**Recent development of re-accelerated rare isotope beams from the light-ion guide**

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This year, the development of re-accelerated rare isotope beams (RIBs) from the light ion guide (LIG) continued. Two mass regions were investigated. First, a mass-89 radioactive cocktail beam composed of $^{89}$Zr and $^{89}$Nb was tested since relatively high intensities were achieved from the LIG. Following the successful re-acceleration of the mass-89 RIBs with the K500 cyclotron in July 2023, a mass-105 RIB containing $^{105}$In, $^{105}$Cd and $^{105}$Ag was prepared with the LIG in April 2024. After re-acceleration by the K500 cyclotron, the mass-105 RIB was used in the first experiment with re-accelerated beam at the Cyclotron Institute to measure $^{105}$In+p and $^{105}$Cd+p elastic scattering. Some preliminary results from this experiment are given in a separate report [1].

For the mass-89 RIB in July 2023, a 22 MeV proton beam from the K150 cyclotron bombarded an enriched $^{90}$Zr target at the light-ion guide target chamber. Proton beam intensities up to 10μA were used. The $^{89}$Nb and $^{89}$Zr ions produced from the p+$^{90}$Zr reactions were stopped in helium gas and transported through the light ion guide to the charge-breeding ECR ion source. In the CB-ECR, the $^{89}$Nb and $^{89}$Zr were charge-bred up to charge state $19^{+}$ and then transported to the cyclotron for re-acceleration. Due to the low intensity of the mass-89 RIB, the K500 cyclotron and beam optics tune were first optimized with a $^{14}N^{3+}$ pilot beam at 15 MeV/u. Once completed, the K500 radiofrequency (RF) was re-tuned -32.3 kHz lower (from 12.6453 MHz to 12.6130 MHz) to account for charge-to-mass (q/m) difference between 14N3+ ions and the mass-89 RIB ions.

Following this slight RF frequency change, the mass-89 RIBs were accelerated by the K500 cyclotron to 15 MeV/u and transported to the MARS target chamber. In the chamber, a ΔE-E silicon detector telescope, composed of an 81.6 μm "ΔE" and a 2002 μm "E" silicon surface barrier detectors, was mounted at 0° with respect to the beam to measure and identify the RIB ions with the energy loss technique. The response of ΔE-E silicon detectors was calibrated prior to the experiment with a 15 MeV/u $^{84}$Kr beam, also accelerated by the K500 cyclotron. The signals from the silicon telescope were amplified with a CAEN 1422A preamplifier with gain 1mV/MeV and the signals were digitized with a CAEN 5780 desktop digitizer. The data were recorded and could be displayed during the experimental runs with the CoMPASS software package.

When the K500 cyclotron RF frequency was changed to 12.6130 MHz, the mass-89 RIBs immediately appeared in the spectra measured by the ΔE-E silicon detector telescope. The initial beam rates were about 66 ion/s for $^{89}Nb^{19+}$ and about 12 ions/s for $^{89}Zr^{19+}$. Various optimizations were carried out, including adjusting the proton beam intensity, optimizing the cyclotron buncher and dees, adjusting slightly the CB-ECR extraction voltage, tuning the LIG and CB-ECR parameters, and scanning the K500 RF frequency to see how the ion transmission changed. Among these changes, increasing the proton beam intensity to 8μA and optimizing the K500 dees and radiofrequency produced the largest improvements. After optimization, the best beam rate obtained for $^{89}Nb^{19+}$ was 100 ions/s and about 20 ions/s for $^{89}Zr^{19+}$. A small amount of $^{89}Y^{19+}$ was also present in the beam. A spectrum from the mass-89 RIB measurements is shown in Fig. 1.

