

## 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 2013. When completed, the upgraded facility will provide high-quality re-accelerated secondary beams in a unique energy range. 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,

- Construction of internal cryopanels for the K150 high vacuum system and
- Development of high energy proton, deuteron beams and heavy-ion beams.

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, restart of the CB-ECR ion source,
- Construction of the Heavy Ion Guide gas cell and transport system, and
- Assembly and installation of the n+ transport system. Below we report on a few of the accomplishments listed above.

### K150 Cyclotron Development

After the successful acceleration and strip extraction of the first H- and D- beams last year, we have extended the range of energies for H- and D- beams, and after repairing the water leak on the deflector we have also accelerated and extracted several positively charged beams.

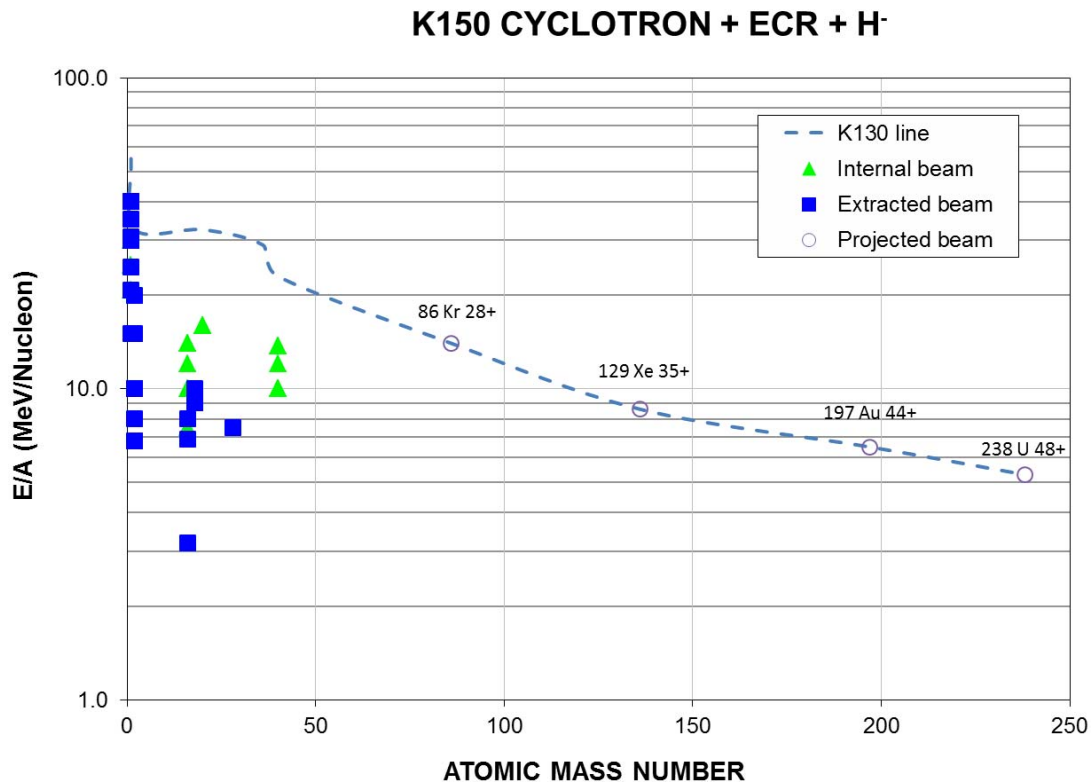
The energy range achieved for protons from H- acceleration is from 15 to 40 MeV, and for deuterons from D- acceleration is from 6.5 to 20 AMeV. We worked on 20 AMeV D- beam last year, but had trouble extracting it. This year we were able to extract the beam by more aggressively varying some of the trim coils from the CYDE calculated values. The differences in 3 trim coils (out of 17) from the CYDE values to the final tuned values ranged from 130 to 430 amps. These differences may indicate some problems with the CYDE field maps. However, we do not want to abandon CYDE, it is certainly good enough to find the beam at inner radii of the cyclotron. So for the near future, we will need to tune the beams with the idea that some trim coils may be adjusted as much as a few hundred amps from the CYDE trim coil values.

For the positively charged beam accelerations, we have so far worked mostly with light ion beams: 7 and 8 AMeV  $^{16}\text{O}^{6+}$ , 9 AMeV  $^{18}\text{O}^{7+}$  and 10 AMeV  $^{18}\text{O}^{8+}$ , and 7.5 AMeV  $^{28}\text{Si}^{9+}$  beams. The RF dee voltage ranged from 30 to 40 kV and the E1 deflector needed from 46 to 56 kV to extract these

beams. The extraction efficiency was better than 65% for all these beams. The deflector will need to be conditioned for higher voltages in order to extract higher energy beams.

