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 2015. 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
- Testing of the internal cryopanel for the K150 high vacuum system.

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

- Testing of the Light Ion Guide (LIG) gas cell,
- Completion of the Heavy Ion Guide transport system equipment. Below we report on a few of the accomplishments listed above.

I. K150 Cyclotron Development

In the past year, we provided 2,038 hours of beams for various experiments, notably four 25-35 MeV proton beams for the STAR/LIBERACE experiments and many 2-3 day duration, ^{12}C, ^{16}O, and proton beams for LIG development, and we also worked on developing an intense 12 MeV/u ^{40}Ar beam. But, problems with the deflector and the ion source have hindered our efforts. Also, we installed a large cryopanel, this will improve the cyclotron vacuum. And we briefly experimented with unbalancing the upper and lower TC01 trim coils to compensate for any magnetic differences due to different components in the upper and lower yoke holes. However as of yet we do not see any effect on our test beams. Several third harmonic beams were tuned, but the answer to why the third harmonics beams are so much less efficient has still eluded us. More evidence of the reality of the discrepancies between the CYDE magnetic maps and our actual cyclotron field was demonstrated when we tried Berkeley’s solutions for two beams, 14 MeV/u ^{18}O^{6+} and 5 MeV/u ^{40}Ar^{9+}. The Berkeley solutions, which are similar to the CYDE solutions, did not work for our cyclotron, and an additional +250A on TC12 for one beam and +230A on TC14 for the other beam were needed to bring the two beams out to the extraction radius. The 200-300A corrections are consistent with the discussion about the TOSCA modeling of the K150 cyclotron, described in the last year’s Progress Report. The energy of the beams, especially the stripped extracted protons, is better understood thanks to STAR/LIBERACE group’s determination of the proton beam energies. We now know that actual strip extracted beam energy is 94% of the nominal setup energy of the cyclotron. Even with the deflector pushed out to its outer limits, it seems that we need to strip extract about 1” earlier than the usual deflector extracted beams in order to minimize beam losses on the parked deflector. With the knowledge about the proton beam energies, we have started to calibrate the 160 degree Analyzing Magnet. And so with that calibration, there is a general agreement between the nominal beam energy from the cyclotron and the resulting Analyzing Magnet setting in transporting that beam to the experimental areas. Fig. 1 shows all the beams from K150 up to April 2014.

