NEUTRON-RICH BEAMS FROM ^{252}CF FISSION AT ATLAS – THE CARIBU PROJECT*

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Abstract

Construction of the DOE Californium Rare Ion Breeder Upgrade (CARIBU) for the ATLAS facility is nearing completion and certain aspects of commissioning are underway. The facility will eventually use fission fragments from a 1 Ci ^{252}Cf source, thermalized and collected into a low-energy ion beam by a helium gas catcher, mass analyzed by an isobar separator, and charge bred to higher charge states for acceleration in ATLAS. In addition, unaccelerated beams will be available for trap and laser probe studies. Expected yields of accelerated beams are up to ~5x10^{5} (10^{7} to traps) far-from-stability ions per second on target. The facility design, commissioning plans and some results are discussed

INTRODUCTION

The information needed to address many of the current outstanding questions in nuclear physics is obtained with greater and greater difficulty by the experiments that can be carried out with stable beams. In many cases these questions cannot be addressed at all with stable beams.

Most existing facilities probe the proton-rich side in-depth but can access only the periphery of the much larger neutron-rich region. Facilities that will reach further into the neutron-rich region and provide interesting beams into the far neutron-rich region, such as ISACII, FRIB, and RIKEN RIBF [1,2,3], are still in planning, under construction, or just coming online.

The ATLAS facility at Argonne National Laboratory, a national user facility for low-energy heavy-ion nuclear physics research has long provided beams of any desired stable isotope as well as a number of near-to-stability radioactive beams for its users. To provide our users with a broader range of beam choices and reach deeper into the neutron-rich region of nuclei, we have constructed a new 'ion source system' based on fission fragments from ^{252}Cf. The Californium Rare Ion Breeder Upgrade (CARIBU) project for ATLAS will deliver neutron-rich heavy ion beams from the 3% fission branch of ^{252}Cf to allow a large class of important measurements. Figure 1 shows the distribution of fission fragments from ^{252}Cf [4]. The fragment distribution covers a wide region of the neutron-rich side populating some of the most important nuclei, such as ^{132}Sn and $^{100-106}$Zr, for nuclear physics studies. In addition the mass distribution of ^{252}Cf is quite complimentary to that of proton or neutron-induced fission of uranium [4].

The Californium Rare Ion Breeder Upgrade (CARIBU) will make use of this complimentary fission-fragment distribution to provide nuclei which will be thermalized in a helium gas-catcher system scaled from a prototype design originally developed for the RIA facility. This paper gives an overview of the CARIBU facility, discusses the challenges in implementing such a facility, outlines the expected performance, and describes the current status of the project.

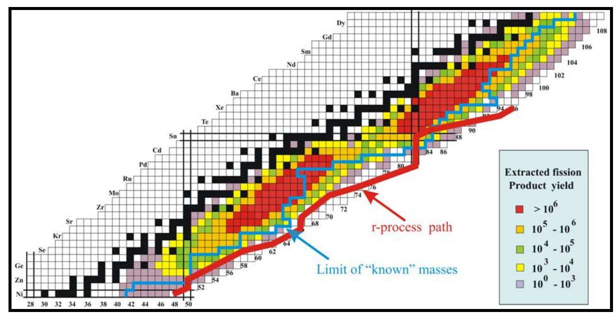

Figure 1: Fission fragment mass distribution and intensity of ^{252}Cf for a 1 Ci source. Intensity curves are for yields after mass analysis assuming 25% total efficiency.

FACILITY DESIGN

The facility nearing completion will consist of six major components:

1. A one Curie ^{252}Cf fission source mounted on a thick stainless steel backing but open in the forward direction except for a thin aluminum layer and a thicker aluminum energy degrader foil. The initial testing and commissioning of CARIBU will take place with weaker sources of ~2 mCi and 80 mCi strength.
2. A helium gas catcher and RFQ cooler system to thermalize the fission products and collect them into a singly- or doubly-charged ion beam with very low emittance (~3 π mm•mrad at 50 keV) and energy spread (~1eV).
3. A sophisticated isobar separator tailored to this excellent quality beam with a mass resolution of approximately 1:20,000 for good beam purity.
4. An ECR charge-breeder ion source for stripping the 1+ (or 2+) ions to a charge state necessary for further acceleration in the ATLAS linac.
5. The ATLAS superconducting linac for acceleration to the necessary beam energy and an un-accelerated beam area for performing measurements with ion and atom traps.

