Status of the light ion guide beam reacceleration and diagnostics

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Following the success of re-accelerating ^{112}In from the Light Ion Guide (LIG) in November 2018 [1], this year we attempted to improve our tuning techniques for the re-accelerated beams. We also worked on reducing the stable beam background originating from intrinsic contamination in the Charge Breeding Electron Cyclotron Resonance Ion Source (CB-ECRIS), which was also studied with some detail last year [2]. Finally, we commissioned the new in-line BEam Analysis Station, or BEAST, which will allow re-accelerated beams to be identified and tuned without the use of the MARS spectrometer [3].

K500 Frequency Scaling Improvements

The main improvement in our re-accelerated beam tuning technique was the development and refinement of the K500 radiofrequency scaling (also known as "frequency jumping") to change from intense, stable pilot beams to the extremely weak, rare isotope beams (RIBs) from the LIG and CB-ECRIS. In previous years, the re-accelerated beam had to be extremely close in frequency to the pilot beam, within about 10 kHz, in order to be easily found and optimized [1]. A larger frequency change of 56 kHz was previously only achieved one time while changing from $^{16}O^{3+}$ to $^{85}Rb^{16+}$, where $^{85}Rb^{16+}$ was a stable ion beam coming directly from the CB-ECRIS [4].

This year, we attempted larger frequency changes up to ±200 kHz away from the pilot beam. This will allow greater flexibility in the choice of pilot beam and perhaps allow for choosing the charge state of the RIB from the LIG with the least amount of background beam from the CB-ECRIS. For the test, the ECR1 ion source was used to make the tuning a bit easier. The pilot beam in the test run was $^{16}O^{3+}$ at 14 MeV/u. The K500 radiofrequency for this beam was 12.2366 MHz and the ECR1 extraction HV was 10.00 kV. For frequency changes greater than 12 kHz, or 0.1% in charge-to-mass ratio, it was found that the ECR1 extraction voltage also needed to be scaled by the same amount. Thus, for larger K500 frequency changes, two parameters needed to be changed to go from the pilot beam to the beam of interest.

With the two parameter change technique, changing the K500 frequency and ECR1 extraction HV for $^{16}O^{3+}$ frequency -1.2% (-147 kHz for the K500 frequency and -0.12 kV for the ECR1 voltage) allowed $^{27}Al^{5+}$ to be accelerated and observed at the end of the MARS spectrometer. Similarly, $^{63}Cu^{12+}$ and $^{84}Kr^{16+}$ are +1.668% higher in charge-to-mass ratio than $^{16}O^{3+}$, and thus can be accelerated by changing the K500 frequency for $^{16}O^{3+}$ by +204 kHz and the ECRIS extraction voltage +0.17 kV).

It is important to note that other parameters, such as the cyclotron "dee" voltages and beam line magnets were not changed during this test. In the future, these parameters will need to be optimized also to maximize the intensity of the reaccelerated beams.

CB-ECRIS Coating and Liner Studies

It is hypothesized that the majority of the stable beam contamination originating from the CB-ECRIS arises from the interaction of the plasma in the ion source with its internal components, in particular, with its plasma chamber. The CB-ECRIS plasma chamber is composed of Al-7075 alloy, which contains 6% Zn, 2.5% Mg, 1.5% Cu, and other trace amounts of other metals [5]. This accounts for the contamination observed in previous tests [2]. While the ECR1 source plasma chamber is composed of somewhat cleaner Al-6061 alloy, contamination is measurable from that ion source as well.

