

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 to the fourth quarter of calendar year 2011. 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 them in the K500 cyclotron.

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

- Installation of equipment for the K150 high vacuum system,
- Installation and testing of the dee inserts for the central region of the cyclotron,
- Installation and testing of the negative ion source,
- Development of high intensity 30 MeV proton beams,
- Final assembly of K150 beam lines, and
- Procurement of the radiation monitoring system for the K150 cyclotron.

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

- Procurement of the radiation shielding for the ion guide cave,
- Construction of the Heavy Ion Guide gas cell and transport system,
- Installation and testing of the CB-ECR ion source, and
- Assembly and installation of the n+ transport system.

Below we report on a few of the accomplishments listed above.

Initial Results from Center Region Calculations with Batwings

The dee inserts (Berkeley batwings), see Fig. 1, were installed in October of 2009. These titanium inserts are electrically connected to the dee and dummy dee and narrow the dee gap both horizontally and vertically in the center region. The proper alignment of the batwings is very important, especially the vertical placement with respect to the median plane, and it took a lot of effort by our mechanical engineer and crew to install the batwings.

The dummy dee side batwing was installed first. It was accessible from the deflector side with the deflector table removed from the dee tank. Three transits set up along orthogonal axes were used to verify the alignment of the batwings: one at 0° looking along the dee (see Fig. 2a), one at 90°, and one looking up through the center hole on the lower yoke (with the inflector removed). The batwing was

mounted to the upper dummy dee support bracket, which already had two mounting holes drilled. (The dummy dee did not have to be removed from the cyclotron.) The vertical position of the batwing was

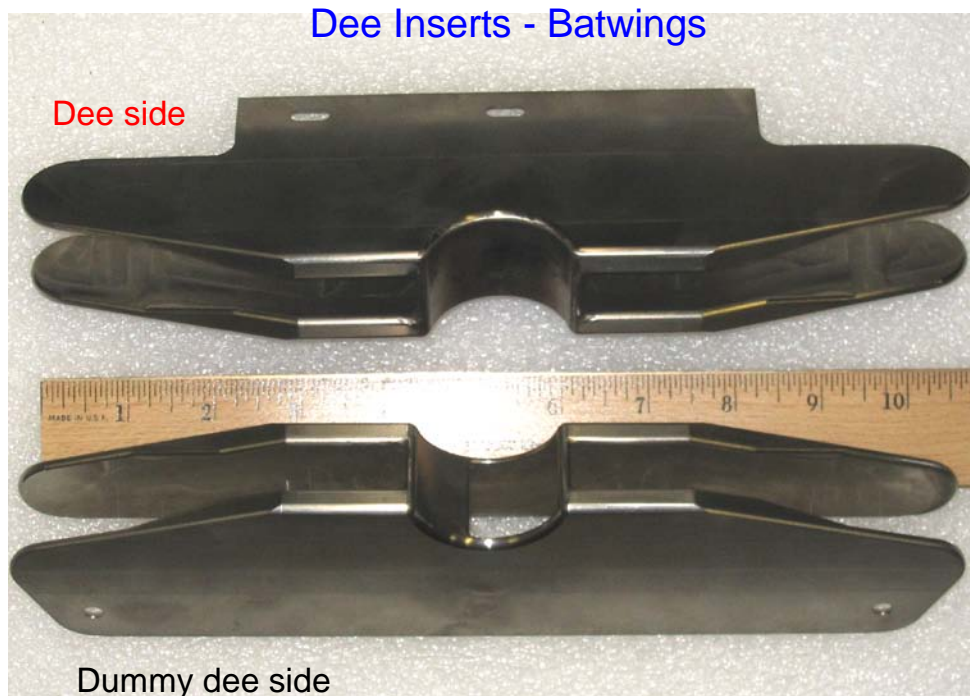


FIG. 1. Dee and dummy dee inserts.

adjusted by the height of spacers between the batwing and the mounting bracket. The batwing was mounted to the dummy dee bracket by passing two grooved posts, which were mounted on the top of the two spacers which in turns were fastened onto the batwing, through the mounting holes and capturing the posts with spring loaded clips from above (see Figs. 2b and 3). It took many iterations – mounting the batwing and checking for the alignment, and then taking it apart and adjusting the mounting mechanism - to install the batwing properly. Having to manipulate the batwing from 6 feet away in the 6 inch vertical gap of the cyclotron added to the difficulty of the task.