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6. Additional diagnostics systems in ATLAS to provide the necessary information for beam tuning and delivery.

The entire assembly of fission source, gas catcher, and isobar separator is mounted on one high-voltage(HV) platform. The ECR charge breeder is mounted on a second HV platform connected by a beam transfer line. Both platforms can be biased at voltages of up to 200 kV with a common power supply in order to provide the ions with the necessary velocity (~0.008c) for injection into the linac. The facility is housed in a new building addition attached to the ATLAS facility. A schematic overview of the facility and its relationship to the existing ATLAS Positive Ion Injector linac is shown in Figure 2. The new room addition is isolated from the rest of the facility and maintained at a slightly negative pressure to minimize the possibility of dispersing material into the rest of the facility under accident conditions. Charcoal traps in the exhaust line trap active elements such as iodine to reduce the quantity released to the atmosphere. The room will be exhausted through a HEPA filter system which will trap solid radioactive fragments from pump exhaust and any accidental leakage into the room. The beta activity release rates are continuously monitored.

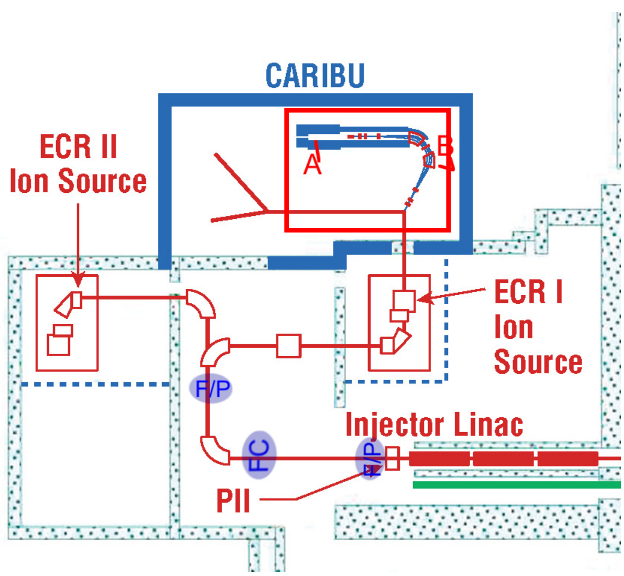

Figure 2: CARIBU floor plan showing the major elements. The 252Cf source is located at position 'A'. The high resolution isobar separator is mounted on the CARIBU platform at position 'B'. "F/P" refers to weak beam diagnostics with profile and ion counting ability, whereas "FC" refers to ion counting only.

Gas Catcher/RFQ Cooler

The ability of helium gas catchers to slow down and thermalize nuclear reaction products and fission fragments has been demonstrated over the past few years and this method is in routine use at ATLAS [5] with a weaker ^{252}Cf source as well as radioactive beams produced by ATLAS-delivered beams in an in-flight production geometry. A prototype gas catcher system suitable for the Facility for Rare Isotope Beams (FRIB) has been developed [6] and tested. The ion range distribution stopped in such a gas catcher for ^{143}Ba is shown in Figure 3 as calculated with SRIM [7].

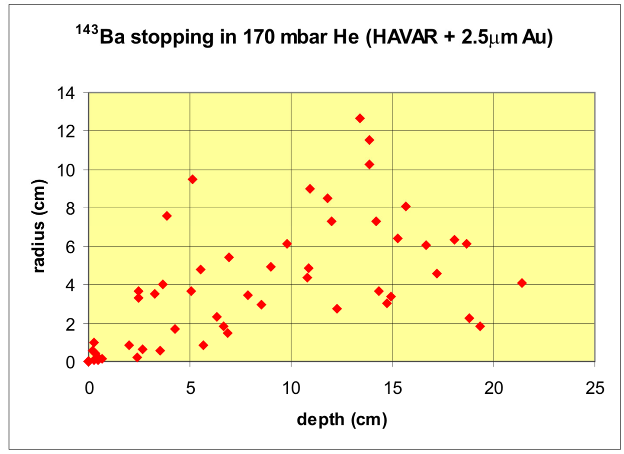

Figure 3: Ion stopping distances in 170 mbar helium gas after initial slowing in a gold degrader foil. Lifetime studies of various foils indicate that aluminum is a better degrader material and will be used instead of gold.