This year, we tried two ideas to reduce or eliminate the stable beam contamination from ECR1 and the CB-ECRIS. The first idea was to leak silane gas (SiH_4) into the ion sources. Prolonged exposure of the ion source plasma chamber to SiH_4 has been shown in the past to improve the intensity for some ions. Also, through interaction with oxygen ions in the plasma, the SiH_4 is converted to solid SiO_2, which condenses on the walls of the plasma chamber. It was hoped that the SiO_2 would coat the inside surface of the plasma chamber and prevent the plasma from interacting with the aluminum alloy and thus reduce or eliminate the stable beam contamination. To test this possibility, a test was conducted with the K500 cyclotron and the MARS spectrometer to see if the rate of $^{64}Zn^{12+}$ from the CB-ECR was reduced after treatment with SiH_4. First, the rate of $^{64}Zn^{12+}$ was measured at MARS before the SiH_4 treatment. Then, the CB-ECR was treated with SiH_4 gas for about 36 hours. Initially, the CB-ECR did not function and could not support a plasma after the treatment with SiH_4. After treatment with oxygen gas for about 6 hours, the ion source became functional again and the measurement of the ^{64}Zn beam could be repeated with MARS. Unfortunately, there was no difference in the rate of $^{64}Zn^{12+}$ observed with MARS after the SiH_4 treatment; about $1.2{\cdot}10^4$ p/s according to the MARS measurements. The results of this test are summarized Fig. 1. It was also noted that the rate of ^{64}Zn measured increased with the amount of microwave power used for the CB-ECR, independent of the SiH_4.

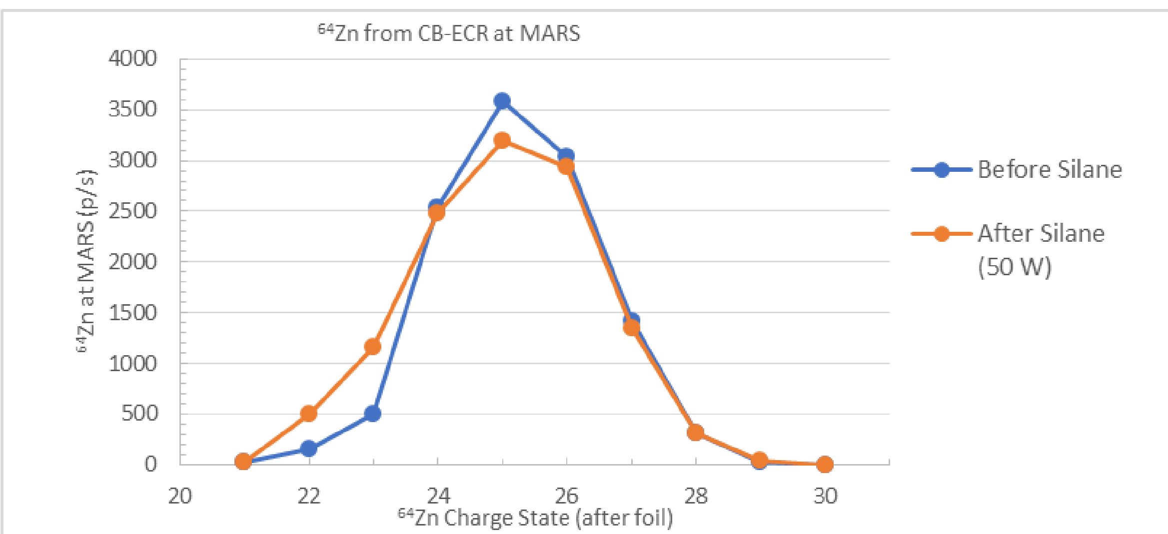

Fig. 1. Measurements of ^{64}Zn beam at 14MeV/u produced from the CB-ECR as observed at the MARS focal plane. The ^{64}Zn beam was stripped with a thin carbon foil at the entrance of MARS and the different charge states were measured individually. The sum of the charge states produced was $1.2{\cdot}10^4$ p/s both before and after the SiH_4 treatment. See text for further explanation.

Following the test, it was found that the SiO_2 coating drastically reduced the charge breeding efficiency for the Light Ion Guide beams. In order to restore the charge breeding performance, the CB-ECR needed to be completely disassembled and thoroughly cleaned.