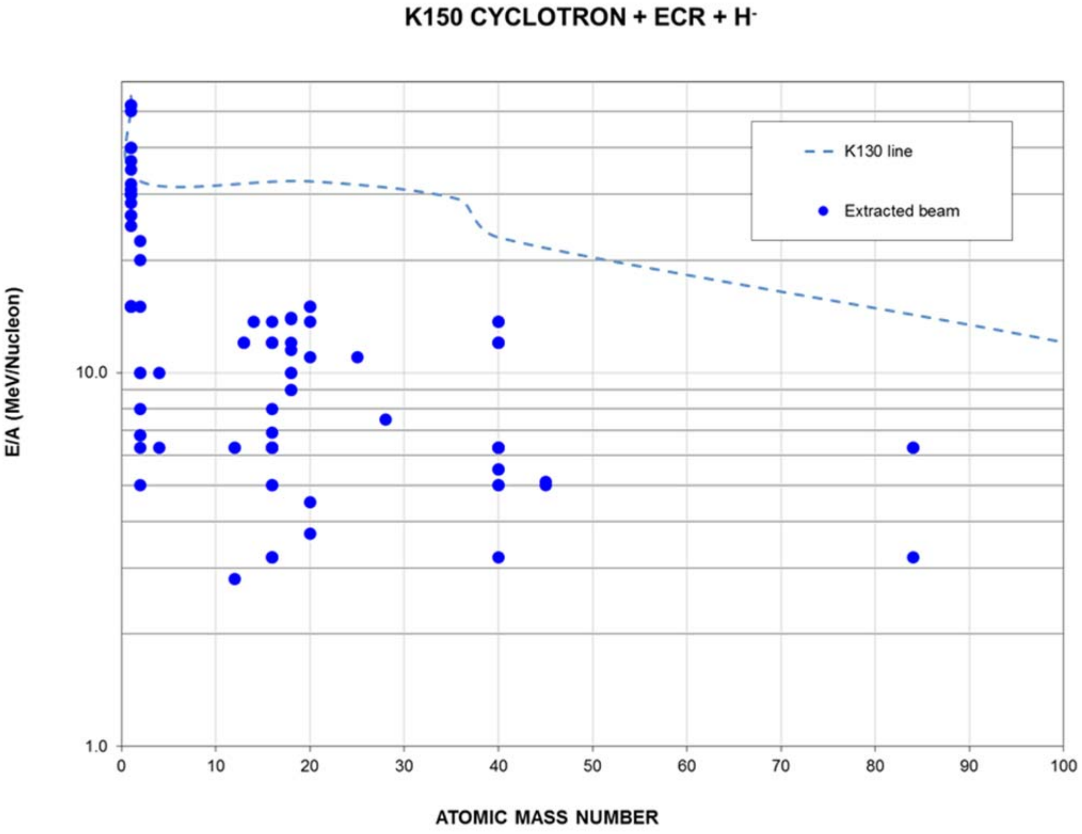

FIG. 1. Extracted beams from the K150 cyclotron with H- and ECR2 sources since May 2010.

II. Third Harmonics Beams

No third harmonic beam was used by any experiment in this time period. Not only do the third harmonic beams suffer from poor throughputs, about 1%, which is only one tenth of the first harmonic beams, they are also afflicted with instability problems (unstable beam intensity plus wandering beam energy). The instability not only makes it difficult to tune the beams, it also makes transporting the beams precisely to the experimental areas very difficult. This resulted in poor quality beams for the experiments. We have tuned out several third harmonic beams and tried to learn about the causes of the instability, but so far other than rather sensitive tunes of the various trim coils, which collectively may cause the instability, we have not found the answer. We hope to scrutinize the beam current near the inflector exit and examine the beam losses at small cyclotron radii to learn more about the problems with the third harmonic beams. Because our usual beam probe travels only to 5” in radius from the cyclotron center, we are in the process of installing another probe to get close to the inflector.

III. ECR2 Ion Source

Several improvements were made to the ECR2 ion source in an attempt to improve the production of the ion beams of ^{40}Ar in high charge states (charge states 11^+ and higher). Prior to the improvements, a measurement of the ^{40}Ar beam production was conducted in July. At this time the source produced 77 μA of ^{40}Ar^{11+}, 31.0 μA of ^{40}Ar^{12+}, 8.5 μA of ^{40}Ar^{13+}, and about 2.0 μA of ^{40}Ar^{14+}. Following the July test, a few possibilities for improvement of the source were recorded. These improvements are described in the following paragraphs.

The first improvement was to attempt to make the temperature of the plasma chamber cooling water lower. It was noted that when the ion source was on with the maximum microwave power possible at the time that the temperature of the cooling water on the ion source plasma chamber increased to above 95°F. This increase in the plasma chamber cooling water temperature corresponded to an increase in the ion source vacuum to above 6×10^{-7} torr, and typical source vacuum was 7 – 8×10^{-7} torr. This relatively high vacuum inside the plasma chamber has been improved to 4×10^{-7} torr by using an external source of chilled water to chill the plasma chamber cooling water through a heat exchanger. After the installation of this additional cooling, the typical operating temperature of the ion source has been more stable at about 85°F.

The second improvement was to increase the maximum voltage for the ion source biased plate. Previously, the maximum possible voltage, as limited by the power supply, was -340 V. It was remarked that the biased plate was often at the highest possible voltage, so it was reasonable to think about trying higher voltages. To increase the voltage, a new power supply that could provide up to -600 V was purchased. It was found later that the optimum voltage on the bias plate for ^{40}Ar ion production was between -350 and -400 V.

The third improvement came from work of the staff on the 14.5 GHz klystron. In 2006, it had been recorded that high microwave power was needed to produce large amounts of ^{40}Ar beam. Several electronic problems were found with the klystron itself which were preventing the power from being increased further. The final improvements came when some small vacuum leaks in the ion source gas system were fixed and the inside of the plasma chamber itself was thoroughly cleaned.

After all of these improvements, a further test of the ECR2 ion source was conducted in September. With the optimized settings of the ion source, ECR2 produced 133 μA of ^{40}Ar^{11+}, 86.0 μA of ^{40}Ar^{12+}, 46.0 μA of ^{40}Ar^{13+}, 19.5 μA of ^{40}Ar^{14+} and 1.3 μA of ^{40}Ar^{16+}. These results have been roughly reproduced on two subsequent tests that occurred after this initial test, in particular, for the ^{40}Ar^{13+}. However, further improvement is needed if the goal of about 100 μA of ^{40}Ar^{13+} out of the ion source is to be reached.

