Cyclotron Institute upgrade project

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On January 3, 2005 the Cyclotron Institute Upgrade Project (CIUP) began with the approval of the CIUP management plan by the Department of Energy Nuclear Physics Office. The project will extend at least to the second quarter of calendar year 2014. When completed, the upgraded facility will provide high-quality re-accelerated secondary beams in a unique energy range in the world. Funding for the upgrade comes from several sources: the Department of Energy, matching support from TAMU, the Robert A. Welch Foundation and beam time sales for testing electronics components at the Cyclotron Institute.

The CIUP is divided into three major tasks: (1) Re-commission of the existing K150 (88”) cyclotron and refurbish beam lines; (2) Construct light-ion and heavy-ion guides and produce 1+ radioactive ions; (3) Transport and charge boost radioactive ions and accelerate in the K500 cyclotron.

As detailed in the Management Plan, effort made during this year on Task 1 included,

- Development of the 13.7 MeV/u ^{40}Ar heavy-ion beam and
- Construction of the internal cryopanel for the K150 high vacuum system.

Progress was also made on Tasks 2 and 3. This included,

- Placement of the ion guide equipment on the ion guide roof planks,
- Rebuild of Big Sol, commissioning of the CB-ECR ion source,
- Final design, construction and testing of the Light Ion Guide gas cell,
- Completion of the Heavy Ion Guide gas catcher and transport system equipment, and
- Assembly and commissioning of the n+ transport system. Below we report on a few of the accomplishments listed above.

K150 Cyclotron Development

With another year of cyclotron operation, we have worked to develop new beams and improve old ones, and we also managed to deliver K150 beams to more experiments than the year before. We have used the H^- source and strip-extraction technique to obtain proton and deuteron beams, and used the ECR2 ion source for all other positive ion beams. Currently the energy range for proton beams is 15 – 40 MeV, and for deuteron beams is 6.8 – 22.5 AMeV. For ECR2 beams, we have accelerated and extracted up to 12 AMeV for $^{13}C^{5+}$, 15 AMeV for $^{20}Ne9^{+}$, and 13.7 AMeV for $^{40}Ar^{14+}$. To extract the argon beam it required 88 kV on the deflector; this is the highest voltage used so far. The extracted intensity of the argon beam was only 11pnA, and so, much more work will be needed on the source, on the cyclotron vacuum, and other areas to get to the goal of 900 pnA. All the extracted beams from the K150 cyclotron are shown in Fig. 1. Thus far the H^- beams have achieved the best throughput, the ratio of the beam currents on the FC02 faraday cup (extracted beam) to the ILC02 cup (injected beam) to measure the injection and acceleration efficiency, at around 20 to 35%. Typical 1st harmonic ECR2 beams gave 10 to 15% throughput. The throughput for the 3rd harmonic beams averaged 1% or less, they will require more attention in the coming year. Because of the operational limits of the RF system, which is 5.6 – 16 MHz, above 6.3 AMeV the cyclotron runs in the first harmonic mode, and below 5.6AMeV it operates in the 3rd harmonic mode; there exists an energy gap between 5.6 and 6.3 AMeV for the cyclotron.

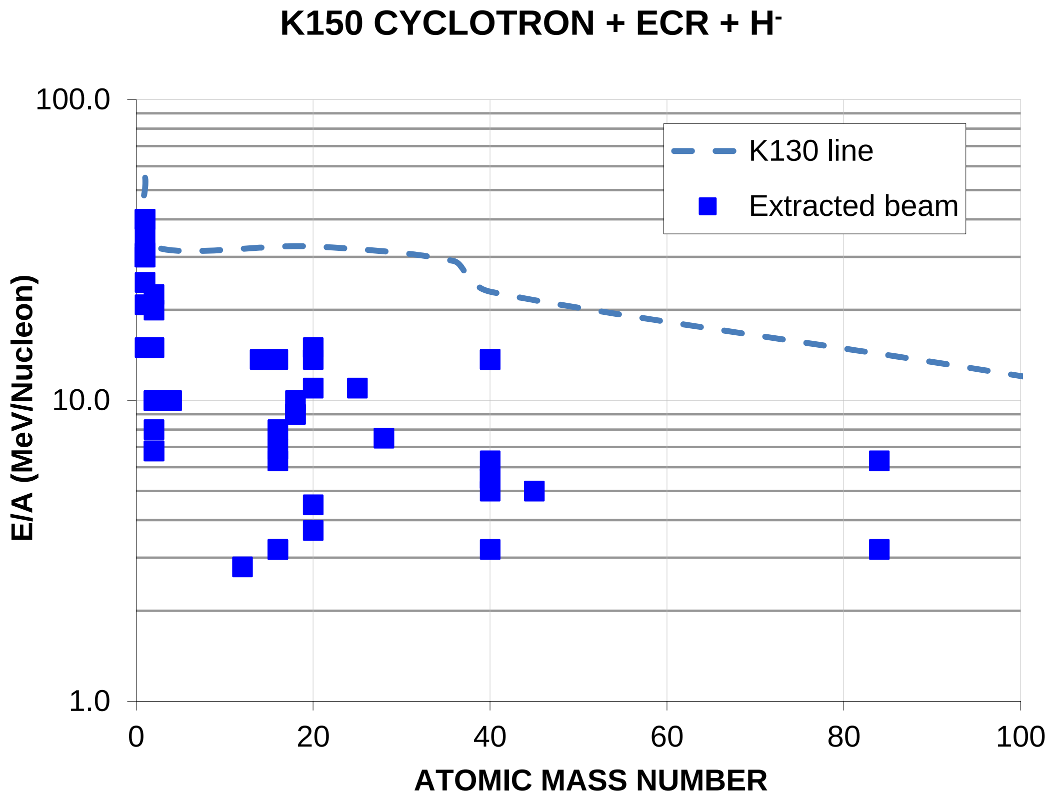

FIG. 1. Extracted beams from the K150 cyclotron with H^- and ECR2 sources since December 2009.

