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CHARGE-BREEDING OF RADIOACTIVE IONS AT THE TEXAS A&M CYCLOTRON INSTITUTE

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Abstract

Singly charged, radioactive ions produced by high-energy protons in an ion-guide on-line target-cell have been charge-bred in an electron cyclotron resonance ion source (CB-ECRIS) and subsequently accelerated to high energy by the K500 cyclotron at Texas A&M University. The 1+ ions were accelerated to near the extraction voltage of the ECRIS and then decelerated through the injection-end magnetic mirror field of the ECRIS. The charge-breeding efficiency was only at most 1% into one high charge-state, and as a consequence another method of injection into the ECRIS is being attempted. Direct injection from a 1+ ion source via an rf-only sextupole ion-guide or SPIG has been accomplished with no high-voltage deceleration of ions through the mirror field into the ECRIS. Direct injection of 1+ radioactive ions via a longer (2.5 m) SPIG transporting products from the target-cell to CB-ECRIS is now being implemented.

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 primary method is to first stop radioactive products from beam-target collisions and transport them as low-charge-state ions using the ion-guide on-line technique. This technique was pioneered and continues to be developed at the University of Jyväskylä Cyclotron Laboratory [2]. Using this technique both a light-ion guide (LIG) for reaction products resulting from energetic, light-ion beams (p. d, ^{3}He, or α) and a heavy-ion guide (HIG) for reaction products resulting from energetic, heavy-ion beams are being developed. These ions are then injected into CB-ECRIS for charge-breeding to higher charge states. A low-energy beam of ions of one selected charge-state is then transported to the K500 superconducting cyclotron for acceleration to high energy. Figure 1 illustrates the scheme. Now only the LIG will be considered.

LIGHT ION GUIDE

For LIG an energetic beam of light ions impinges on a thin 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 the helium can be pumped away. The ions are guided by a small electric field through an aperture in a skimmer electrode after which they can be accelerated to form a low energy (~10kV) beam.

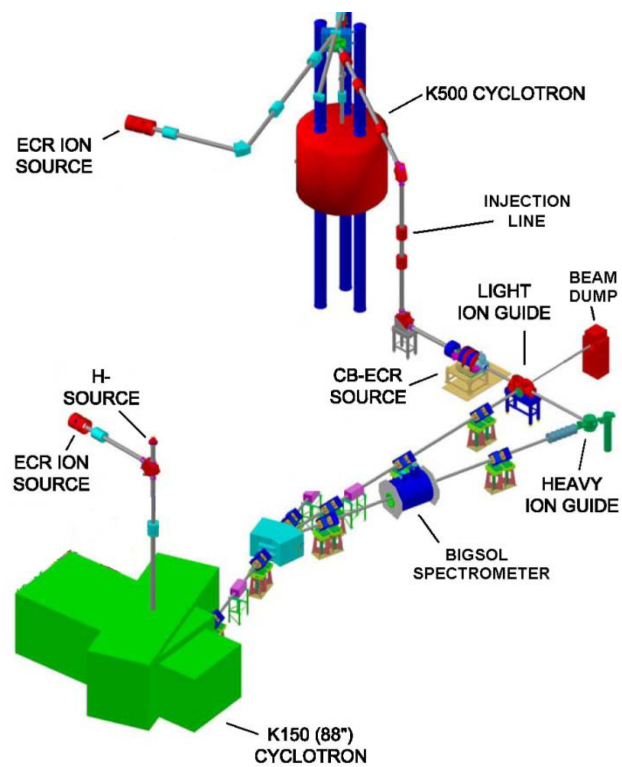

Figure 1: Simplified Layout of the Texas A&M Radioactive Beam Facility.

One disadvantage of this technique is that the ions 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 an rf-only sextupole ion guide through a sequence of pumping baffles before being accelerated [3]. References [4] and [5] detail the development of the rf-only ion guide which consists of a parallel array, usually sextupolar, of conducting rods or vanes with low-power,

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high-frequency rf impressed. The rods are alternately phased by 180° so that rf fields of parabolic 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 the helium is pumped away. In reference [3] it is shown that ions accelerated by some initial voltage of several 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. The SPIG, modelled after reference [3], consists of two sections with two pumping baffles, the first and second sections approximately 8 cm and 40 cm long, respectively, and using 4 mm diameter stainless steel rods arrayed around a 10 mm inner diameter. The exciting frequency is approximately 2 MHz and tuned to minimize reflected power. The target-cell and SPIG are 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.