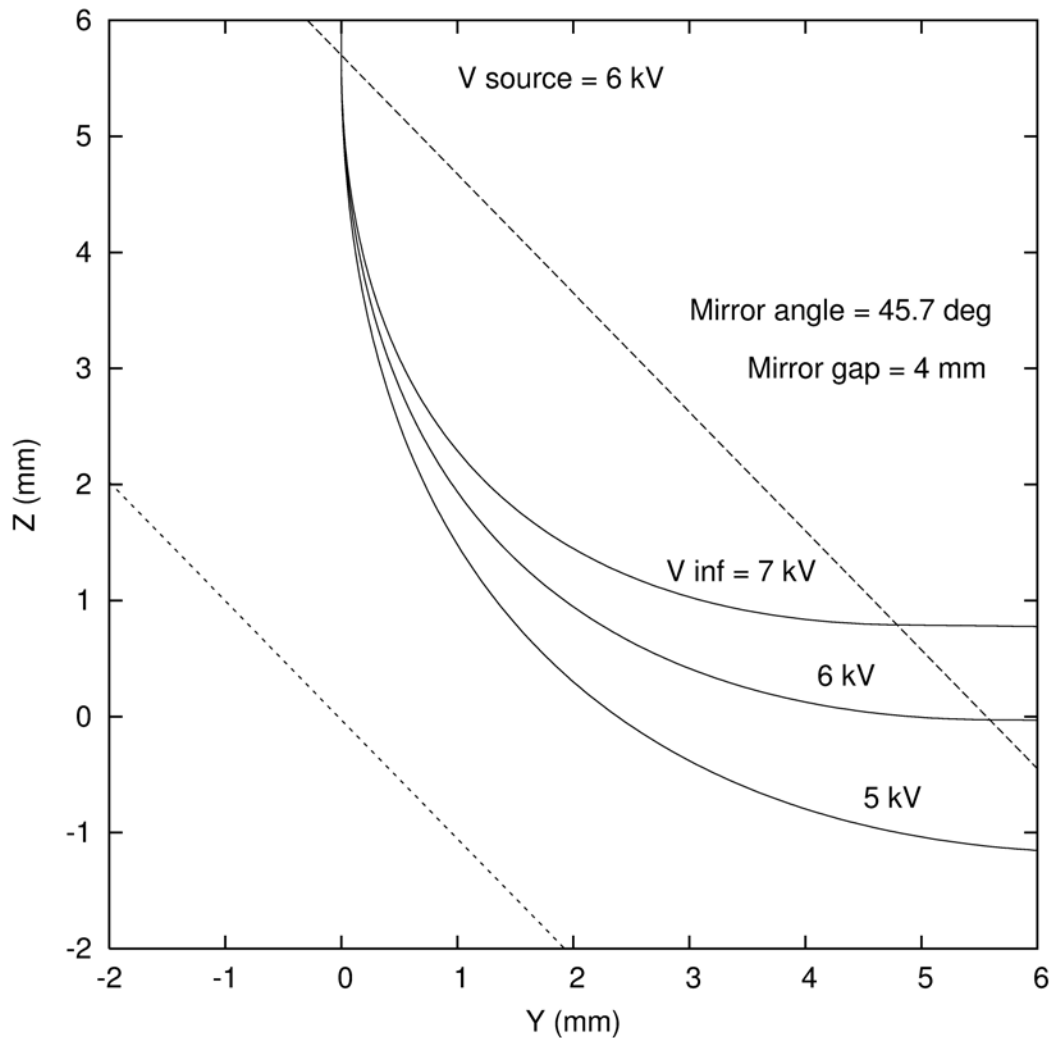
We have also worked on a few third harmonic beams, but we have not had much success in developing them. One experiment requested a 5 AMeV  $^{40}\text{Ar}$  beam, but because the beam orbital frequency turned out to be below our RF frequency range, it was tried as a third harmonic 15 MHz beam. At this high frequency, conditioning the RF dee was found to be very slow and difficult. After several days of conditioning the dee, the voltage was not high enough and the injection into cyclotron was poor and ultimately the beam could not be extracted. Then, shifting to a lower energy and hence to a lower frequency, we were able to accelerate and extract a low energy third harmonic beam, namely 3.2 AMeV  $^{16}\text{O}^{4+}$  beam at 12 MHz. However, this beam will need much more work to improve the beam intensity, as the injection into the cyclotron and the internal transmission of the beam was poor.

We have also begun development for the 13.7 AMeV  $^{40}\text{Ar}^{13+}$  beam in the anticipation of the heavy ion guide program. We have accelerated  $^{40}\text{Ar}^{13+}$  ions to 10 and 12 AMeV, and  $^{40}\text{Ar}^{14+}$  to 13.7 AMeV, but they were not extracted. The needed deflector voltages to extract the beams were beyond what the deflector could presently hold. Typically the injection efficiency from ILC02 into the cyclotron (as measured at 6" on the beam probe) was only about 10%, and the internal transmission from 6" to 39" was 70%. To get to the beam intensity goal of 0.9  $\mu\text{A}$  on FC02, it is obvious that the ECR2 output must be increased by employing two frequency heating, the cyclotron vacuum must be improved, and the deflector must be conditioned to hold high voltages. Fig. 1 shows all the beams, both internal and extracted, that we have run since Dec. 2009, after the installation of the dee inserts.