The gas catcher used in CARIBU will have a large diameter (0.5 m) to stop the isotropically emitted fission fragments and a total length of approximately 1.3 m. Once thermalized, the ions remain charged in the gas and are pushed toward the extraction end by DC fields, focused toward the nozzle and repelled from the walls by an RF field covering the entire volume. Extraction and final focusing is enhanced by the sonic gas flow through the nozzle into a radio frequency quadrupole (RFQ) focusing channel.

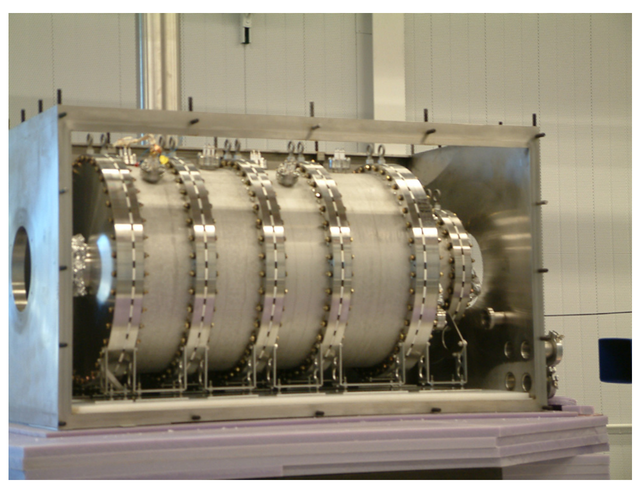

Figure 4: Assembled gas catcher mounted in isolation box. In operation both gas catcher and box are filled with one quarter to one half atmosphere helium. The enclosing rectangular box is 1.47 m long.

The RFQ, consisting of two main RFQ sections each about 30 cm long and micro-RFQs in the transition gaps that define pumping regions, guides and cools the ions while the helium extracted with the ions is pumped away in three pumping stages. This design results in extracted ion beams with low energy spread and excellent transverse emittance; $\delta E \sim 1$ eV and $\varepsilon \sim 3\pi$mm mrad at 50 keV [8]. The assembled gas catcher is shown in Figure 4 and the RFQ components are shown in Figure 5.

Figure 5: Two stage RFQ cooler for maintaining small beam size as helium gas in pumped away in three differential pumping stages. MicroRFQ seen on top flange of left assembly maintains focusing forces through the differential pumping isolator. Left RFQ is 30 cm long for scale.

Isobar Separator

Good beam purity is desirable in all cases, but is very difficult to achieve due to the extremely small mass differences for neighboring isobars. This is most serious near the valley of stability where good separation requires a mass resolution of 1:50,000. As one moves further away from the stable region the mass differences increase and, for most cases, a mass resolution of 1:20,000 provides significant discrimination from the unwanted isotopes. With the expected beam quality, it is possible to achieve a mass resolution of 1:20,000 using a compact magnetic dispersion-only design without energy correction. The geometry of such a separator is indicated in Figure 2 with a total bend of 120 degrees. The mass analysis must be performed at a beam energy of approximately 50 keV in order to achieve the required resolution. This portion of the project has been significantly delayed due to the slow delivery of the magnets from the vendor. The magnets are now in transit from the manufacturer. The design details of the isobar separator are presented by Davids and Peterson in this conference [9].

ECR Charge Breeder Source.

To reach Coulomb barrier energies (E/A ~ 5 MeV/u), the ATLAS linac must be provided with ions whose charge-to-mass ratio (q/M) ≥0.15. Thus the 1+ (or 2+) ions provided by the gas catcher system must be stripped to higher charge states. This task will be accomplished by transporting the ions to an ECR ion source operating as a charge breeder [10], stopping the ions in the ECR source and stripping the ions, as in normal ECR ion source operation. Work by Lamy et al. [11] has shown charge breeding efficiencies of around 5% for solid materials and over 10% for gases. For the CARIBU project, we use these efficiencies for our operating goals.

