

# FIRST BEAMS PRODUCED BY THE TEXAS A&M UNIVERSITY RADIOACTIVE-BEAM UPGRADE\*

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## Abstract

The first test beams of radioactive ions produced by the ion-guide-on-line (IGOL) system coupled to an electron-cyclotron-resonance ion source for charge-breeding (CB-ECRIS) have been accelerated to high energy by the Texas A&M K500 cyclotron. The radioactive ions were produced by energetic protons, provided by the K150 cyclotron, impinging on foil targets. Low charge-state ions were then swept by a flow of helium gas into an rf-only sextupole ion-guide (SPIG) which transported them into the plasma of the CB-ECRIS. The K500 cyclotron and beam-line transport were tuned with analog beam before tuning the radioactive beam.

## INTRODUCTION

Reference [1] gives a complete description of the Texas A&M upgrade. As part of the upgrade the K150 cyclotron has been re-commissioned to use as a driver for the production of radioactive ions. The method is to first stop radioactive products from beam-target collisions and transport them as low-charge-state ions using the IGOL technique. This technique was pioneered and continues to be developed at the University of Jyväskylä Cyclotron Laboratory [2]. Using this technique, a light-ion guide (LIG) is being developed where reaction products result from energetic, light-ion beams (p, d,  $^3\text{He}$ , or  $\alpha$ ) impinging on a foil target. These products remain as  $1+$  ions and can be injected into CB-ECRIS for charge-breeding to higher charge states. A low-energy beam of ions of one selected high charge-state is then transported to the K500 superconducting cyclotron for acceleration to high energy. Figure 1 illustrates the scheme where protons and deuterons result from stripped accelerated negative ions. The high-energy radioactive beam is transported from the K500 to a detector station for analysis. Eventually the radioactive beams will be used for experiments.

## LIGHT ION GUIDE AND SPIG

For LIG an energetic beam of light ions impinges on a thin foil target to produce radioactive products (via (p, n) for example) that then exit the target to encounter a rapid flow of helium gas. The products are mainly in the ionized state, and in the helium this ionization is reduced to the  $1+$  charge-state, taking advantage of the unfavorable energetics of neutralization of  $1+$  heavy ions colliding with neutral helium. The flow of helium through

the target cell ushers the  $1+$  ions through an orifice into a highly pumped region where a large fraction of the helium is pumped away. Originally the ions were guided by a small electric field through an aperture in a skimmer electrode after which they could be accelerated to form a low energy ( $\sim 10$  kV) beam.

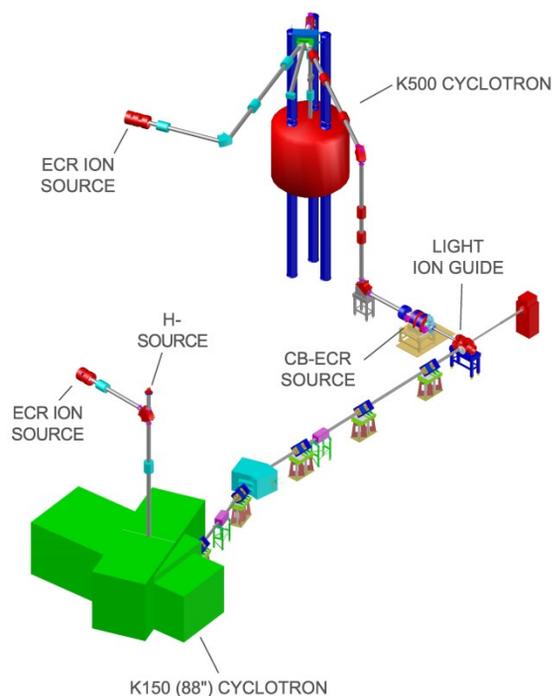


Figure 1: Simplified layout of the Texas A&M light-ion-guide scheme.