**FIG. 1.** Beams that ran on the K150 cyclotron with H<sup>-</sup> and ECR2 sources since Dec. 2009.

Comparing the throughputs (ILC02 to FC02 transmission) of the H- beams and the ECR2 beams, it is clear that H- beams have much better throughputs, getting about 30% for the H- beams, 15 to 20% for D-, and 10 to 15% for the ECR2 beams, all with the first and second harmonic bunchers turned on. In a direct H- versus ECR2 test, with the cyclotron set for 25 MeV acceleration for 1H- and proton, for the H- beam up to 50% of the injected beam was measured at 10'' on the beam probe, whereas only 10% of the injected H+ was found on the beam probe. The internal transmission was about the same at 95% for both the H- and H+. (The H+ was not extracted.) The D- beams also had good injection efficiency of around 30 to 50%, but the internal transmission struggled from 30 to 60% for 6.5 to 20 AMeV accelerations. The obvious difference between the H- beams and the ECR2 beams is the emittance. The H- beams enjoy much a smaller emittance and a smaller beam spot on the inflector.



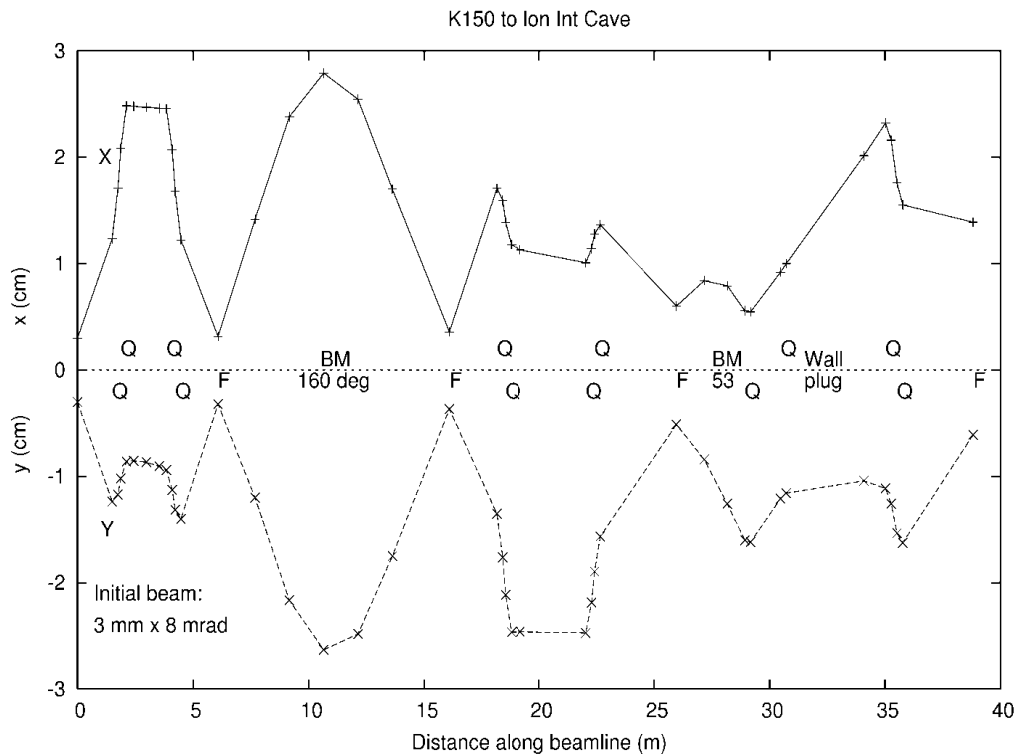
**FIG. 2.** Y-Z projection of a vertically injected particle through the mirror inflector. The dashed lines represent the grounded grid on the top and the HV electrode on the bottom. The three curves show the trajectories from three different inflector voltages.

The mirror inflector gap, from the electrode to the grounded grid, was increased from 1 mm to 4 mm in April 2012, and this has helped to increase the beam injection into cyclotron by doubling the beam intensities for some beams. Because the gap widening was obtained by lowering the electrode while keeping the grid the same position, there are some concerns about the z position of the injected beam. Fig. 2 shows the importance of having a small spot at the mirror inflector. The finite extent of the beam spot at the inflector translates into the vertical size into the cyclotron. Thus, having a small emittance helps to achieve a small spot at the inflector and a small vertical size and a larger acceptance into the cyclotron.

We met the proton beam intensity milestone by transporting 10  $\mu$ A of 30 MeV protons into the Light Ion Guide cave in April, 2011. The beam transport efficiency was good (for a large emittance beam), transporting 91% of 11  $\mu$ A on FC02 into the LIG cave.