An existing ATLAS ECR ion source has been modified into a charge breeder for this purpose [12]. The source, shown in Figure 6, first operated in a charge breeding mode in May 2008 and has since been operating for development of charge breeding efficiency. Stable active metal beams from a surface ionization source [13] have been used in these first charge breeding tests. A charge state distribution after charge breeding for cesium beams is shown in Figure 7. Results displayed in Table 1 show that these initial achieved efficiencies are quite encouraging, but the goal of 5% efficiency has not yet been achieved. One of the techniques that we believe will improve efficiency is the use of two RF frequencies to heat the plasma. Initial tests with cesium show up to a factor of two improvement for the highest charge states and approximately a 20% improvement for the peak charge state. Additional work with stable gases is planned soon.

Table 1: Stable-beam charge breeding efficiency

Ion Species	Efficiency: One/Two Frequency Heating
$^{85}Rb^{11+}$	0.8%/ -
$^{85}Rb^{13+}$	1.8/-
$^{85}Rb^{15+}$	3.8/-
$^{85}Rb^{17+}$	0.8/-
$^{133}Cs^{16+}$	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

The first acceleration of a charge bred beam from the CARIBU ECR Charge Breeder occurred in October 2008. A team of Rick Vondrasek, Bob Scott and Gary Zinkann injected a $^{85}Rb^{1+}$ beam into the ECR charge breeder and selected the 13+ charge state for further acceleration in the Positive Ion Injector (PII) linac. The beam output energy from the linac was 123 MeV (1.45 MeV/u). This was the first actual acceleration of an ECR charge-bred beam in the Western Hemisphere and represented a significant step in the development of the CARIBU ECR Charge Breeder.

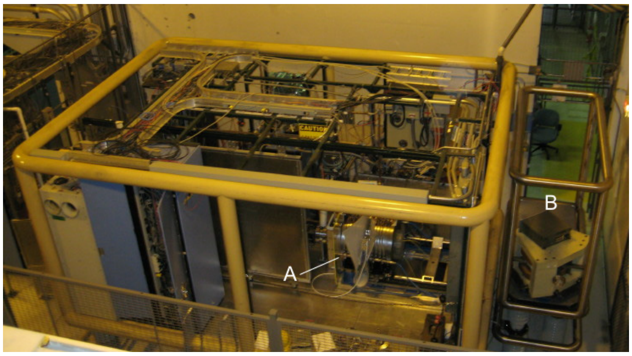

Figure 6: The ECR charge breeder ion source (A) mounted on its HV platform. The switching magnet directing stable beams for development and setup is seen on the right hiding the 1+ source (B).

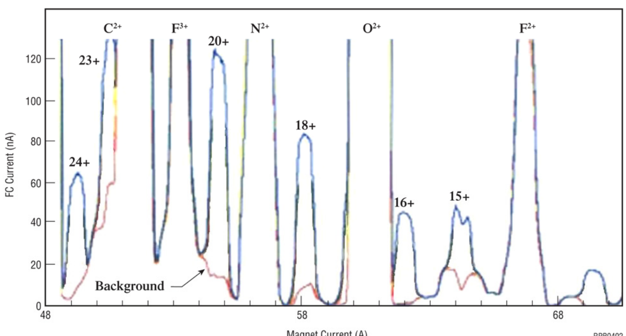

Figure 7: Charge state distribution for $^{133}Cs^{1+}$ beam injected into the ECR CB ion source. The red plot shows the background with no 1+ beam going into source.

Source Shield Cask

Shielding design and radiological monitoring and protection are important issues. CARIBU is designed to allow hands-on maintenance on most of the facility and to work near the source during beam development. The initial mass separation takes place on the first high voltage platform and will contain most of the unwanted activity on the platform in the beam transport system leading into and through the first 60^{o} magnet of the isobar separator. We have designed and constructed a source shielding system that allows for installation of the source as well as storage of the source in a shielded environment during periods of maintenance that require access to the gas catcher interior or other portions of the nearby beam transport system.

An unshielded 1 Ci ^{252}Cf source produces a radiation field of approximately 46 Rem/hr at 30 cm. and so personnel involved in this project must be protected at all times. The californium source will be delivered in a DOT-approved shipping cask. Upon arrival it must be removed from the shipping containers and installed in the CARIBU associated equipment. This transfer will take place in a shielded facility with remote manipulators for handling the source. After the transfer is made into the CARIBU equipment, it must be transported approximately 0.5 miles to ATLAS.