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

Table1: Reactions.

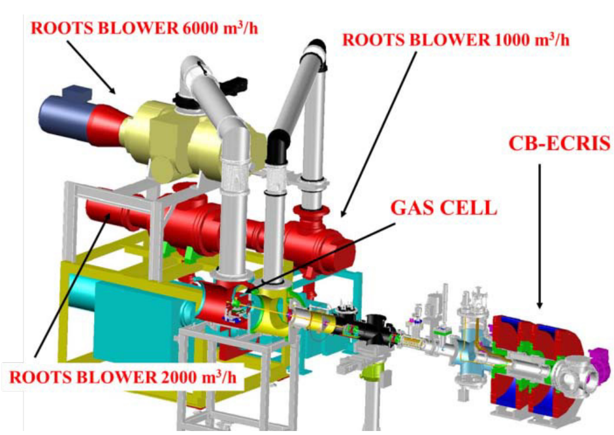

Figure 2: LIG and CB-ECRIS.

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}Ga, ^{58}Cu, and ^{114}In with the highest efficiency obtained (approximately 1%) for $^{114}In^{19+}$ ions which were reaccelerated in the K500 cyclotron [8]. The number of radioactive ions injected into CB-ECRIS ranged between approximately 2x10^4 ions/μCoulomb (^{64}Ga and ^{114}In) to 3x10^3 ions/μCoulomb.

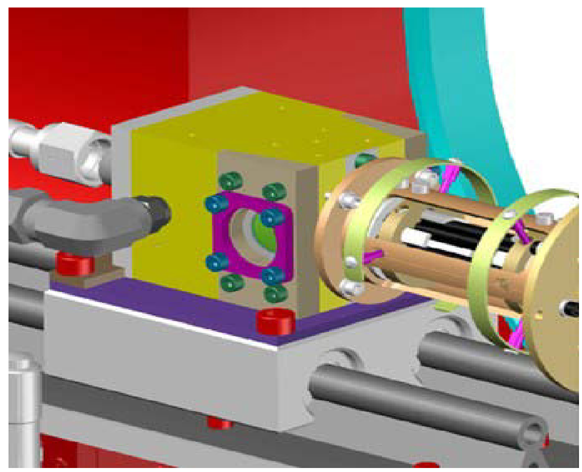

Figure 3: The target-cell and first SPIG section.

DIRECT INJECTION

The short distance (2.5 m) between the target-cell and the CB-ECRIS makes aligning and properly focusing the 1+ beam difficult. Also larger target-cell apertures and higher target-cell pressures cause higher concentrations of helium to migrate into CB-ECRIS. Finally, there is the possibility that a portion of the plasma is 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 ion-guide on-line system is being investigated. With this method the ions travel 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 the center 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

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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

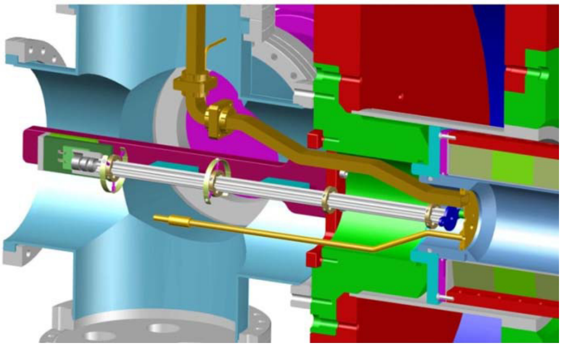

Figure 4: 40 cm SPIG injecting directly into the plasma chamber of CB-ECRIS.

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 pnA of Cs^{24+} out of 70 pnA of Cs^{1+} measured hitting the plasma chamber and 15 pnA hitting the down-stream faraday cup). The efficiency peaked at a difference between the source voltage and the CB-ECRIS voltage of 8.5 volts with 5.8 volts FWHM. Charge-breeding of potassium was also attempted with similar results.