We transported a K150 beam into the MARS cave for the first time in Nov. 2011. The beam height of various magnets through the 12° dipole to the Indiana magnet, which bends the beams into the MARS spectrometer, needs to be re-aligned. One benefit that came from sending a beam to MARS was that using the calibrated MARS dipole the energy of the K150 beam was determined, and this in turn was used to calibrate the 160° dipole magnet.

We have also re-configured the old ion interaction beam line to accommodate the STAR/LIBERACE experiment staged in cave 4. We have of course had several K150 beam into the BM04 (the Maryland dipole), however the difficulty of this beam transport was with the steep 53 degree bending through the BM04, which produced asymmetric focusing for x and y, see Fig. 3. To partially



**FIG. 3.** TRANSPORT calculated X and Y beam profiles through to the newly re-configured Ion Interaction cave.

correct for this, we installed two separated quadrupoles just after BM04, first one to refocus the y side then to slightly focus x and also to parallelize the y side going into the cave. In the cave the experimenter's target was positioned about 3 m downstream of the last quadrupole doublet, in order to control the divergence of the beam through the target chamber. At the experimenter's target position the x-beam magnification is large, so in order to achieve a small beam spot the object slits need to be very small; while this reduces the beam, the experiment only needs a few of nA of proton or deuteron beams.

### Ion Guide Hall

All power supplies, transmitters, HV transformers, and control equipment for the Ion Guides, CB-ECR ion source and n+ transport system have been positioned above the roof planks of the ion guide hall (Fig. 4). The safety interlock system to protect the cyclotron personnel from electrical and radiation hazards posed by the CB-ECR ion source and high voltage platform have been installed and tested. Final coupling of the Light Ion Guide to the CB-ECR ion source is under development.



**FIG. 4. Left:** Equipment for the light ion guide shown positioned above the roof planks of the ion guide hall. Placement above the roof planks removes the equipment from the high radiation environment of the ion guide hall. **Right:** The three tier roots blower system and high voltage safety cage for the light ion guide system shown completed in the ion guide cave.

### Big Sol Rebuild

The repair of Big Sol involved a complete rebuild of the cryostat. The superconducting bobbin was the only original piece to be reused. In the spring of 2011, Big Sol was transported to a local machine shop and the cryostat was carefully cut open to remove the bobbin. The entire rebuild of the cryostat has occurred at the cyclotron lab.

Fig. 5 shows the original superconducting bobbin being fit into its new cryostat and the final assembly of Big Sol installed in Cave 2 and connected to its original cryogenics and power supply systems. The cryostat was cleaned with dry nitrogen gas and pumped down several times. The cryostat

was then cooled down with LN2 and finally filled with LHe from the cryogenics transfer system from the K500 cyclotron. Initial testing shows that the liquid helium leak rate has diminished substantially from the rebuild project.

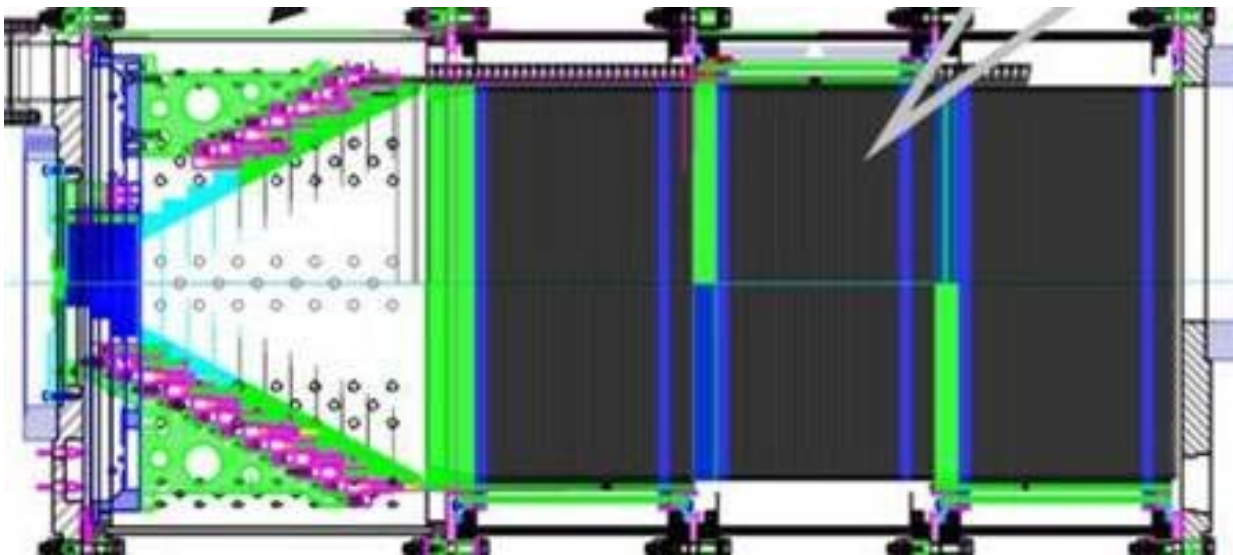
One problem that was found was the LN2 feed line freezes if the nitrogen liquid flow is stopped. The problem is believed to exist in the chimney where cold helium gas meets the LN2 lines and can be fixed by cutting into chimney and rerouting the LN2 feed lines.



