittance Measurement System

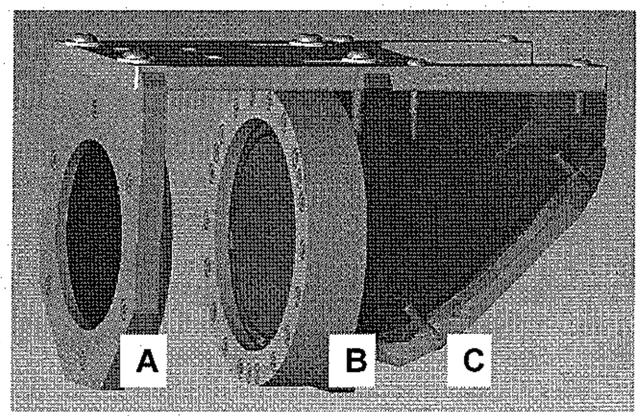
[35] Previous groups have observed that the breeding efficiency increases when the beam emittance is reduced[4]. A similar effect was observed with our tests using a set of 4-jaw slits immediately downstream of the surface ionization source as a means of controlling the beam intensity. As the beam intensity was reduced from 100 to 10 nA of incoming 1+ beam, the breeding efficiency improved. At the time of the tests however, an emittance measurement system was not installed. It is still not clear if the observed effect was attributable to the change in beam intensity or a change in beam emittance.

[36] An emittance measurement system has now been installed. The system[5] consists of a mask which has 20 μm laser drilled holes, 0.5 x 0.5 mm spacing, on a 40 mm tantalum disk. Behind the mask is a CsI crystal (40 mm). 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, and at present a wide dynamic range micro channel plate has been ordered.

[37] The CsI crystal based system has been used to measure the emittance of a 300 enA Rb^+ beam at 14 kV. Emittances of x-x′: 2.4e-2 π·mm·mrad (5 rms, normalized) and y-y′: 2.1e-2 π·mm·mrad have been measured.

[38] B. Improved vacuum

[39] The low charge state injection line and charge breeder have base pressures of 2.0e-8 Torr with no plasma present. The injection line pressure increases to 1.0e-7 Torr with plasma, and increases further to 3.0e-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.

[40] 

[41] FIG. 2. 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.

[42] C. Transfer tube position

[43] The transfer tube is currently in a fully retracted position ~5.5 cm from the magnetic maximum. The breeding efficiency for 17+ was continuing to improve as the tube was being retracted (from 6.9% to 8.5% for ~1 cm of travel), indicating that an optimum position is still to be found. The source will be opened and the tube repositioned in its linear mount thus allowing it to be further retracted from the plasma.

[44] VI. ACKNOWLEDGEMENTS

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