New K150 Beam Line for STAR/LIBERACE

We described in our last progress report the re-configuring of the old ion interaction beam line into cave 4 for the STAR/LIBERACE experiments. They ran seven times in 2012, using five proton (24 to 39 MeV) and deuteron (13 MeV) beams with the H^- source in the spring and summer, and two ECR2 beams, a 40 MeV helium and a 33 MeV carbon beam in the fall. For each run, the experiment lasted about a week and the source and cyclotron were stable for the duration of the experiment. The new beam line to the experiment worked well. However, the experimental requirement for a tiny beam spot with a moderate beam divergence at the experiment's target meant using very tight object slits which resulted in throwing away more than half of the extracted beam at the FC02 beam box. Furthermore, the momentum slits following the analyzing magnet were also narrowed to produce a clean, small beam spot, resulting in more beam losses. However, for the proton and deuteron beams there was enough beam current from the cyclotron to deliver a few nA to the experiment.

H- Ion Source Improvement

A 20 degree tilt has been added to the beam line below the H$^-$ source. The tilt prevents dust from the filament from making its way through the extraction hole and to the cyclotron inflector. Previously a build up of dust would eventually cause an electrical short and the inflector would need to be pulled and cleaned. A bending magnet was added at the 20 degree bend (see Fig 1) to steer the H$^-$ beam to the cyclotron inflector.

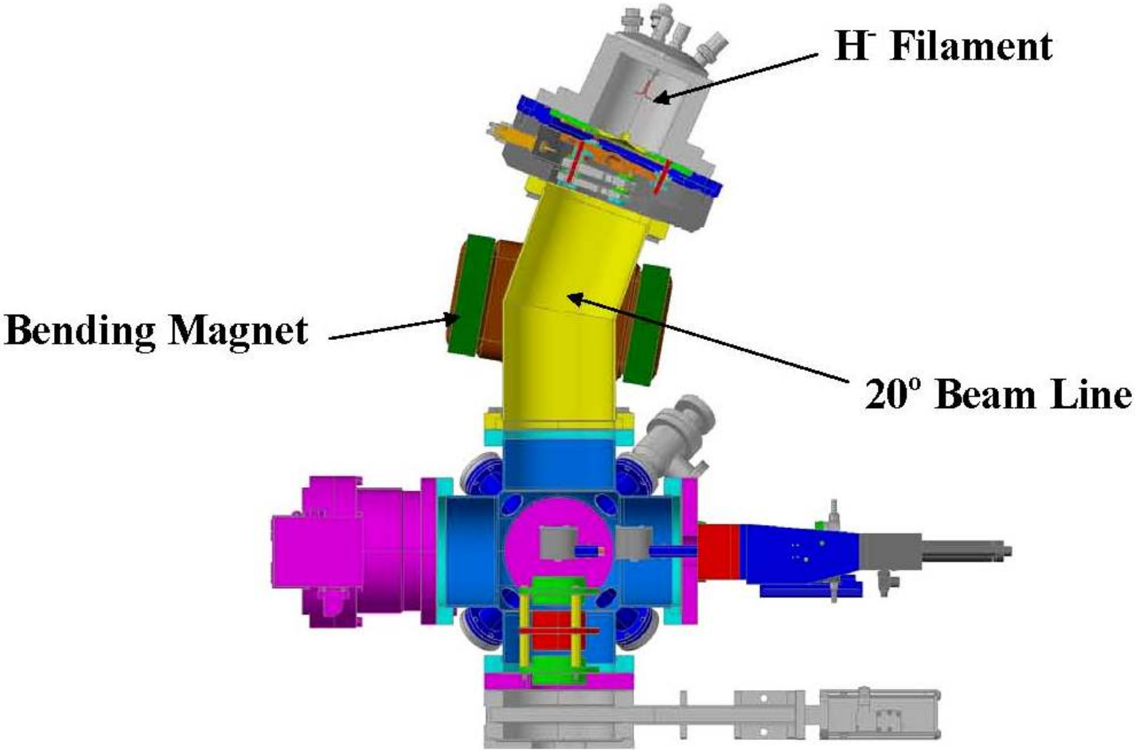

FIG. 2. A 20 degree tilt has been added to the beam line below the H$^-$ source. The tilt prevents dust from the filament from shorting the cyclotron inflector. A bending magnet was added to steer the H$^-$ beam to the cyclotron inflector.

13.7 AMeV40Ar Beam Development

Developing an intense 13.7 AMeV40Ar beam is important for the heavy ion guide program and we have worked on this beam from time to time throughout 2012. Initially the Ar beams ran as internal beams without extracting them because the required deflector voltage was higher than it could hold at that time. Using mainly $^{40}Ar^{14+}$, we sought to optimize the cyclotron tune for beam transmission and also to assess the vacuum attenuation for the argon beam (as compared to lighter ion beams such as ^{14}N or ^{16}O). Finally in December 2012, after spending a week of conditioning the deflector, we were able to sustain 88 kV on the deflector and extract the 13.7 AMeV $^{40}Ar^{14+}$ beam. We obtained 11 pnA on FC02 from 340pnA on ILC02, for a 3% throughput. Since a very similar charge-to-mass $^{14}N^{5+}$ beam at the same energy was obtained at 5% throughput, this comparison pointed out the importance of having a better cyclotron vacuum for running heavier beams. In addition to a better vacuum with the installation of cyropanels in the near future, we anticipate increased argon beam currents from the ECR2 ion source using the two frequency heating (Fig. 3) and a better cooling on the plasma chamber. Also, changing to a spiral inflector and increasing the source voltage (and also in turn the inflector voltage) will probably be necessary to reach the 900 pnA intensity goal for this beam.