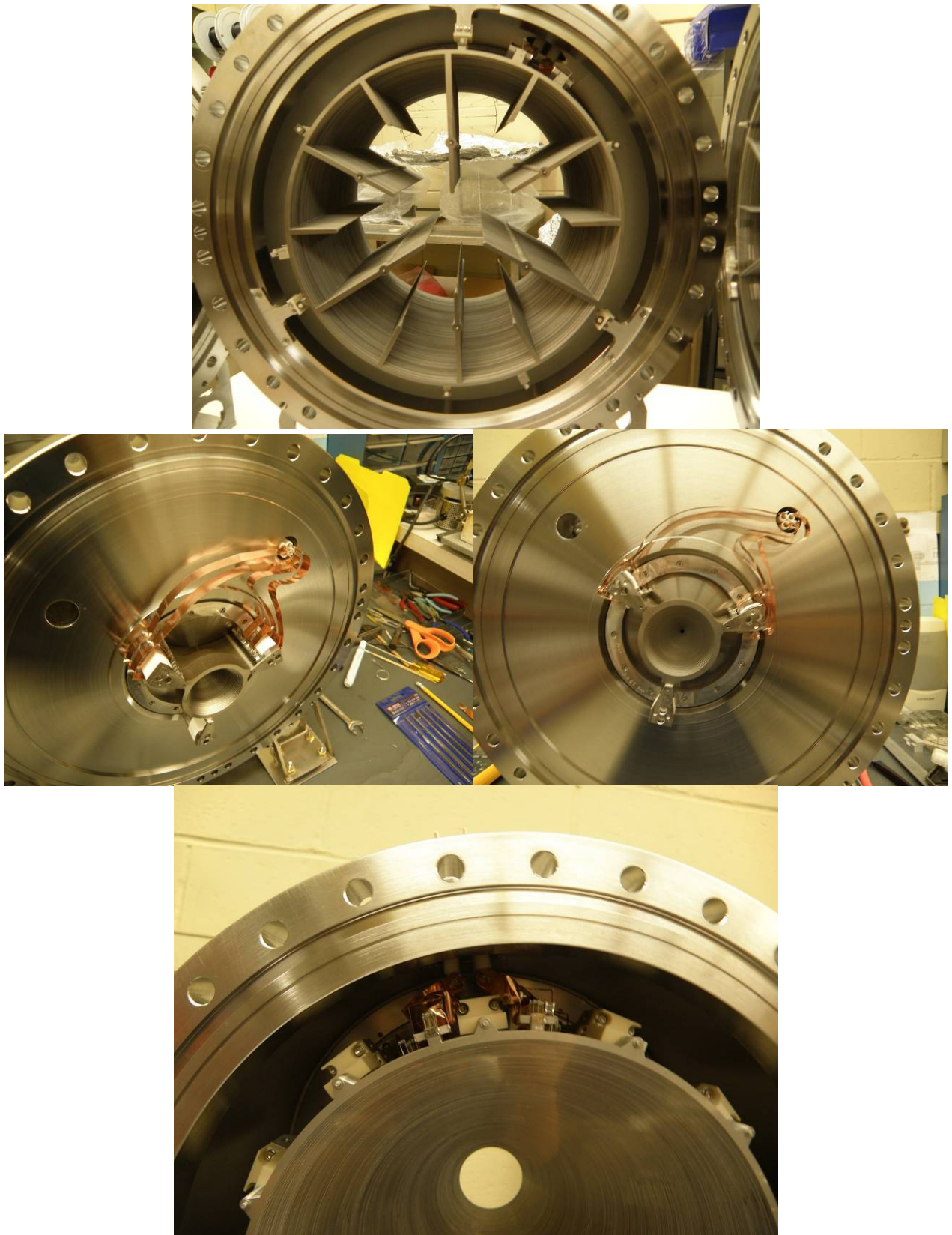
**FIG. 5.** Left: The original superconducting bobbin fit into its new cryostat. Right: Final assembly of Big Sol positioned back in its original location in cave 2 and reconnected with its original cryogenics and power supply systems.

### Heavy Ion Guide and Gas Cell

The Gas Catcher has been completely assembled including the Cone and the three Body sections. A diagram of the system is shown in Fig. 6. Pictures of the Body and Cone sections of the RF Gas



**FIG. 6.** Diagram of the RF gas catcher which includes the RF Cone and three Body Sections. The Cone, two Body sections and 1/2 of the third Body section have been assembled.