One disadvantage of the skimmer is that the ions can encounter a significant pressure of helium in the acceleration region which introduces an energy spread in the beam. In order to counter this, a system was introduced where before acceleration the thermalized ions travel along a SPIG through a sequence of pumping baffles before being accelerated [3]. References [4, 5] detail the development of the SPIG which consists of a parallel array, usually sextupolar, of conducting rods or vanes with low-power, high-frequency rf impressed. The rods are alternately phased by  $180^\circ$  so that rf fields of parabolically increasing intensity are set up in the interior of the sextupole. Ions travel through the channel between the rods contained by the rf fields while a larger fraction of the helium is pumped away. In reference 3 it is shown that ions accelerated by some initial voltage of several

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hundred volts are thermalized by collisions with the high pressure of helium before the first pumping baffle and even cooled. As a consequence, the ions exit the SPIG into the low pressure region with only a thermal energy spread.

### INITIAL SET-UP

Figures 2 and 3 illustrate the LIG-to-CB-ECRIS geometry and the target-cell. Three large Roots blowers are used to handle the large flow of helium gas exiting the target-cell. At first the SPIG was modelled after reference [3] and consisted of two sections with two pumping baffles, the first and second sections approximately 8 cm and 40 cm long, respectively, and used 4 mm diameter stainless steel rods arrayed around a 10 mm inner diameter. The exciting frequency was approximately 2 MHz and tuned to minimize reflected power. The target-cell and SPIG were held near the extraction voltage of the CB-ECRIS, and the 1+ beam subsequently accelerated to ground immediately after the SPIG. Table 1 lists four reactions that were focused on.

Table1: Reactions

Reaction	Cross-section [mb] @ $E_p$ [MeV]	Half life
$^{64}\text{Zn}(p,n)^{64}\text{Ga}$	161 @ 14.3	2.6 m
$^{58}\text{Ni}(p,n)^{58}\text{Cu}$	40 @ 14.3	3.2 s
$^{46}\text{Ti}(p,n)^{46}\text{V}$	124 @ 14.3	422 ms
$^{114}\text{Cd}(p,n)^{114}\text{In}$	510 @ 10.3	71.9 s

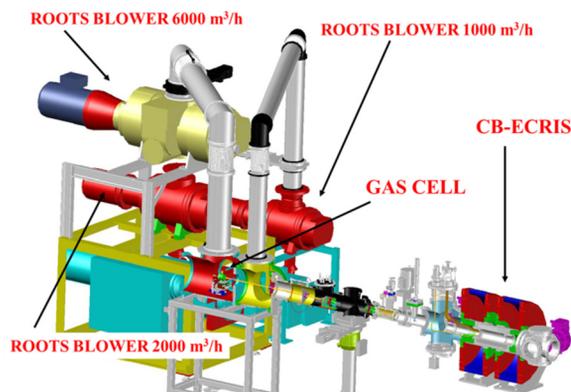


Figure 2: LIG and CB-ECRIS.

The 14 GHz CB-ECRIS [6] is located 2.5 meters from the target-cell. Since it is constructed with a totally surrounding hexapole, it is difficult to achieve a symmetric geometry on the injection end due to microwave and gas injection. This symmetry is important in the volume where injected beams are encountering the electric field that decelerates the beam into the plasma chamber [7]. Various injection geometries have been tried, including one where the plasma chamber was opened up and extended on the injection end and the microwaves injected into the extension. Charge-breeding was observed for  $^{64}\text{Ga}$ ,  $^{58}\text{Cu}$ , and  $^{114}\text{In}$  with 1% being the highest efficiency obtained for one charge-state.

