K150 operations and development

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We had another busy year operating the K150 cyclotron. For the reporting period we logged over 3859 hours of beam-on-target and 2772 hours for beam developments, see Table I. Included in the beam-on-target time was 3199 hours (2703 for physics and 496 for chemistry) for in-house science experiments, 396 hours for the SEE tests, and 264 hours for the LLNL-Burke experiments. The big users of the K150 beams were the LIG (light ion guide) project, the Rogachev group, and the SEE tests.

Table I. 2018-2019 operational time.

Time	Hours	% Time
Beam on target	3859	44.2
Beam development	2772	31.7
Scheduled maintenance	2104	24.1
Unscheduled maintenance	1	0.0
Total	8736	100.0

As was in the past years, proton beams from 10.3 to 28.5 MeV were produced for the LIG project throughout the year. In November of 2018, the production of the radioactive species ^{112}In (14.4 minute half-life) from a ^{114}Cd target and subsequent charge breeding and re-acceleration with K500 were investigated. Using the CB-ECR ion source the charge bred $^{112}In^{21+}$ ions, along with $^{16}O^{3+}$ which was used as a pilot beam, were accelerated to 14 AMeV from the K500 cyclotron and were then sent to the MARS spectrometer for analysis. The beam switch from $^{16}O^{3+}$ to $^{112}In^{21+}$ was accomplished by shifting the K500 RF frequency by +6.5 kHz. The MARS analysis identified the beam as ^{112}In along with two other contaminants (from the ion source) of similar intensities to the ^{112}In; it was verified that the ^{112}In was indeed produced from the LIG gas cell. Thus this 14 AMeV $^{112}In^{21+}$ became our first accelerated radioactive beam. This test is described in detail in a separate section.

The energies of some beams were limited by the deflector voltage, and we made some progress in better utilizing the deflector to push those beam energies higher. For example, it required 88 kV on the deflector to extract 13.7 AMeV $^{40}Ar^{14+}$ beam in Dec. 2012. Recently we were able to extract a higher 15 AMeV of the same $^{40}Ar^{14+}$ beam with 72 kV. Another example was with the $^{3}He^{2+}$ beam. In June 2018 76 kV was needed to extract a 21.5 AMeV beam, but recently we were able to extract a higher 24 AMeV at much more manageable 64 kV. The deflector consists of a high voltage electrode and a grounded septum and each is positioned independently by moving the entrance and exit pivot points. The gap between the electrode and the septum obviously depends on the positions of the electrode and the septum, and the gap size is not well determined for various possible pivot positions. (A fairly accurate ¼ scale model of the deflector exists, and it is driven at the same time as the deflector, and so the model would track the positions of the deflector electrode and the septum. Therefore, by measuring the gap on the model, the gap on the deflector may be measured, however, the positions of the deflector parts to that of the model have not been calibrated recently.) A few years ago the deflector gap was measured at one set of pivot settings (pivot #1=50600, #3=50600, #2=49007, #4=52440), and the entrance gap was 6.5 mm and the exit gap was about 14 mm. The first thing that was tried was to close the exit gap (for example: moving only pivot #3 from 50600 to 50900, which would narrowed the exit gap from 14 mm to about 7 mm), and this greatly helped to lower the required deflector voltage. Then, while keeping the entrance and exit gaps tight, the entrance or the exit pivots for the HV electrode and the septum were moved together in or out in trying to improve the extraction efficiency and also to lower the deflector voltage if possible. These efforts have increased the energy for some beams, and in particular, raised the $^{4}He^{2+}$ beam energy up to 24 AMeV with 77 kV on the deflector.

With the improved operation of the deflector, the idea of producing 15 AMeV beams of light to heavy ions on the K150 for SEE experiments became possible. The 15 AMeV beams are heavily used on the SEE experiments on the K500 cyclotron, more so than higher 25 or 40 AMeV beams from the K500. Reallocating some 15 AMeV beams from K500 to K150 cyclotron for some SEE experiments would be useful, as it would free up valuable time on the K500 cyclotron. The SEE testing station is already in place for the K150 cyclotron; the testing station has been used with proton beams for a few years. We intend to develop a number of 15 AMeV beams with ions of charge-to-mass (z/A) around 0.35 from 14 N to 63Cu or 78Kr. The light $^{14}N^{5+}$, $^{20}Ne^{7+}$, and $^{40}Ar^{14+}$ beams have already been accelerated and extracted, and these beams required deflector voltages from 66 to 71 kV. In developing these beams, the main magnet operated above 2000 A for the first time. We still need to develop a heavier beam, such as ^{63}Cu or ^{78}Kr, to complete the 15 AMeV SEE beams for K150. The copper will be run with a sputter fixture mounted inside the ECR2 ion source. Krypton is a gas, and with 3 other gases plus oxygen gas as support gas to handle, a new gas system will be needed for the ECR2 ion source to facilitate beam changes.