The second idea to reduce the stable beam contamination from the ECR sources was to insert a thin aluminum liner composed of an alloy with less trace contaminants. Ideally, a "pure" aluminum sheet would have been used for the test, but pure aluminum is difficult to machine and manipulate. Thus, an aluminum liner, end plate, and bias plate made of aluminum 1050 series alloy [5] was made. This alloy is composed of 99.5% aluminum and contains, in particular, less than 0.05% zinc. The test was conducted on the ECR1 ion source and, if successful, could then be tried on the CB-ECR. Ideally, it would have been possible to completely cover all surfaces of ECR1 with the 1050 series aluminum. However, at the time of the test, the ion source extraction plate made of 1050 series aluminum was not ready. It was also not possible to cover all the surfaces of the plasma chamber with the 1050 series aluminum. Nevertheless, about 75% of the internal surface of the ECR1 plasma chamber was covered.

A similar test with the K500 cyclotron and the MARS spectrometer was conducted for testing the liner. The $^{64}Zn^{12+}$ at 14 MeV/u beam intensity was measured before and after the installation of the 1050 series aluminum liner. Again, no difference in the ^{64}Zn beam intensity at MARS was observed. This presents two possibilities: either the extraction plate of the ion source, which was not made of the 1050 series aluminum, was a significant source of the ^{64}Zn beam background, or the 0.05% Zn content of the 1050 series aluminum was still enough to generate the low rate of beam observed in the test. Thus, even though this method of reducing the Zn beam background did not produce favorable results, future investigation of this method with more extensive source coverage and/or more "pure" aluminum liners may be interesting.

BEam Analysis Station (BEAST)

A new chamber housing the Beam Analysis Station, or BEAST, with beam viewers, detectors, and a faraday cup has been installed for testing in cave 3 upstream of the MDM spectrometer. The BEAST will be used to identify and optimize the beam tunes of the relatively low intensity beams from the Light Ion Guide. The Light Ion Guides ideally will be tuned with the BEAST only and will not require use of the MARS spectrometer.

The BEAST contains the following components. First, a low-noise faraday cup on an actuator is available. The faraday cup is readout through a 20 ft long triaxial cable with a Keithley 6514 ammeter [6]. It was shown to have sensitivity with beam intensities as low as 3 femtoamperes. Perhaps even lower beam currents could be observed with a shorter triaxial cable, which seems to be the principle source of the background noise on the measurement. Second, 2 beam viewers, also on actuators, are installed. With a low-light camera and new viewers, beam spots with intensities as little as 10^3 p/s can be observed in real-time for beam spot optimization. Third, an apparatus housing 2 photo-multiplier tubes and a thin BC-400 plastic scintillator, also mounted on an actuator, is available. This device is intended mainly as a beam counter and is able to measure light ion beam intensities up to about 10^6 p/s. It could also function as a time-of-flight start detector for future applications. Fourth and finally, a target ladder and rotatable silicon detector telescope are available for identification of the particles in the beam at low intensity (less than 10^3 p/s). At higher intensities, a thin gold target could be inserted with the target ladder and the silicon detector can be rotated off the beam axis, reducing the intensity of an intense stable beam background while allowing possible observed of a weaker intensity rare isotope beam from the Light Ion Guide. The BEAST chamber, as installed in cave 3, is shown in Fig. 2.

Fig. 2. The BEam Analysis Station (BEAST), and associated equipment, as installed in cave 3. See text for further explanation.

[1] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2018-2019), p. IV-17, http://cyclotron.tamu.edu/progress-reports/2018-2019/SECTION IV.html.

[2] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2018-2019), p. IV-23, http://cyclotron.tamu.edu/progress-reports/2018-2019/SECTION IV.html.

[3] R.E. Tribble, R.H. Burch, and C.A. Gagliardi, Nucl. Instrum. Methods Phys. Res. **A285**, 441 (1989).

[4] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2015-2016), p. IV-16, http://cyclotron.tamu.edu/progress-reports/2015-2016/SECTION IV.html.

[5] https://en.wikipedia.org/wiki/Aluminium_alloy

[6] https://www.tek.com/keithley-low-level-sensitive-and-specialty-instruments/keithley-high-resistance-low-current-electrom