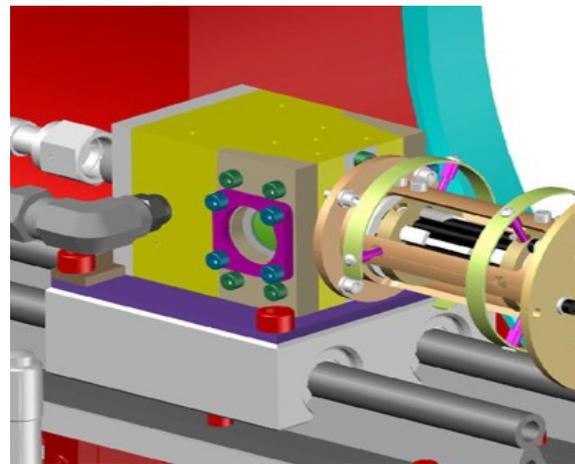


Figure 3: The target-cell and first SPIG section.

### DIRECT SPIG INJECTION

The short distance between the target-cell and the CB-ECRIS made alignment and proper focus of the 1+ beam difficult. Also larger target-cell apertures and higher target-cell pressures caused higher concentrations of helium to migrate into the acceleration region and even into the CB-ECRIS. Finally, there was the possibility that a portion of the plasma was back-extracted by the presence of grounded elements in the injection region. With these considerations in mind, in the next phase a method of direct injection of the radioactive ions produced by the IGOL system was investigated. With this method the ions travel from the target cell along an extended SPIG directly into the CB-ECRIS plasma chamber, and these problems can be more easily avoided.

As a first test a 1 meter-long SPIG was positioned through of a Glaser lens that was similar to the coil on the injection end of the CB-ECRIS and capable of producing a comparable magnetic field. Transport of ions along the SPIG was little affected by the full field of the Glaser as its coil current was increased to its maximum.

Next an aluminosilicate ion gun fabricated by HeatWave Labs, Inc. for the production of singly-charged alkali ions was placed at the entrance of 40 cm long SPIG, and the exit end of the SPIG placed on axis near the maximum axial magnetic field at the injection end of the CB-ECRIS (Fig. 4). This arrangement resulted in a good charge-breeding efficiency (Fig. 5), although this was difficult to precisely quantify due to the difficulty of measuring the output from the SPIG directly. An estimate of the output was made using a measurement of the current hitting the plasma chamber added to the current measured hitting a faraday cup down-stream of the CB-ECRIS with no high voltage applied to the plasma chamber or SPIG. This measurement indicated an efficiency as high as 10% into one charge-state (8.4 pA of  $^{133}\text{Cs}^{24+}$  out of 70 pA of  $^{133}\text{Cs}^{1+}$  measured hitting the plasma chamber and 15 pA hitting the down-stream faraday cup). The efficiency peaked at a difference between the source voltage and the CB-ECRIS voltage of

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8.5 V with 5.8 V FWHM. Charge-breeding of potassium demonstrated similar results.

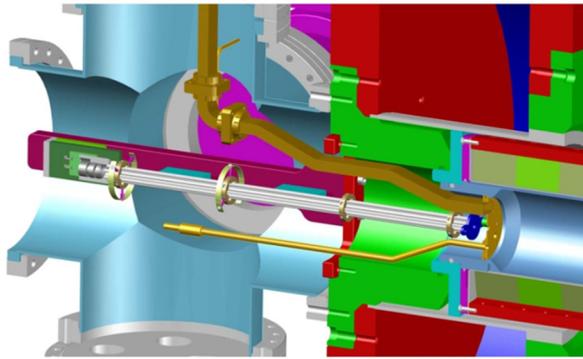


Figure 4: 40 cm SPIG injecting directly into the plasma chamber of the CB-ECRIS.