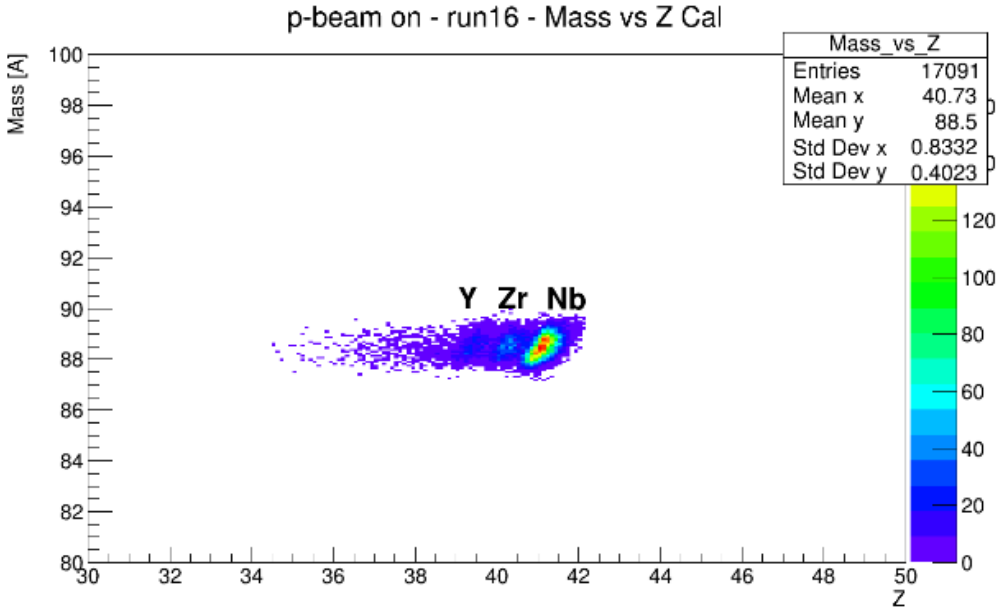


FIG. 1. Results from the mass-89 RIB tune as measured with the ΔE-E silicon detector telescope. The measured energy losses for ions were calibrated in this spectrum to illustrate the mass and proton number of the ions.

For the mass-105 RIB in April 2024, a 22 MeV proton beam from the K150 cyclotron bombarded an enriched $^{106}$Cd target at the light ion guide target chamber. Proton intensities up to 12μA were used. The mass-105 RIB ions ($^{105}$In,$^{105}$Cd and $^{105}$Ag) were stopped in helium gas and transported to the CB-ECR where they were charge-bred up to charge states 22+, and 19+. For the first part of the experiment, the K500 cyclotron and beam optics were tuned with a $^{86}Kr^{18+}$ pilot beam at 15 MeV/u. Then, the RF was changed from 12.6453 MHz to 12.6550 MHz to accelerate the mass-105 RIBs in charge state 22+. The resulting accelerated ions were detected and identified with the same ΔE-E silicon detector telescope and associated data acquisition electronics used for the $^{89}$Nb/$^{89}$Zr development run, except this time the detector telescope was mounted in the BEam Analysis STation (BEAST) chamber in cave 3 [2]. The BEAST chamber was mounted just upstream of the experimental chamber. A picture of the setup in this case is shown in Fig. 2. The maximum mass-105 RIB rates measured were about 6 ions/s of $^{105}In^{22+}$ and about 12 ions/s of $^{105}Cd^{22+}$. $^{105}Ag^{22+}$ was also present at a very low rate. The $^{86}Kr^{18+}$ pilot beam also could not be eliminated by the cyclotron RF change and was still visible on the detector at a rate of about 12 ions/s.