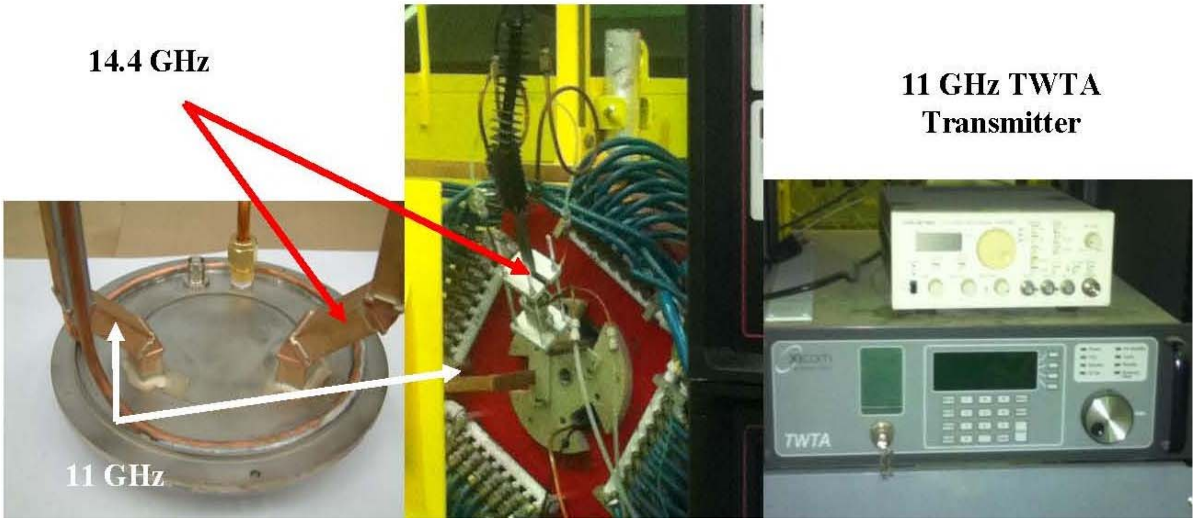

FIG. 3. Dual frequency heating system for ECR2. A new back plate has been built and installed to accept dual wave guides from both (11 GHz and 14.4 GHz) transmitters.

Third Harmonic Beams

Below 5.6 AMeV, the beams are accelerated in the third harmonic mode for the K150 cyclotron. We have worked to develop 2.5 to 5.5 AMeV for ^{12}C, ^{16}O, ^{20}Ne, and heavier ^{40}Ar, ^{45}Sc and ^{84}Kr beams. The throughput for the third harmonic beams has been poor, only 1%, as compared with 10-15% for the first harmonic beams. While we expected a smaller throughput for the 3rd harmonic beams because of a tighter RF acceptance and also a larger vacuum attenuation effects for slower beams, nevertheless the 1% throughput has been disappointing. There were several difficulties for running the 3rd harmonic beams. Initially, it was difficult just to keep the RF on, especially for the 15 MHz and higher frequency beams, but after conditioning the RF for long periods this problem has mostly dissipated. It did not help that a 3rd harmonic beam seems to need about 30% higher dee voltage than if it ran as a 1st harmonic beam. (This also means that for 3rd harmonic beams the number of turns in the cyclotron is 23% less than first harmonic beams, or about 250 to 300 turns.) Next, it was found that the beam tune was very sensitive to various cyclotron parameters such as the dee voltage and the main magnet and trim coil settings, much more so than the 1st harmonic beams. Often a small change of 1-2 A on a trimcoil was enough to destroy the beam tune. Despite not having the most efficient beam tune, several 3rd harmonic beams, such as 2.8 AMeV ^{12}C^{4+}, 4.5 AMeV ^{20}Ne^{6+}, and 5.5 AMeV ^{40}Ar^{11+}, were delivered for experiments. The beam with the best throughput so far has been a 5.0 AMeV ^{16}O^{5+} beam, which achieved 3% (1.3 out of 45 μA), helped in part by the new grid on the inflector and optimized position of the inflector height in Mar. 2013. However, in tuning with ^{16}O^{4+} at the same energy a few days later, with the main magnet raised about 300 A above the ^{16}O^{5+} setting, the throughput for ^{16}O^{4+} did not match that of the ^{16}O^{5+} beam. This again showed how difficult it is to tune the 3rd harmonic beams. But, we expect these 3rd harmonic beams will improve in the future with further experiences in beam tuning and improved cyclotron vacuum after the installation of the cryopanel.

CYDE and Beam Tuning

For a given beam, tuning the K150 cyclotron involves setting 18 parameters: the main and 17 trim coils. (The RF frequency is another parameter, but it is basically fixed by the energy of the beam.) These parameters are calculated with the help of the CYDE program. We had successes with CYDE solutions, but as it was mentioned in the last year's progress report, for some beams the solutions did not fully work. And without varying some trim coil values (from the original CYDE solution), especially the TC13, TC14 and TC15, some beams could not be accelerated out to the extraction radius. For some of those beams the adjustments to the TC14 and TC15 were substantial, as much as several hundred amps from the initial CYDE solution. Having to vary the trim coil values seemed to indicate some underlying problems with the field maps used by CYDE. CYDE references a set of old field maps of Berkeley's 88" cyclotron in its calculations, and while our cyclotron is a close copy of Berkeley's, it may not be surprising that the CYDE maps do not quite work for our cyclotron. To get a better understanding of the cyclotron field and to independently test the CYDE maps, the cyclotron was modeled with the TOSCA program. Fig. 4 shows a comparison of the CYDE maps with TOSCA calculations at 765, 1120, 1470, and 1840 A on the main coil (with all the trim coils turned off). The overall agreement is quite good,