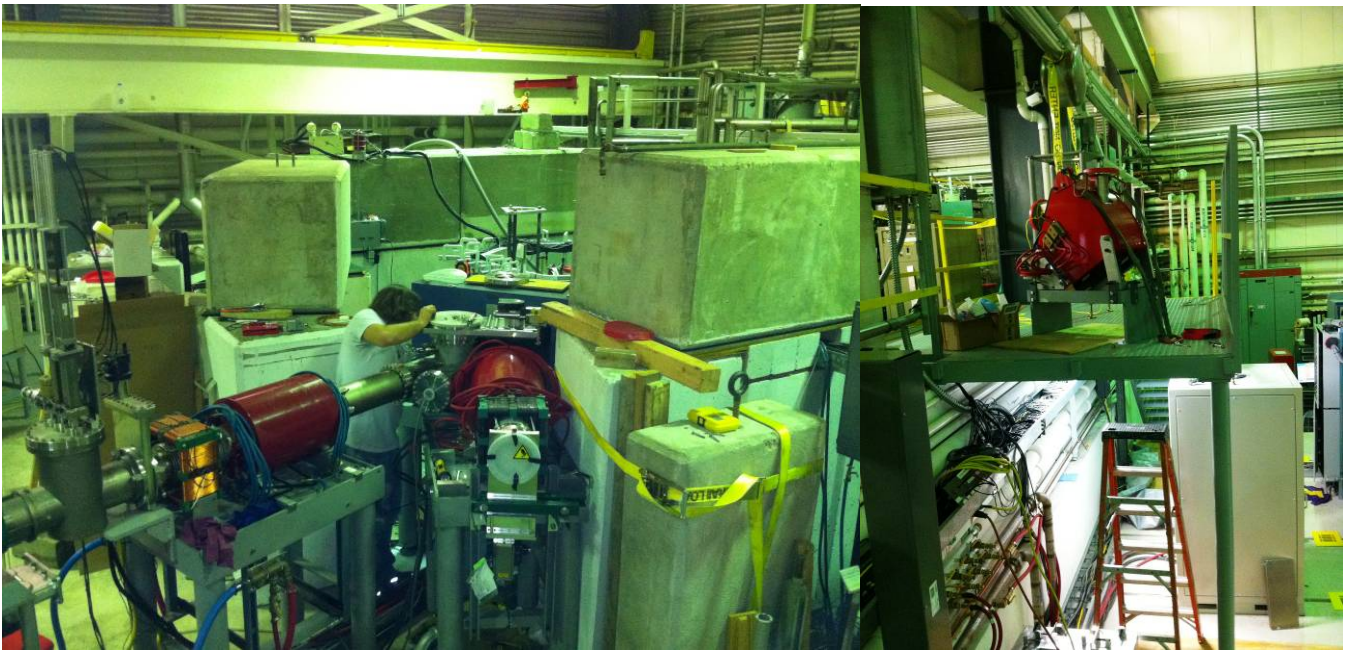


**FIG. 7.** Pictures of the Body and Cone sections of the RF Gas Catcher. Top picture: RF-Body section, Middle: Front part of the RF Cone, and Bottom: Main Part RF Cone.

Catcher are shown in Fig. 7. The entire gas cell assembly is planned to be moved to TAMU in the fall of 2012. The chamber for the Branching System has been completed and delivered. Beam optics components including Einzel lenses and X-Y steering elements are under construction. Preparation of the heavy ion guide cave is underway. The arch crane and flooring material for the HV platform have been installed.

### n+ Transport System

The section of the n+ transport system below the roof planks was installed in the fall of 2011. This section included a Glazer lens, x-y steering magnet, 90° analyzing magnet, two diagnostic stations, two cryopump systems and control system. Assembly of the section of the n+ transport system above the roof planks that connects the CB-ECR ion source to the top of the K500 cyclotron is underway. The radiation shielding around the top of the K500 cyclotron was removed during the January maintenance period and n+ Solenoid #5, new BM2 and new BM3 magnets were installed (Fig. 8). The remaining components are now being installed and the entire n+ transport system is nearly completed. Fig. 8 shows the installation of the n+ BM2 magnet and its support structure with staircase. The n+ transport system should be completed and tested with beams by the fall of 2012.