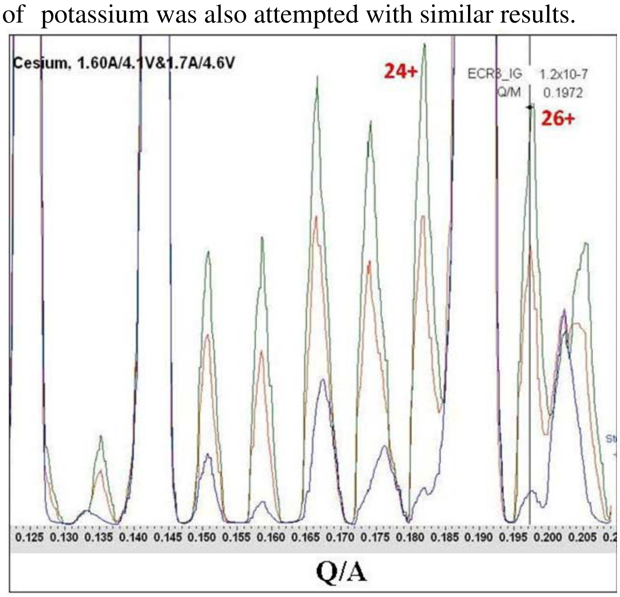

Figure 5: Spectrum of charge-bred Cs. The red and green peaks are Cs charge-states resulting from different 1+ source power levels. The blue is background. 370 enA full scale.

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 vapor) and nitrogen (from small leaks). The vacuum never improved at the injection end of CB-ECRIS to below $1x10^{-7}$ 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 eμA.

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 turbomolecular pumps in between. The entire LIG to CB-ECRIS system will be tested first using a radioactive thorium source placed in the target cell. Later a proton beam will be used to create products for eventual acceleration by the K500 cyclotron.

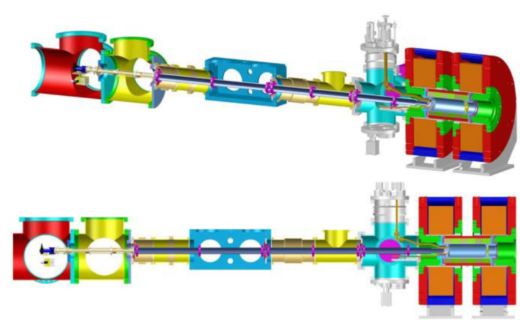

Figure 6: 2.5 meter SPIG joining LIG to CB-ECRIS.

Figure 7: Vaned SPIG and pumping baffle.

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FUTURE PROGRESS

The vaned SPIG assembly has been installed, and connections are now being made. It is hoped that injection by an rf-only ion guide will prove an efficient and easily tuned alternative to the accel-decel scheme. If this method proves feasible future progress will focus on a mechanism for moving a section 0f the SPIG out of line so that a detector station can be positioned in-line in order to accurately measure the output of radioactive products from the LIG. Finally strategies for increasing efficiencies for all species and decreasing breeding times and contamination can be explored.

REFERENCES

[1] D. P. May, B. T. Roeder, R. E. Tribble, F. P. Abegglen, G. Chubaryan, H. L. Clark, G. J. Kim, G. Tabacaru and J. Ärje, P*roceedings of the 20th International Conference on Cyclotrons and their Applications, Vancouver, Canada (2013)*.

[2] J. Ärje, J. Äysto H. Hyvönen, P. Taskinen, V. Koponen, J. Honkanen, K. Valli, A. Hautojärvi and K. Vierinen, *Nucl. Instrum Methods, A* vol. 247, pp. 431-4373, (1986)

[3] P. Karvonen, I. D. Moore, T Sonoda, T Kessler, H. Penttila, K. Peräjä, P Ronkanen and J. Äystö, Nucl. Instrum Methods, B266 (2008) 4794-4808.

[4] H. J. Xu, M. Wada, J. Tanaka, H. Kawakami, I. Katayama, S. Ohtani, *Nucl. Instrum Methods*, vol. A333, pp. 274, (1993) .

[5] M. Wada, Nucl. Instrum Methods, vol. B319, pp. 450-456, (2013).

[6] W. D. Cornelius, Proceedings of the 18th International Workshop *ECR Ion Sources, Chicago, Illinois,* pp. 167-175, (2008).

[7] R. Vondrasek, A. Levand, R. Pardo, G. Savard and Scott, *Rev. of Sci. Instum.,* vol. 02A913, (2012).

[8] B. T. Roeder, F. P. Abegglen, J. Ärje, G. J. Kim, A. Saastamoinen and G. Tabacaru, *Cyclotron Institute Progress in Research Texas A&M Univ. 2016-2017*, vol. IV-17.