Later in the experiment, a higher rate for the mass-105 RIB ions was desired. It was found that the CB-ECR was producing more of the RIB ions in the 19+ charge state. So, the cyclotron was re-tuned with an $^{83}Kr^{15+}$ pilot beam at 12 MeV/u. In this case, the K500 RF was changed from 11.3666 MHz (pilot beam) to 11.37775 MHz (mass-105 RIBs). The latter RF was chosen to

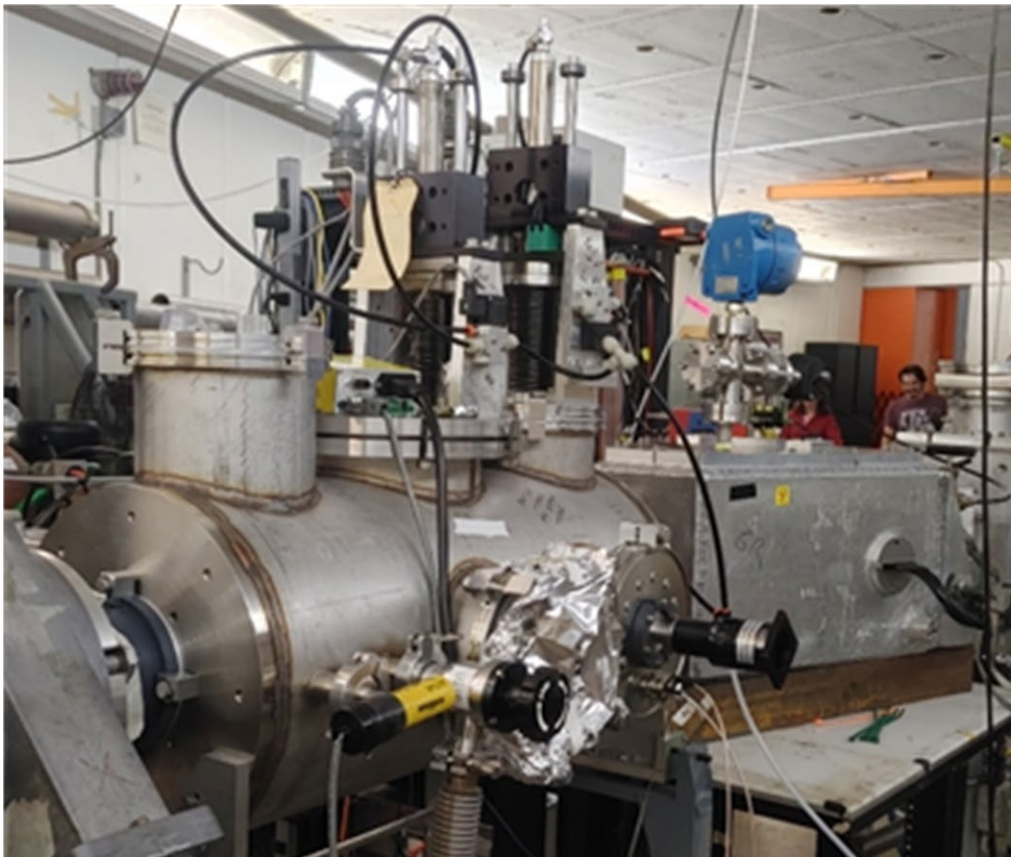

FIG. 2. Picture of the experimental setup for the Mass-105 RIB run. The BEAST chamber with the tuning detectors for the Mass-105 RIB is shown on the left and the experiment chamber is shown downstream on the right of the picture.

optimize the transmission of $^{105}In^{19+}$, which was the RIB of the highest interest for the experimenters. For most of the experiment, the mass-105 RIB rates were about 20 ions/s for $^{105}In^{19+}$ and about 50-60 ions/s for $^{105}Cd^{19+}$, as measured with the silicon detector in the BEAST chamber. This result is expected because the production cross section is expected to be about 4 times higher for $^{105}Cd$ vs. $^{105}In$ [3], even though the cyclotron tune was optimized for $^{105}In^{19+}$. However, near the end of the experiment, it was found that the rate of $^{105}In^{19+}$ could be optimized even further by gating directly on the $^{105}In^{19+}$ in the CoMPASS data acquisition software and tuning the cyclotron dees and buncher on the gated event rate. With this technique, the best rate obtained for $^{105}In^{19+}$ was 35 ions/s, which also came with 70 ions/s of $^{105}Cd^{19+}$ and 20 ions/s of $^{105}Ag^{19+}$. A spectrum showing the optimized tune for the mass-105 RIB is shown in Fig. 3. Some stable mass-94, mass-116 and mass-127 contamination was also present in the beam at a very low rate ( < few counts/sec ). These ions arise from residues in the CB-ECR plasma chamber, as has been noted in previous LIG runs [4]. In total, the experiment ran for about 2 weeks.