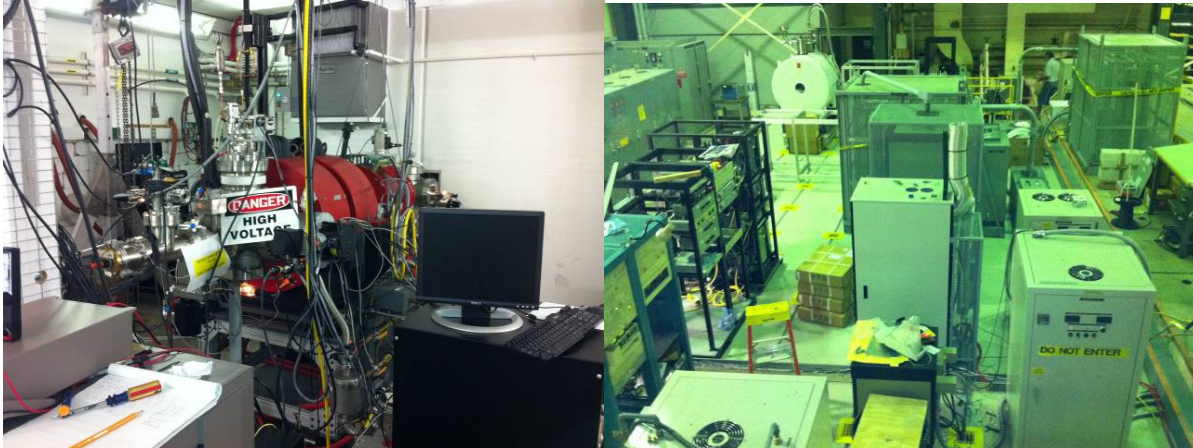


**FIG. 8. Left:** The construction of the horizontal section of the n+ transport system that connects the CB-ECR ion source to the top of the K500 cyclotron has begun with the placement of the N+ Solenoid #5, new BM2 and new BM3 magnets. **Right:** The installation of n+ BM2 magnet and its support platform with staircase. The n+ transport system should be completed and tested with beams from the CB-ECR ion source by the fall of 2012.



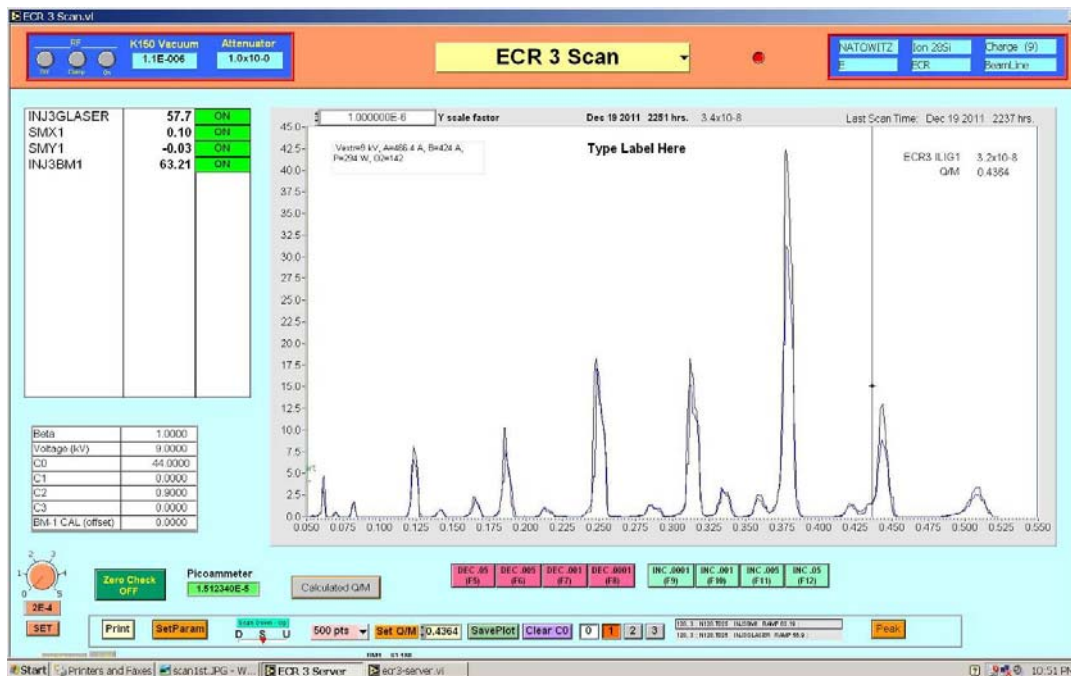
## Restart of the CB-ECR Ion Source

After a break in operation of nearly 6 months, the CB-ECRIS was turned on in the fall of 2011 with the coil power supplies and RF microwave transmitter mounted on the roof planks above the ion guide hall (Fig. 9). The extraction plate of the CB-ECR ion source has been modified. The diameter of the extraction opening was increased from 5 mm to 8 mm and three additional holes were made in order to increase the pumping speed of the plasma chamber. The locations of the holes were carefully chosen not to interfere with the shape of plasma.



**FIG. 9.** CB-ECR ion source (left) has been restarted with its support equipment mounted above the ion guide hall roof planks (right).