Further improvement of the ion source output may be possible if the source vacuum can be improved by cooling the plasma chamber even more than it is currently being cooled and attempting to further optimize the settings for the ion source (magnetic field, microwave power, gas flow, etc.). One possible setting that we are currently investigating is the frequency of the second microwave (TWTA). Previously, this frequency had been 11.33 GHz, but the possibility that a higher frequency might improve the production of the ion beams of the higher ^{40}Ar charge states is currently being investigated.

IV. 12 MeV/u $^{40}\mathrm{Ar}^{13+}$ Beam Development

Last year, we were able to accelerate and extract 13.7 MeV/u $^{40}\mathrm{Ar}^{14+}$, getting 11 pnA on FC02. We needed 88 kV on the deflector. To increase the beam intensity we dropped the charge state by one, but in order to manage the deflector voltage we lowered the beam energy to 12 MeV/u. The expected deflector voltage is about 85 kV, whereas for the 13.7 MeV/u $^{40}\mathrm{Ar}^{13+}$ it would have been 95-97 kV. We did extract 12 MeV/u $^{40}\mathrm{Ar}^{16+}$ with 70 kV on the deflector, and then 12 MeV/u $^{16}\mathrm{O}^{6+}$ with 75 kV. We conditioned the deflector up to 81 and 80 kV on two separate occasions to extract 14 MeV/u $^{18}\mathrm{O}^{7+}$ and 15 MeV/u $^{20}\mathrm{Ne}^{9+}$ beams, but we could not push it any higher, and the 12 MeV/u $^{40}\mathrm{Ar}^{13+}$ beam was not extracted. However, we did work on beam tuning for the maximum beam transmission out to the extraction radius, getting up to about 14% of the injected beam current. As our goal is at least 10% throughput (from ILC02 to FC02 transmission efficiency), then with a 70% extraction efficiency, not an unreasonable number, this can be achieved. Given that the Berkeley's AECR-U, similar to our ECR2, achieved 9 puA of Ar^{13+}, it seems possible to extract 0.9 puA of 12 MeV/u $^{40}\mathrm{Ar}^{13+}$ from the cyclotron.

V. Cryopanel Installation

A large cryopanel was designed, built, and installed in June of 2013, for the K150 cyclotron, see Fig. 2. It has two separate channels for LN2 and LHe cooling. The cryopanel was cooled with LN2 and beam tested with 6.3 MeV/u $^{40}\mathrm{Ar}^{11+}$. The graph in Fig. 3 compares the intensity of the beam measured at various radii through the cyclotron without and with the cryopanel cooled. The intensity of the beam measured at ILC02 (after ECR2) was ~42 μA. The measured vacuum of the cyclotron only improved from 1.3×10^{-6} torr to 1.2×10^{-6} torr; however the ion gauge reads the vacuum at the outer edge of the cyclotron and the cryopanel is positioned well inside the cyclotron. With the cryopanel cooled to 74°K, the improvement in intensity was found to be ~21% on average throughout the cyclotron and ~25% at extraction. It was hoped that the effect of improving the beam intensity at the center region would have been greater, as this is the region where losses due to charge exchange from poor vacuum are the greatest. It was also hoped that the improvement in the vacuum would have increased the overall intensity by factors of 2 or greater.

FIG. 2. Top – Cryopanel for the K150 cyclotron. Bottom – Installed cryopanel in the K150 cyclotron. The cryopanel is stood off from the trim coil cover with three feet, one is very short near the center of the cyclotron, and two others are at outer radii.