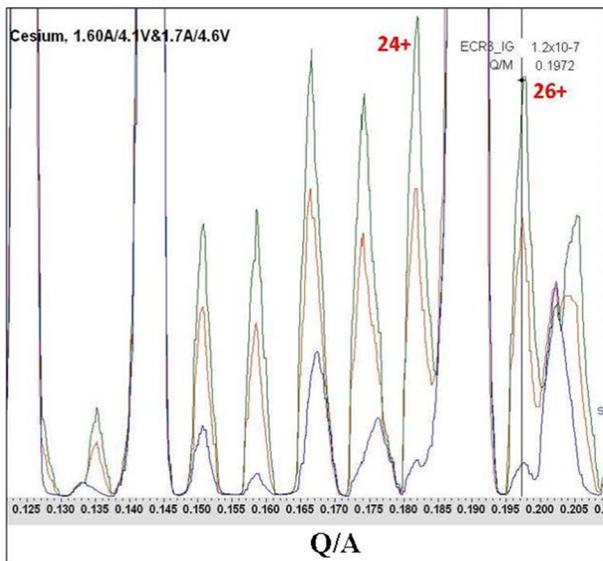


Figure 5: Spectrum of charge-bred  $^{133}\text{Cs}$  for two ion-source outputs. The largest peaks are charge-states of oxygen and nitrogen, the underlying peaks are background.

One observation is that the efficiency of charge-breeding continued to improve as the vacuum improved, although as shown by Fig. 5 there was still the presence of oxygen (from water vapour) and nitrogen (from small leaks). The vacuum never improved at the injection end of CB-ECRIS to below  $1 \times 10^{-7}$  Torr, and the introduction of support gas only served to depress the charge-breeding efficiency. The charge-state distribution was quite high even though the microwave power was low (88 watts as measured at the transmitter above the cave shielding). The total extracted current was less than  $80 \mu\text{A}$ .

Figure 6 illustrates the direct injection scheme and Fig. 7 shows the installed SPIG positioned in the injection end of CB-ECRIS (opposite extraction). The SPIG is made up of vanes instead of rods for more structural

stability. In addition to the two pumping baffles from the former scheme, there are two additional baffles with pumping by turbo-molecular pumps in between. The entire LIG to CB-ECRIS system was tested first using a  $^{133}\text{Cs}^{1+}$  source at the position of the target cell and then using a radioactive thorium source placed in the target cell. Both tests yielded about 50% global efficiency.

Finally, a proton beam was used to create products for acceleration by the K500 cyclotron. The charge-breeding efficiency was much improved. Intensities of  $^{64}\text{Ga}^{14+}$ ,  $^{63}\text{Zn}^{14+}$ ,  $^{114}\text{In}^{20+}$  and  $^{112}\text{In}^{21+}$  were 680, 897, 610 and 974 ions/ $\mu\text{C}$ , with production per unit cross-section of 4.2, 1.7, 1.1, and 1.2 ions/ $\mu\text{C}$ -mbarn, respectively.

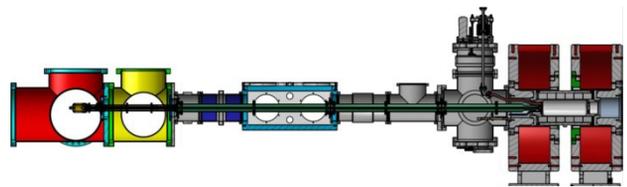


Figure 6: 2.5 meter SPIG joining LIG to CB-ECRIS.



Figure 7: Vaned SPIG and pumping baffle.

## CYCLOTRON ACCELERATION OF RIBS

The next step was the attempt to accelerate charge-bred radioactive ions and then detect them along with contaminating ions in order to determine the purity of the accelerated beams. Close analogs were used as described in [8], so it is certain that the radioactive ions were accelerated, but because of recently low proton-beam intensity most beams were totally obscured by contaminants. Contaminants included elastics from the target cell as well as close heavier analogs arising from the CB-ECRIS. Oxygen and nitrogen both were always present in CB-ECRIS and were thus convenient to use as analogs.