Initial tests showed an improved ECR ion source performance; most likely from better pumping of the plasma chamber through the extraction plate. It was found that the ion source also accepted higher

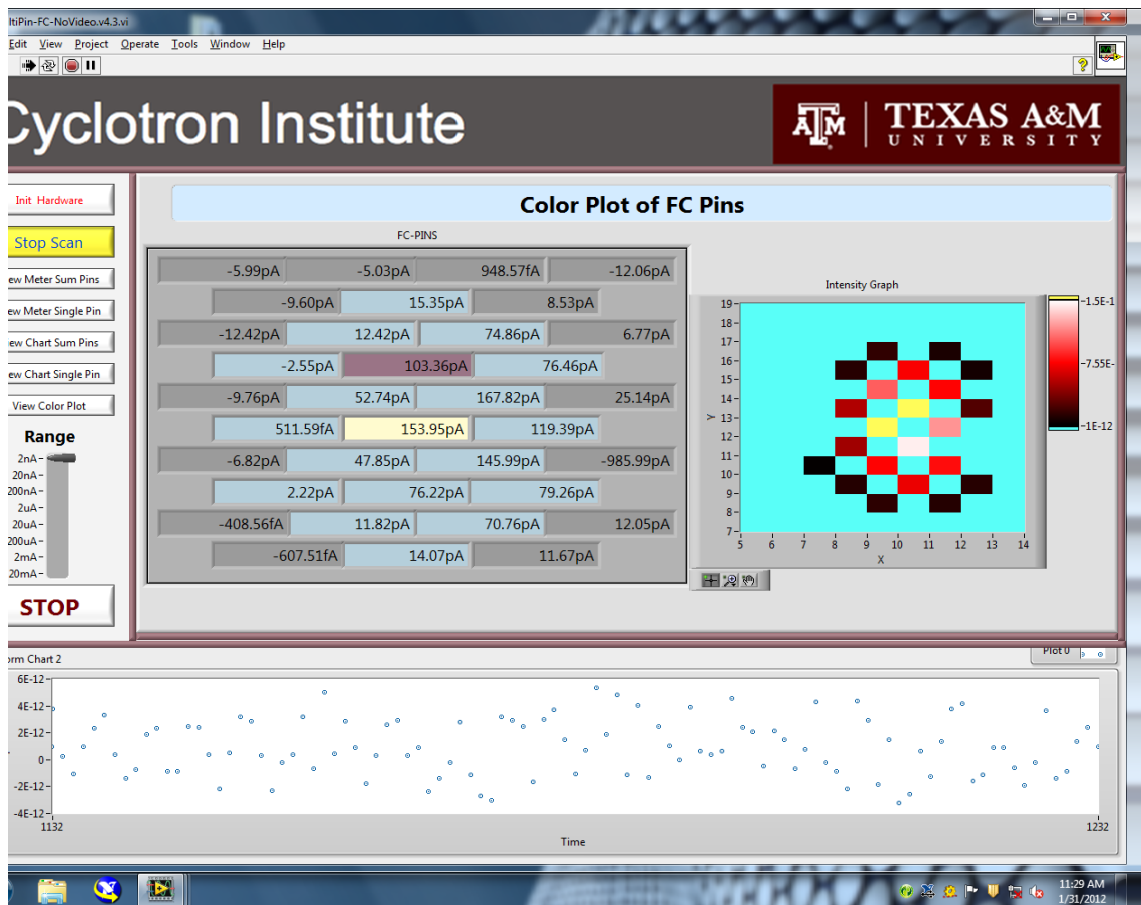


**FIG. 10.** The “best performance” of the CB-ECR ion source after startup – producing 40  $\mu\text{A}$  of  $^{18}\text{O}^{6+}$  with only ~250 watts of microwave power.

microwave power, but that higher power did not always produce optimal performance – indicating that the ion source needs further conditioning time to clean up the plasma chamber walls. Fig. 10 shows the “best performance” of the CB-ECR ion source – producing 40  $\mu\text{A}$  of  $^{18}\text{O}^{6+}$  with only  $\sim 250$  watts of microwave power.

The ion gun was loaded with rubidium and installed with the Argonne electrostatic steerer, Einzel lens and the Faraday cup array to the entrance of the CB-ECR ion source. New power supplies for the injection system that can be remotely controlled from above the ion guide hall have been installed. The first tests showed an improved transmission rate of 50 % of the 1+ rubidium beam into the CB-ECR ion source – where prior tests without the Argonne steerer showed less than 1% transmission. SIMION calculations show that a transmission rate of 90 % rate could be reached. This reduction in our transmission is probably from slight misalignments in the system. Fig. 11 shows a screen shot of the acquisition program for the Faraday cup array – showing the majority of the 1+ rubidium beam being focused on a  $\sim 7$  mm diameter spot.

Unfortunately, no evidence of “charge breeding” has been found so far. The injection system of the CB-ECR ion source is suspect and will be developed further.



**FIG. 11.** Screen shot of the acquisition program of the Faraday cup array – the data shows that the majority of the 1+ Rubidium beam was focused on a  $\sim 7$  mm diameter spot.