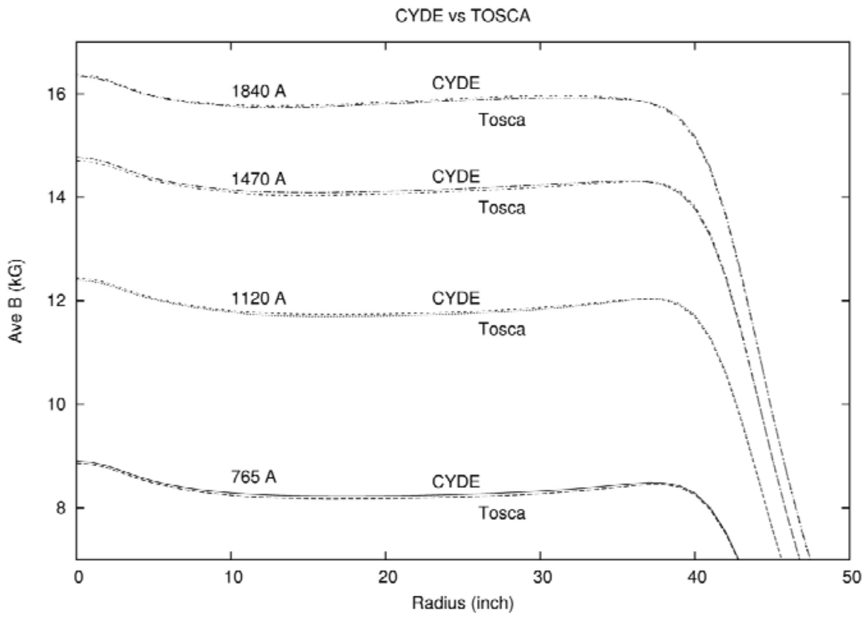

FIG. 4. Comparison of CYDE fields and TOSCA calculated fields at 765, 1120, 1470, and 1850 A on the main coil.

however upon a closer look, for example at 1120 A as shown in Fig. 5, especially around r=10 – 30”, the TOSCA calculated field is about 40 gauss less than the CYDE. The absolute value of the TOSCA field is of secondary importance since the main magnet can always be tuned a few amps higher, however, the difference in the field profiles between the CYDE and TOSCA is significant. The actual TOSCA calculated field was slightly rescaled from the original calculation (by 0.999) to get a better agreement with CYDE near 36” in Fig. 5. If we assume that the TOSCA calculations are true (or closer to the true cyclotron field than the CYDE maps), then the difference in the field from CYDE to TOSCA must be made up in order for the beams to be properly accelerated in the cyclotron, since CYDE calculations

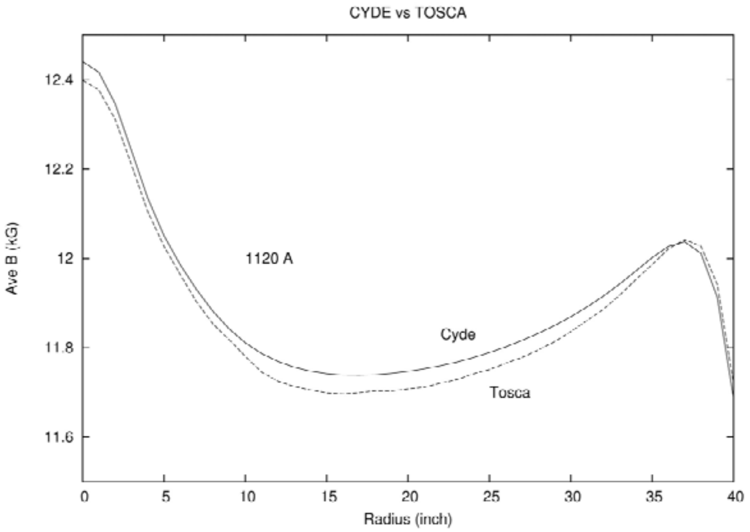

FIG. 5. CYDE has overestimated the field for the region from 10” to 30” by about 40 gauss as compared with TOSCA calculations.

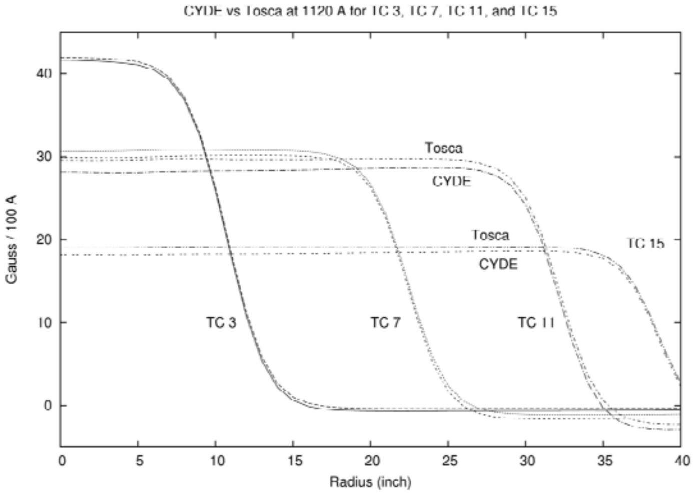

FIG. 6. Field profiles of several trim coils at 1120 A on the main magnet.

determine the necessary cyclotron field for the proper acceleration. The deficit in the CYDE field, about 40 gauss in r=10-30 for the 1120 A case, can be made up by using the trim coils. The field profiles of several trim coils are shown in Fig. 6. The trim coil fields were also modeled with TOSCA, and the differences between the TOSCA calculations and the CYDE maps for various trim coils were only a few gauss. The Trim Coil 13, which contributes about 18 gauss per 100 A (at 1120 A on the main magnet) and effective up 35", would be a good candidate to use to compensate for the CYDE field deficit. With 200 A on the Trim Coil 13 added to the TOSCA field, the overall agreement with CYDE is much better as shown in Fig. 7. Probably there are many other ways to make up for the CYDE field deficit using different groups of trim coils. In practice, we had some successes in tuning the beams using 100 to 200 A more positive on Trim Coil 14and about 50 A more positive on Trim Coil 7. The positive polarity refers to the field direction in the same direction as the main magnet (when accelerating the normal positive ion beams). Therefore running the TC 7 and 14 positive means that these trim coils add to the main coil field, which is the field correction that is predicted by the TOSCA analysis. Incidentally, running TC 13 instead of TC 14 was tried for a couple of beams and the beams did accelerate out to the extraction radius and were extracted to FC02, however using TC 14 gave slightly better results so far. Perhaps some combination of TC 13 and 14 might even work better in the future. However, at this time it is gratifying just to know the underlying reason for using an additional 200 A on TC 13 or 14.