To address these issues it was decided to produce  $^{112}\text{In}$  ( $\tau_{1/2}=15 \text{ m}$ ) by the  $(p, 3n)$  reaction on a  $^{114}\text{Cd}$  target,

charge-breed to 21+, accelerate to 14.0 AMeV and detect using the Momentum Achromat Recoil Spectrometer (MARS) [9]. As detailed in [10] a beam of  $^{109}\text{Ag}$  at 14.0 AMeV from the K500 was used to calibrate the  $\Delta E/E$  silicon detector at the focus of MARS. The beam impinged on a thin carbon foil at the entrance of MARS in order to strip to the higher charge-states that the MARS magnetic dipoles could handle. Q/M ratios of  $^{112}\text{In}^{21+}$  and  $^{16}\text{O}^{3+}$  are 0.18768 and 0.18758, respectively, so the frequency shift from  $^{16}\text{O}$  to  $^{112}\text{In}$  was calculated to be +6.5 kHz. After tuning the  $^{16}\text{O}^{3+}$  to MARS and then making the frequency shift, the rigidity of MARS was set to observe the 34+ through 41+ charge-states of  $^{112}\text{In}$ . Particles with mass 112 dominate the spectra along with a few other ions with Q/M  $\approx$  3/16.

Measurements were taken with the proton beam “on” and “off” the LIG target for 3 minutes each. A sample of these is shown in Fig. 8 for the  $^{112}\text{In}^{39+}$  setting. The  $^{112}\text{In}$  disappears when the proton beam “off” (Fig. 8). A maximum rate of 100 counts/sec for  $^{112}\text{In}^{39+}$  was observed with 2  $\mu\text{A}$  of proton beam. With the other charge-states considered, 330 pps of  $^{112}\text{In}^{21+}$  were delivered to target, and assuming 10% acceleration efficiency  $3.3 \times 10^3$  pps of  $^{112}\text{In}^{21+}$  were produced for a 2  $\mu\text{A}$  proton beam.

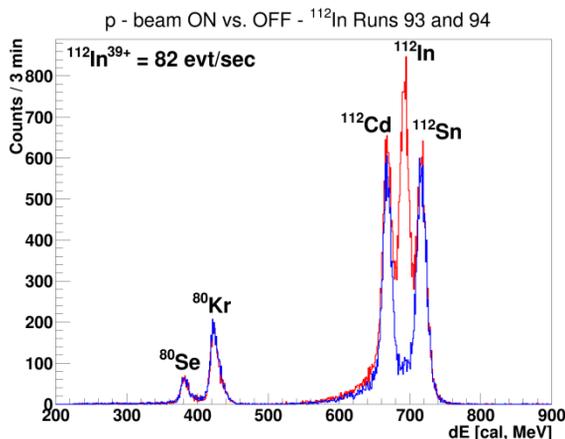


Figure 8:  $\Delta E$  spectra showing the  $^{112}\text{In}^{39+}$  measured in the MARS focal plane. Blue corresponds to proton beam “off” and red to proton beam ‘on’.

## FUTURE PROGRESS

$^{112}\text{In}^{21+}$  is the first re-accelerated radioactive ion beam at the Texas A&M Cyclotron Institute. Since this experiment the intensity of the K500 H-minus-to-proton beam has been increased by more than a factor of ten by fixing leaks in the K150 in addition to adding more cryopumps at the cyclotron periphery. Scaling of the LIG production with light-ion intensity needs to be tested, and higher production will make tuning easier and beam purity higher.

Direct injection by a SPIG proved an efficient and easily tuned alternative to the accel-decel scheme. However, fitting the SPIG into the existing transfer line has resulted in making alignment and servicing difficult

and time consuming. In an effort to solve this problem, a new chamber is now being designed specifically for the SPIG. It will incorporate a single, long port through which the SPIG can easily be removed, or inserted and aligned. Also, room for diagnostics with a possible moveable section of the SPIG is being considered. Finally, strategies for increasing efficiencies for all species and decreasing breeding times and contamination will be explored.

Finally, the performance of the CB-ECRIS can be improved with the repair of small air leaks and the substitution of a low-power, variable frequency travelling-wave-tube microwave (TWTA) amplifier for the high-power klystron, 14.5 GHz transmitter [7].

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