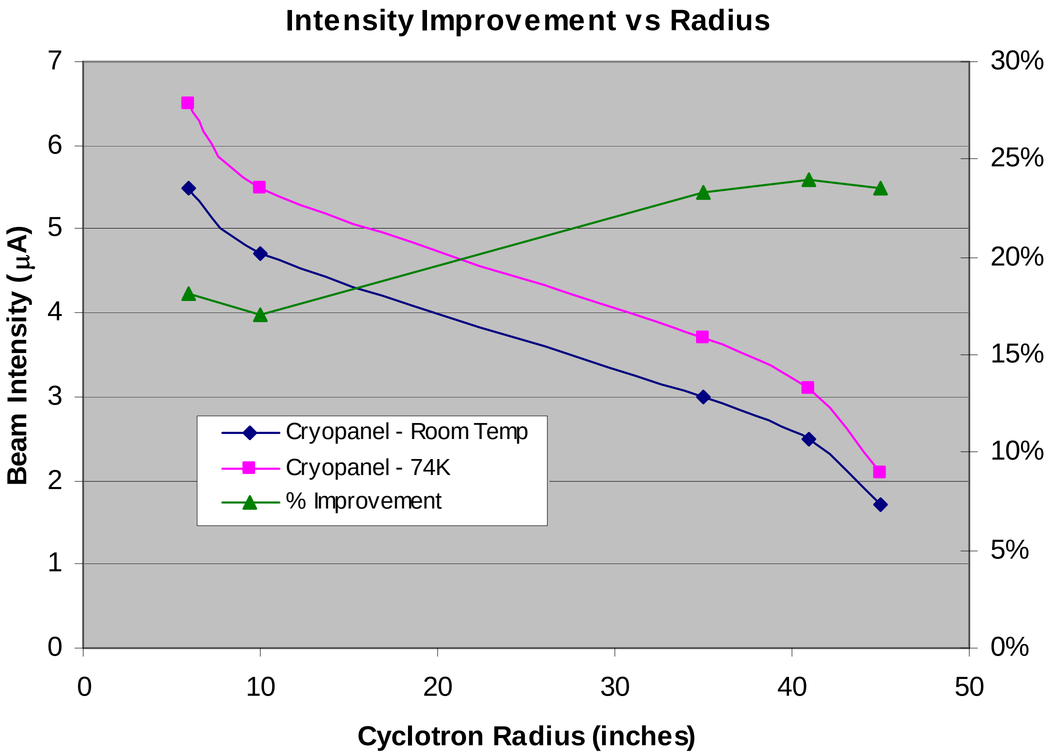

FIG. 3. The intensity of the beam measured at various radii through the cyclotron without and with the cryopanel cooled. With the cryopanel cooled to 74°K, the improvement in intensity was found to be ~25% at extraction.

VI. Light Ion Guide

A tremendous amount of effort has been made on understanding the production and transport of beam induced 1+ ions from the gas cell. The steps below describe the work that has been performed over the reporting period:

Three gas cells with various production targets were fabricated and one was installed in the LIG chamber. The purpose for fabricating multiple gas cells is to allow safe changes of the production targets and entrance / exit windows which in turn will reduce exposure time considerably.

The first experiment with the LIG was performed, using beams of 6.3 MeV/u ^{16}O with no production target. The purpose of the experiment was to test the functionality of the complex systems including the vacuum system, power supplies, safety interlocks and coordination of research and technical staff. With the beam passing through the gas cell, molecular ions of mass of 59 and 73 (impurities in the gas cell) were ionized and transported from the gas cell to the CB-ECR ion source.

The next experiment was made with beams of 6.3 MeV/u ^{12}C and nickel as the production target. By this process, Ni 1+ ions were made by sputtering the target with the ^{12}C beam. Unfortunately, no Ni ions were measured exiting the gas cell. We also tried introducing Kr gas in an attempt to measure ionized Kr. However the yield of Kr ions was found to be extremely low and all attempts to increase the intensity were not successful.

The next experiment was made with beams of 6.3 MeV/u ^{4}He on ^{27}Al target in order to create ^{30}P (beta + radioactive, T1/2 = 2.5 min) as radioactive product. The reaction cross section of the process ^{27}Al(^{4}He,n)^{30}P is approximately 260 mb at 10.53 MeV with the recoil energy ranging between 0.5 MeV to 2.6 MeV. The LIG gas cell is designed to work with very low energy recoil products. Proton or ^{4}He beams will work to catch, thermalize and allow the extraction of radioactive products. Due to the lack of a diagnostic system (detector) after the 1 meter long SPIG, we could check only the production of stable beam at that position. However the correlation between the stable beam production and radioactivity production exists such that the higher the stable beam production is, the higher the radioactive yield it is. To check the radioactive products yield, the analysis magnet following the CB-ECR ion source was set to measure mass 30 in a 1+ charge state. A Germanium detector was installed on the CBECR ion source vertical injection line in order to measure the radioactive yields of the collected products. Unfortunately, no radioactive products were measured.

The unsuccessful experiment with ^{27}Al(^{4}He,n)^{30}P reaction led us to believe that the energy of the recoil products may be too high to exist the gas cell. Therefore we tried using a 15 MeV proton beam on a Ni target to produce ^{58}Cu. The cross section of the reaction ^{58}Ni(p,n)^{58}Cu is about 50 mb. For this reaction, the recoil product energy is lower than from ^{27}Al(^{4}He,n)^{30}P therefore the efficiency of gas cell should be higher. Unfortunately once again, no radioactive products were found regardless of a steady stable beam current coming out of the gas cell.

Since the lack of radioactivity exiting the gas cell from the production targets was not understood, tests with the open ^{228}Th radioactive source were performed once again. With the source placed in the gas cell (but with no beam going through the gas cell) good production of the daughter products was measured exiting the gas cell and transported through the CB-ECR ion source. However, when the beam was passed through the gas cell at high intensity, no daughter products were measured coming from the gas cell. Only when the beam was reduced to low intensity (~40 nA) were the daughter products measured exiting the gas cell.