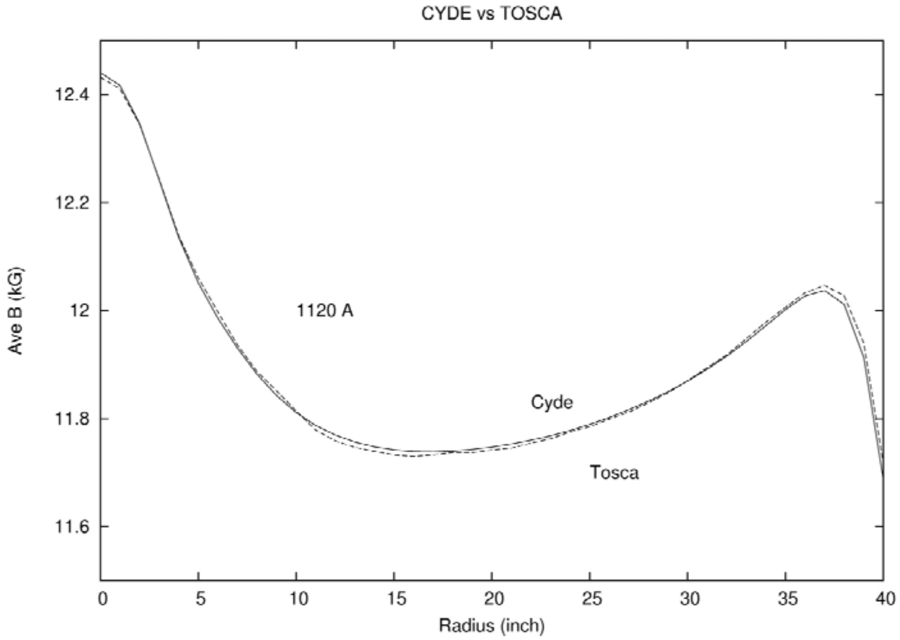

FIG. 7. Comparison of the CYDE field with the combined field of the TOSCA and 200 A on TC 13.

K150 Vacuum System

The dee tank will be equipped with one internal liquid nitrogen (LN2) cryogenic panel. As shown in Fig. 8, the panel will be placed as close to the central region of the cyclotron as possible where transmission losses from poor vacuum are the greatest. The panel system has been designed to accept liquid helium (LHe) as well. The high vacuum system will provide a vacuum pressure of low 10^{-7} torr for intense heavy ion beams.

In March 2009, a used CTI 1400 20 liters/sec LHe refrigeration system was obtained from HARC (Houston Area Research Center). After it is refurbished by the Cyclotron staff, this unit could be used to feed LHe or cold He gas to the cryopanel system of the K150 cyclotron. All internal pieces have been fabricated and the plan is to have the cryopanel installed and tested with LN2 by the end of June 2013. LHe or cold He gas will be added later in the project.

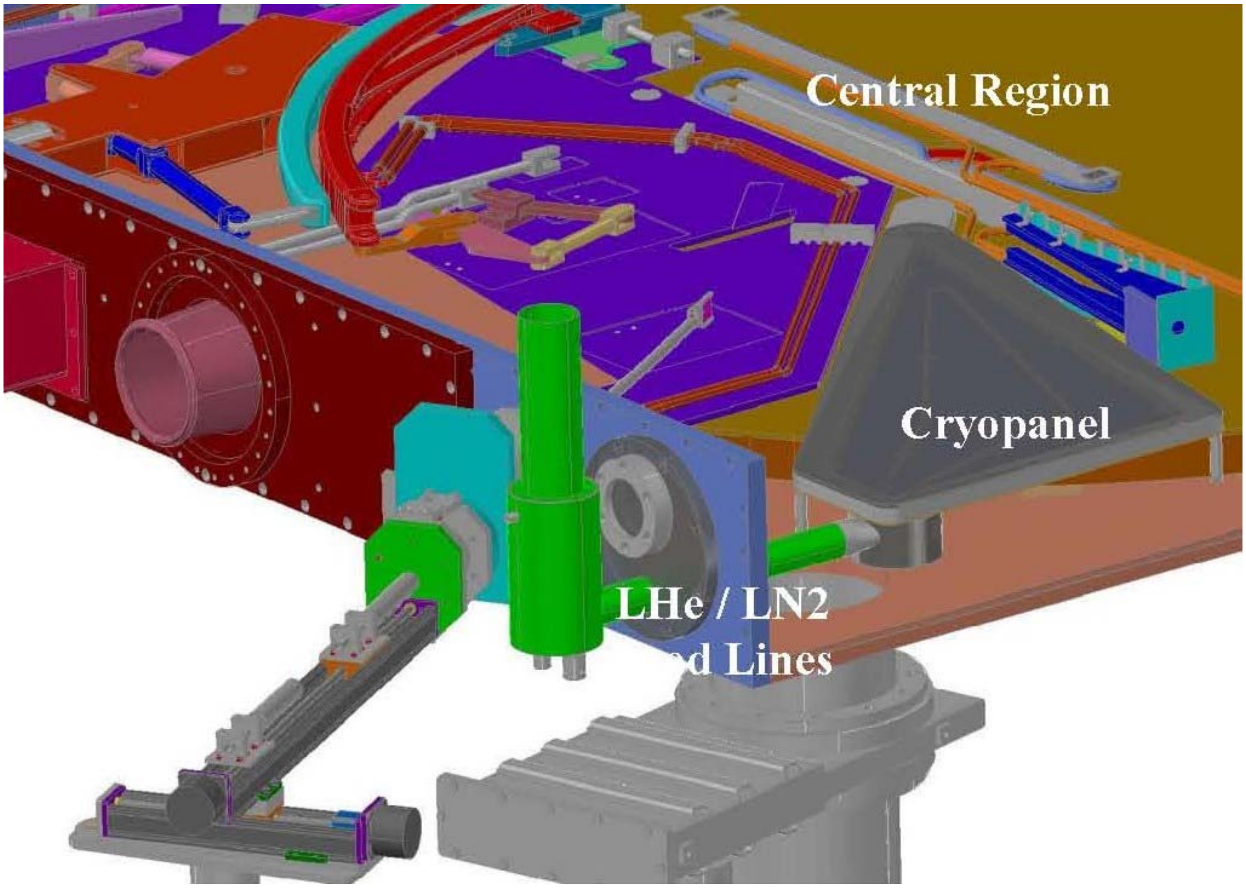

FIG. 8. Position of the LHe / LN2 cryopanel in the dee tank. The tip of the panel is placed close to the central region of the cyclotron where transmission losses from poor vacuum are the greatest.