The source will be stored and transported in a neutron and gamma shield cask. The cask will form part of the CARIBU shielding when in place but also is the shipping cask for the on-site transport. The shield cask was designed to withstand a drop of up to one foot without rupture, according to finite element mechanical stress analysis. Initial testing of the system using the 2.2 mCi source will not require the full shielding necessary for the 1 Ci source and will allow ease of testing and modification.

Shielding from the fission-generated neutrons requires a sandwich of a few centimeters of high-Z material and steel for primary γ-ray absorption and ~0.60 m of borated polyethylene for neutron absorption, followed by a few centimeters steel shielding to attenuate the secondary γ-ray flux and provide structural integrity and fire protection. This level of shielding will reduce the radiation field to approximately 1 mrem/hr at 30 cm from the outer surface of the shielding. The shield cask housing the source and providing much of the shielding near the source is shown in Figure 8.

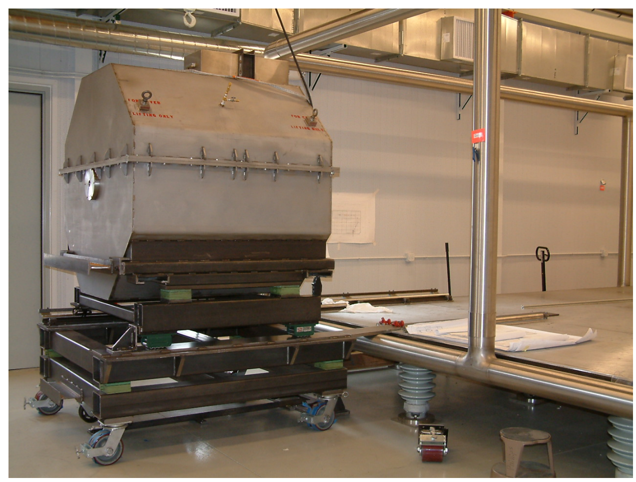
Figure 8: CARIBU shield cask shown in position to be rolled onto the CARIBU HV platform.

The associated beamline leading from the gas catcher/RFQ cooler to the isobar separator must also be heavily shielded. In addition to neutrons from ^{252}Cf decay, significant quantities of decaying fission fragments will be accumulated on the gas catcher walls, magnet chamber and other beamline walls. Shielding of this γ/β radiation is simple during operation, but it does present a challenge for maintenance activities both in terms of the potential for direct exposure and the need to limit any possibility for spreadable contamination. These shielding requirements are discussed more fully in the paper by Baker, et al [14] at this conference.

CURRENT PROJECT STATUS

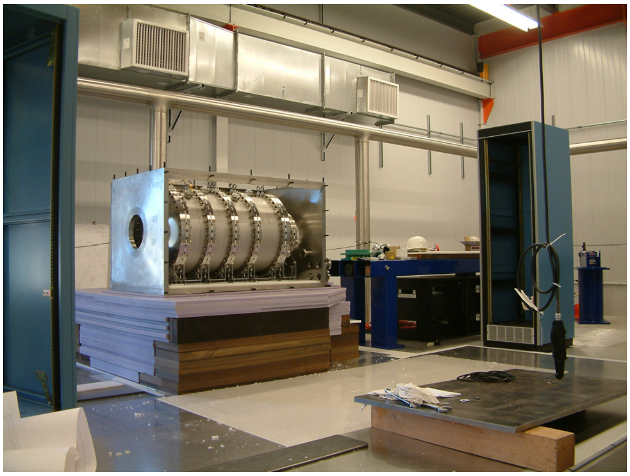

Figure 9. CARIBU High voltage platform assemble showing current status as of this conference.

As of the week of this conference installation of the last components on the CARIBU high voltage platform are moving forward. We estimate that first beams for the gas catcher may be out near the end of May 2009. The isobar separator dipole magnets are also expected to have arrived by then and installation of that system should allow initial calibrations to begin in that same time period. By July we expect to have available and installed the 80 mCi intermediate-strength ^{252}Cf source which will be sufficient to achieve the project's commissioning goals. Simple initial experiments with CARIBU can take place with the intermediate strength source, but full operation of the facility for science must await receipt of the 1 Ci ^{252}Cf source. The delivery date for that source is not firm but is projected to be available by the end of calendar year 2009. A rich research program is then expected which will make optimum use of the beams from CARIBU using HELIOS, GAMMASPHERE and the large solid angle acceptance detectors available at ATLAS.

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