In the fall of 2018, the K150 vacuum started to deteriorate, going from $1\text{x}10^{-6}$ to $\sim 4\text{x}10^{-6}$ torr. Then the end of 2018, due to small water leaks from cooling lines for the dee stem, the vacuum deteriorated even more and the vacuum attenuation of the beam became more noticeable. To keep the cyclotron running, cooling the cyropanel inside the cyclotron with LN2 was necessary to stabilize the K150 vacuum to about $3\text{x}10^{-6}$ torr and it allowed the completion of the scheduled beams to the end of year. During the maintenance period in the early months of 2019, a lot of time and efforts were spent to look for and then patch several small water leaks on cooling lines for the dee stem in the resonator tank. As the access to the cooling lines was very limited under the dee stem cover, it was difficult not only to locate these leaks but the repair was only possible using epoxy, likely a temporary fix. Since the repair of the leaks the K150 vacuum has improved to $7\text{x}10^{-7}$ torr, and this agrees with observed improved internal beam transmission. A few other things are planned to improve the vacuum, such as replacing a couple of 8” cryopumps on the dee tanks with 10” pumps, and a complete cleaning of the diffusion pump.

Following the K150 vacuum improvements, several beam development tunes were conducted to test if the lower measured vacuum increased beam transmission in the cyclotron and the beam intensity that could be extracted from the cyclotron. The easiest comparison to make was with the 15 MeV H^{-}

beam tune that is routinely used for testing the Light Ion Guide. These comparisons for beam tunes before and after the vacuum improvements are summarized in figure 1. In the plot, 15 MeV H^- beam tunes are shown as recorded in November 2015 (blue line), April 2018 (red line) and March 2019 (green line). On these occasions, the K150 measurements were $2.5*10^{-6}$, $3.0*10^{-6}$, and $9.7*10^{-7}$ respectively, and the latter tune from March 2019 was done following the vacuum improvements. In November 2015, the maximum intensity for 15 MeV H^- that could be extracted was 7 µA. For the same beam in March 2019, 24 µA was extracted. Large increases in extracted intensity were also observed for heavy ion beams from ECR2, such as the $^{40}Ar^{11+}$ tune at 6.3 AMeV. More high intensity beam developments tests are planned for the coming year.

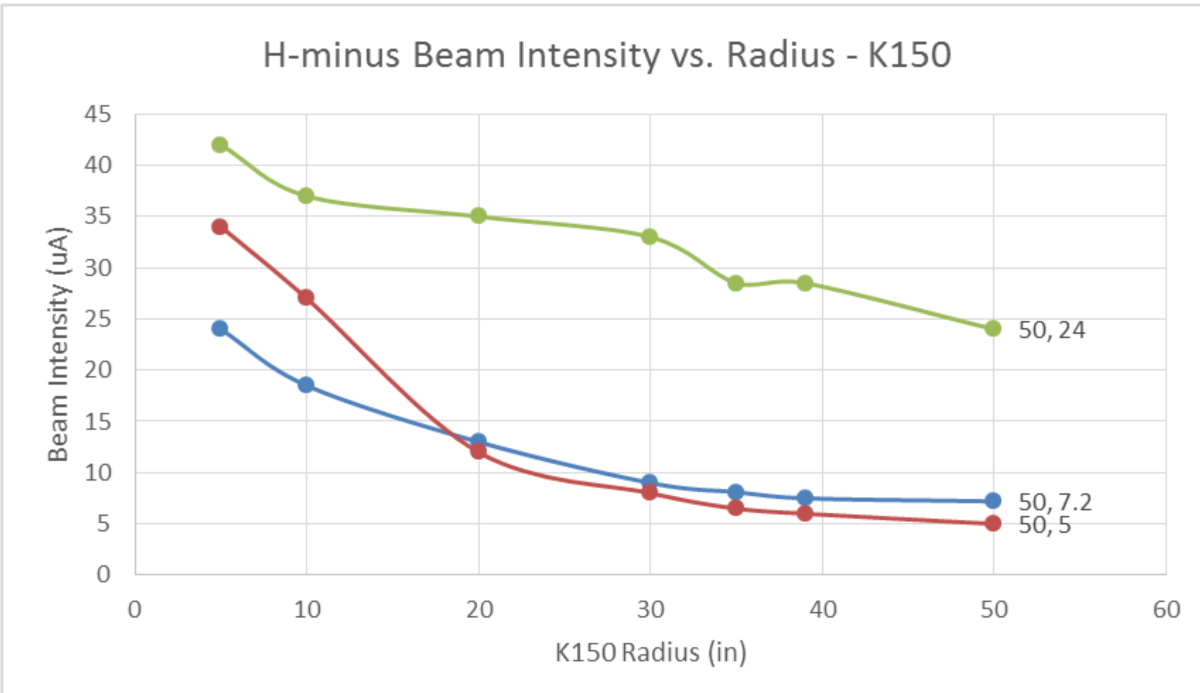

FIG. 1. Plot of beam intensity vs. radius for the K150 cyclotron for the 15 MeV H^- beam. In the plot, the blue data are from the November 2015 tune, the red data are from the April 2018 tune, and the green data are from the March 2019 tune. The radius = 50 inches in the plot represents the extracted beam from the cyclotron. Note that the March 2019 data, shown in green, shows the large improvements in transmission and extracted intensity possible with the improved K150 vacuum. See text for further explanation.