Light Ion Guide

The tubes connecting the 3x tier roots blower system to the light ion guide chamber were installed (Fig 9) and the Light Ion Guide HV platform was tested up to 8 KV.

FIG. 9. The tubes connecting the 3x tier roots blower system to the light ion guide chamber have been installed and the Light Ion Guide HV platform was tested up to 8 KV.

The light ion guide gas cell and SPIG assembly were connected to the CB-ECR ion source as shown in Figure 10. Following the gas cell is a 1 meter long SPIG, then a 30 cm February 2013, the SPIG/Einzel transport system was tested and optimized with the ^{228}Th radioactive source positioned in the gas cell. The products from the ^{228}Th source were successfully transported from the gas cell and into the CB-ECR ion source with 99% transport efficiency. However due to the low intensity of the daughter products (20 pA), the daughter products were not charge bred and injected into the K500 cyclotron. Beam induced 1+ ions will be transported next and finally, radioactive ion products created from the gas cell.

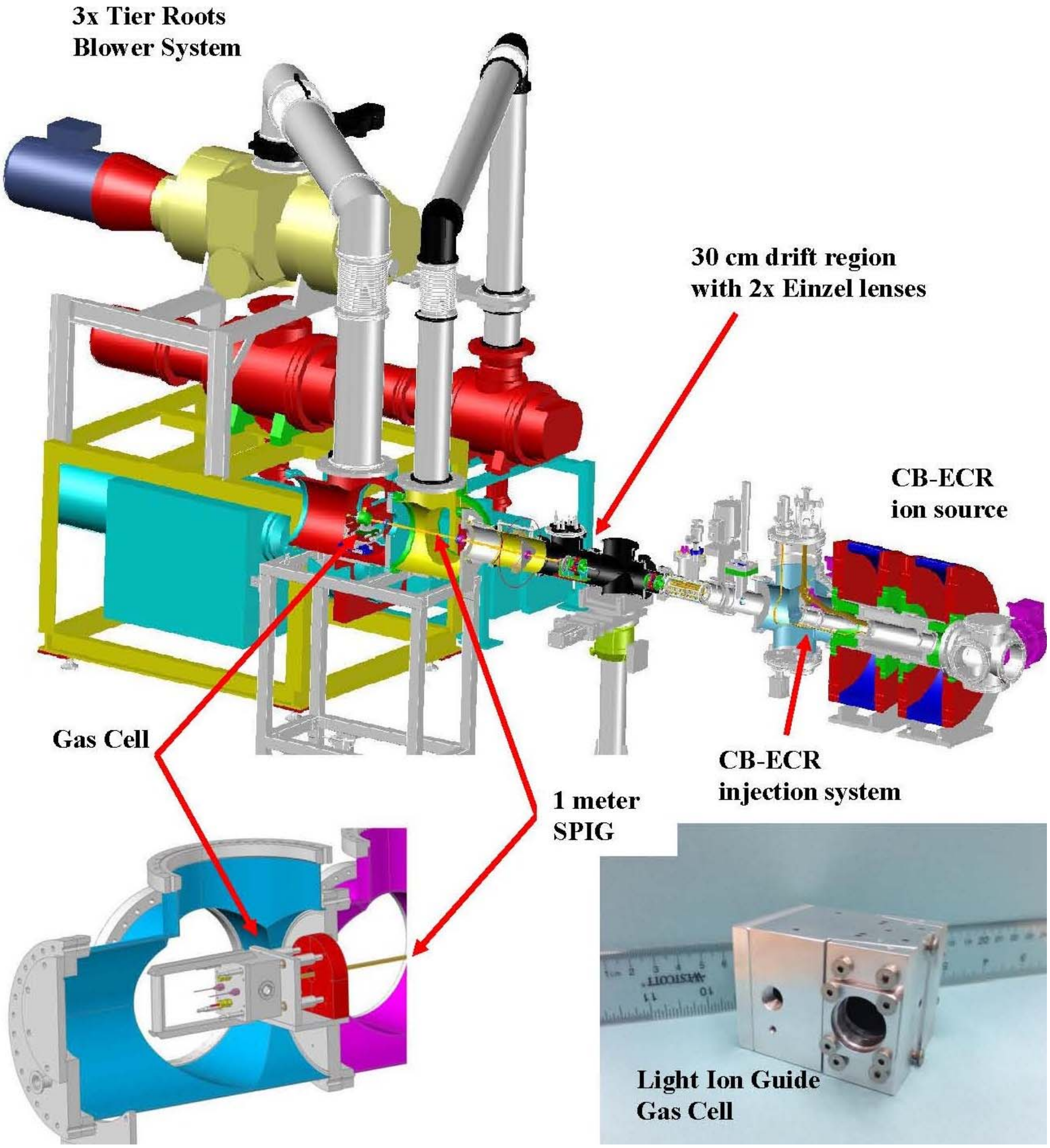

FIG. 10. Light ion guide system assembly. Following the gas cell is a 1 meter long SPIG, then a 30 cm drift region with two Einzel lenses before the injection system of the CB-ECR ion source.

Heavy Ion Guide

The Gas Catcher has been completely assembled including the Cone and the three Body sections (Fig 11). The vacuum box and support stand are under construction. The gas catcher will be moved to TAMU in June 2013 after the vacuum box and stand are completed (Fig 12). The chamber for the Branching System has been delivered and internal components are built (Fig 11). Beam optics components including Einzel lenses and X-Y steering elements are completed.