Using the information learned with the open ^{228}Th radioactive source with respect to beam intensity, we once again tried an experiment with a 15 MeV proton beam on a ^{nat}Zn target to produce radioactive 1+ ions of ^{64,66,68}Ga. With the beam intensity kept low at ~40 nA, radioactive products were measured exiting the gas cell and were transport through the CB-ECR ion source.

After the radioactive beam production from the gas cell was demonstrated, the production efficiency effect was investigated. Two sizes (1mm and 2mm diameter) were tried as exit holes for the target gas cell. Collection plates were installed directly after the exit holes. After 15 minutes of collection, the plates were placed in front of a Germanium detector for 30 minutes and the gamma line of 991 KeV was collected to determine the production amounts. Table I summarizes the measurements and shows very high efficiency in the production of radioactive ^{64}Ga atoms from the 2 mm hole.

Table 1. Peak integrals of the ^{64}Ga keV line and the corresponding production percentages from 1 and 2 mm exit holes.

Hole Dia. (mm)	Beam Intensity (nA)	991 keV line – Peak integral	Atom Percentage
1	650	9,213	12 %
2	500	14,715	90 %

Despite the positive result of production from the gas cell, the transport of the radioactive ions through the RF sextupole was not successful perhaps caused by neutralizing effects from the primary beam. A new RF sextupole with a better shielding and a larger acceptance has been designed and is shown in Fig. 4.

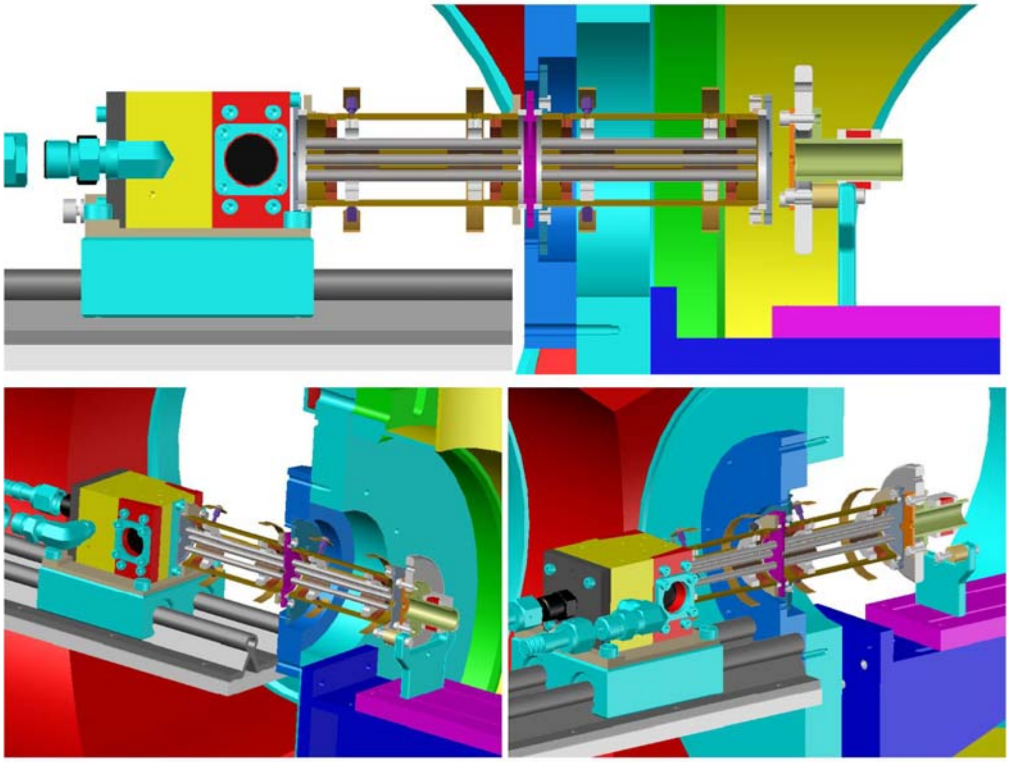

FIG. 4. The design for the new LIG RF sextupole.

VII. Heavy Ion Guide

The vacuum box for the gas catcher and the support stand have been finished and installed in the ion guide cave, see Fig. 5. The gas catcher has been installed inside the vacuum box.

FIG. 5. The support stand with the vacuum box shown installed in the heavy ion guide cave. The gas catcher is shown installed inside the vacuum box.