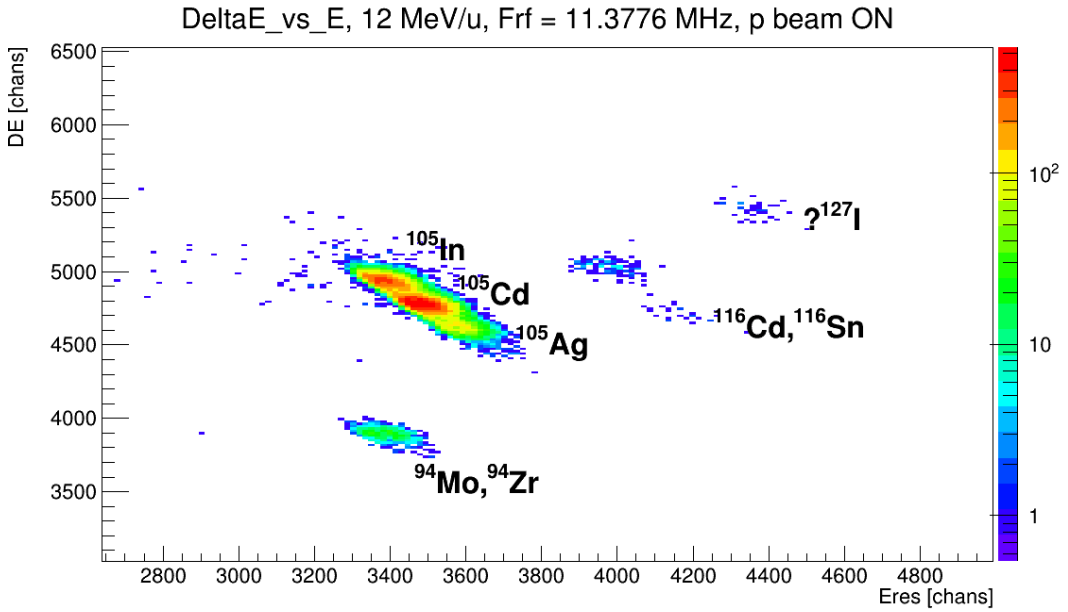


FIG. 3. Spectrum showing the composition of the Mass-105 RIB cocktail beam as measured by the silicon detector telescope in the BEAST chamber in a 300s test run. Mass-94, mass-116 and mass-127 contaminants from the ion source were also present at very low rate.

In conclusion, two new re-accelerated rare isotope beam cocktails were prepared by the light ion guide and re-accelerated by the K500 cyclotron. In both cases, the maximum total RIB rates obtained were around 100 ions/s and were mostly limited by the production cross sections and the CB-ECR charge-breeding efficiency. The mass-105 beam cocktail containing $^{105}$In, $^{105}$Cd and $^{105}$Ag was used for an elastic scattering experiment that lasted 2 weeks. Further developments to improve the beam intensities and to produce other re-accelerated rare isotope beams are planned for the coming year.

[1] M. Barbui *et al. Progress in Research*, Cyclotron Institute, Texas A&M University (2023-2024), p. I-??;http://cyclotron.tamu.edu/progress-reports/2023-2024/SECTION I.html.

[2] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2019-2020), P. IV-13; http://cyclotron.tamu.edu/progress-reports/2019-2020/SECTION IV.html.

[3] *TENDL-2017*, https://tendl.web.psi.ch/tendl_2017/tendl2017.html.

[4] 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.