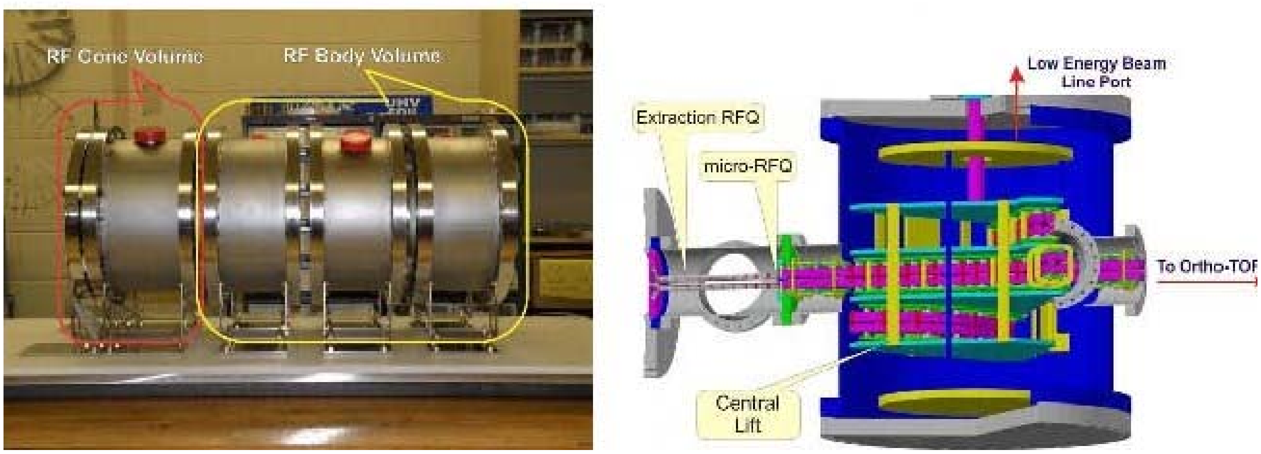

FIG. 11. Left: Gas catcher is complete and ready to be transported to TAMU. Right: Branching system chamber has been received and the internal components are built.

FIG. 12. Left: The vacuum box for the gas catcher is under construction and nearly finished. Right: The support stand is finished and ready for the vacuum box.

Big Sol Rebuild

Big Sol has been repaired, tested and is ready to be moved from Cave 2 over to the K150 Cyclotron vault on the heavy ion guide beam line. The problem of the frozen internal LN2 lines has been resolved. The solution involved rerouting the entry point of the LN2 feed to the body of the cryostat (Fig 13). To make the repair, a hole was cut in the side of the outer vessel of the chimney, lines cut and rerouted. The cryostat was filled again and LHe consumption was measure to be less than 2 liters per hour which is 5 times better than before the repair. Cryogens were flowed through the cryostat for two weeks to ensure that the repair was true.

FIG. 13. Left: Outer heat shield around body of Big Sol (note: the chimney is not installed in this picture). Right: LN2 is fed from above and originally looped around the chimney before branching off to the body. The repair redirected the feed directly to the body as shown by the white arrow.

CB-ECR Ion Source

In early fall of 2012, charge breeding of Rb was first demonstrated by the ion source. The breeding efficiency was measured to be low at ~2-5% and improvements were made to the injection scheme.

The first improvement involved adding a tube (Fig 14) at the entrance of the Einzel lens. With the tube in place, we observed a large improvement in the transport of injected ions through the plasma chamber (plasma not ignited). The tube helped to shield the ions from the non-symmetric electrical fields generated by the gas line and other pieces along the injection region.

The second improvement involved blocking the microwaves from the plasma chamber from back streaming through the injection hole and into the injection region. We observed a large improvement by adding a wire mesh over the injection hole of the plasma chamber. The mesh continued the electric field of the plasma chamber and deflected the microwaves from entering the injection region. A third improvement involved replacing the entrance microwave plug with another one, having a bigger opening (3/4”). The transport efficiency was found unchanged however we observed charge breeding for the first time after all three improvements were made.

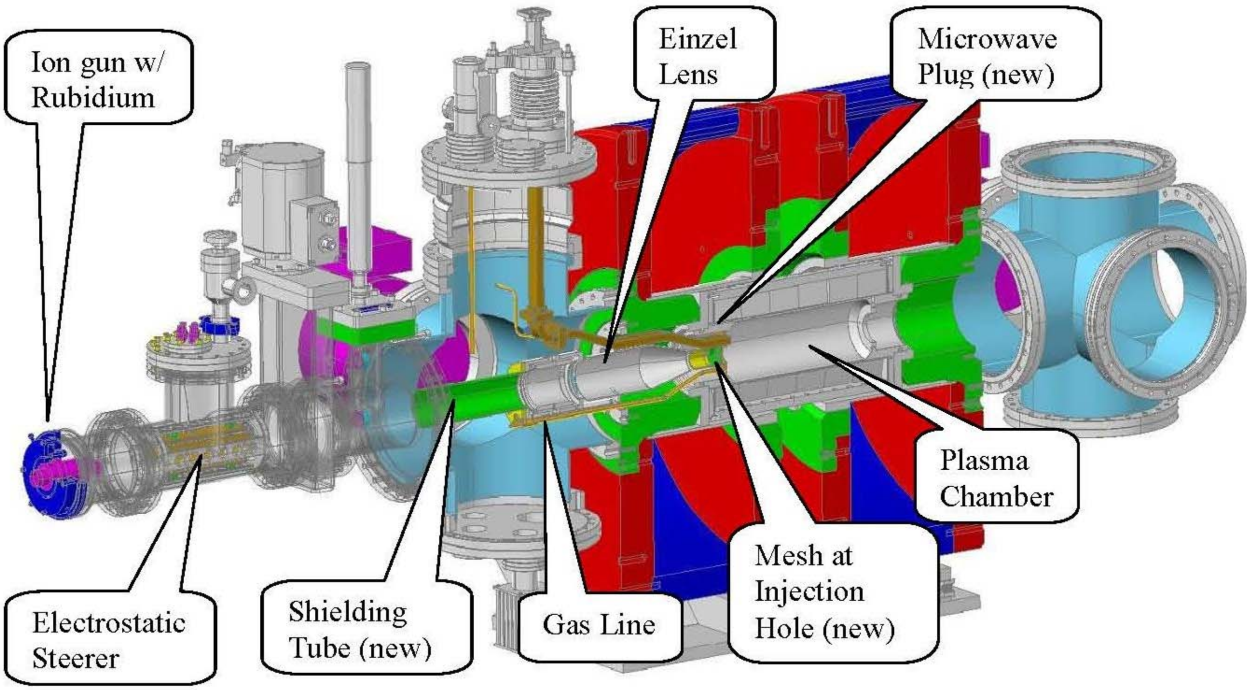

FIG. 14. View of the CB-ECR showing the new tube insert.

In December 2012, after further tuning we were able to find better operating conditions and the charge breeding effect was more pronounced. Charge breeding was also demonstrated with different 1+ sources including with Rb and Cs (Fig 15). One puzzling effect was that the breeding efficiency of Rb was found to be under 10% but was measured to be much higher for Cs at 80% or greater. It is possible that the Faraday cup at the entrance of the CB-ECR ion source was not measuring the current properly and will be studied further.

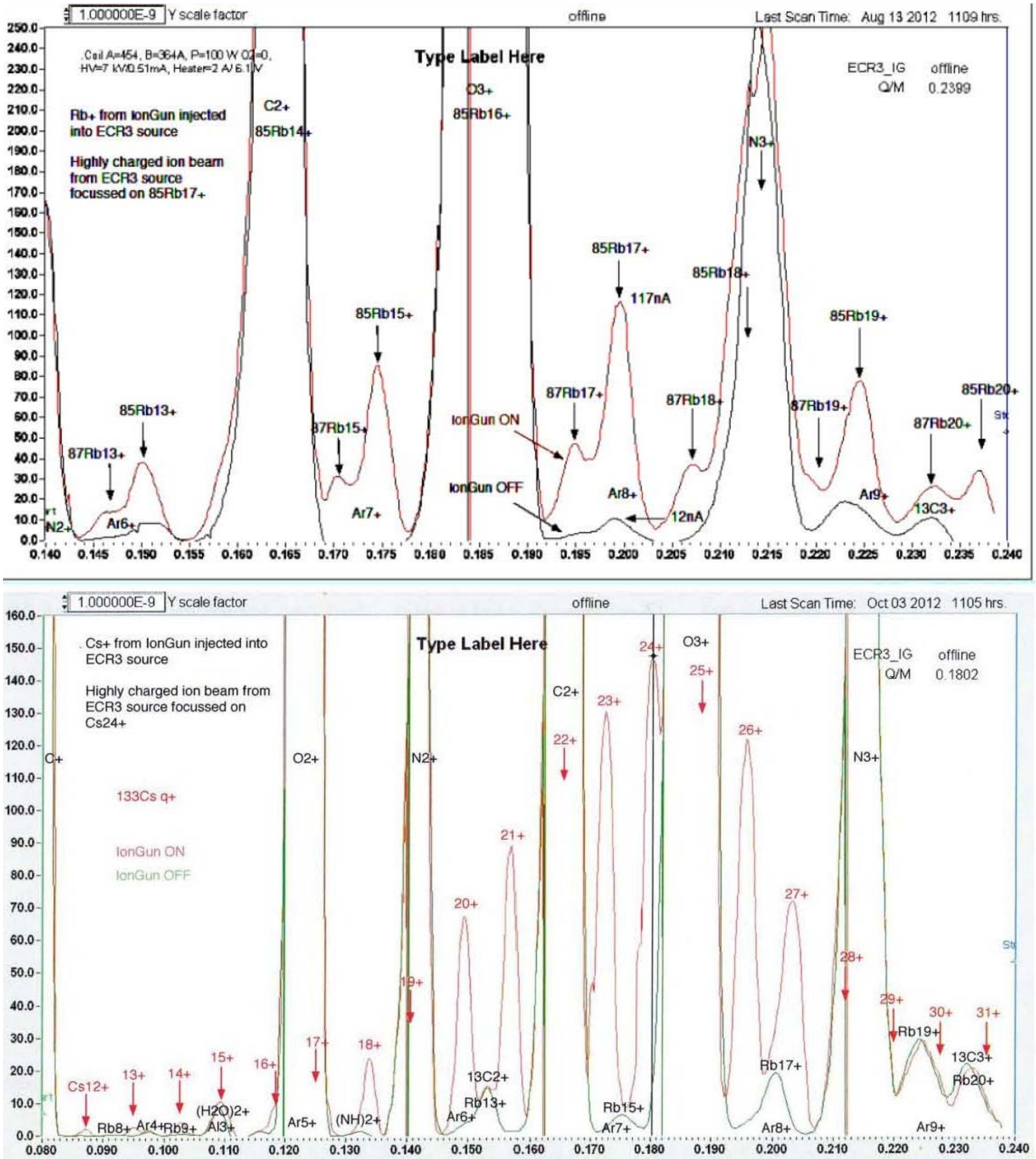

FIG. 15. Charge breeding analysis of Rb (above) and Cs (below) with the CB-ECR ion source. The total breeding efficiency of Rb was found to be <10%, which for Cs was found to be ~80%.

n+ Transport System

With the n+ transport system fully assembled, the computer control system was completed and the injection line was tested with the charge bred beams from the CB-ECR ion source then accelerated in the K500 cyclotron and extracted. The throughput from the exit of the CB-ECR ion source to the exit of the K500 cyclotron was measured to be as high as 13.8% (Table I).

Table 1. Charge bred ions transported by the n+ transport system and accelerated by the K500 cyclotron. Throughput was measured to be as high as 13.8%.

Ion	**Beam Energy (MeV/u)**	**Extracted Current from K500 (nA)**	**Throughput – from CB-ECR to K500 (%)**
85Rb15+	10 MeV/u	4.0 nA	13.8 %
85Rb17+	15 MeV/u	6.4 nA	10.0 %
133Cs24+	10 MeV/u	14.0 nA	12.9 %