The dee side insert was installed by retracting the dee stem and moving the dee into the rf resonator tank. The insert was first mounted onto the end of a 10"x8"x0.25" copper plate, and then the insert and the copper plate were mounted onto the upper inside dee. The dee is lined with 10" wide graphite plates that run from the front to the back of the dee. The graphite plates are attached to the dee by regularly spaced screws and clamps along the seams. The graphite plates in the middle section of the dee had been removed years earlier and the clamps which remained were used to secure the copper plate along with the dee insert. Once again it took several iterations to mount and push the dee and the batwing into the position, and then to check the position of the batwing as well as the gap between the batwings.

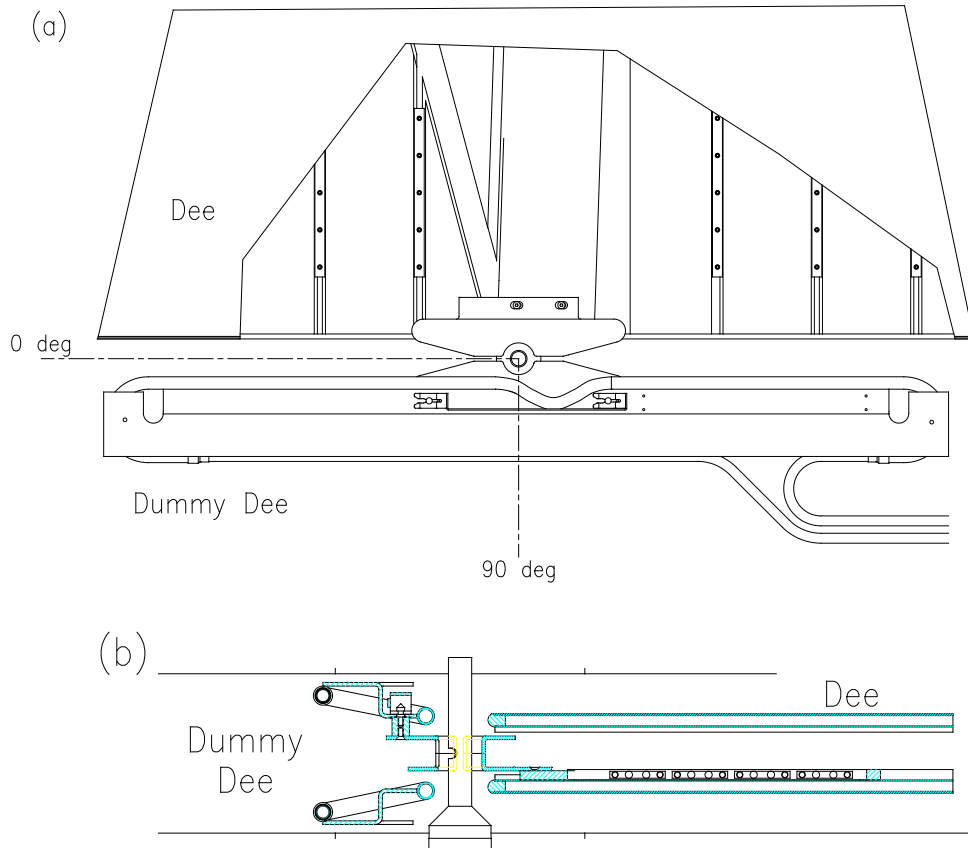


FIG. 2. (a) Top view and (b) side view of the dee and dummy dee and the batwings.



FIG. 3. Photo of the dummy dee side batwing after the installation.

After the dee inserts were installed, we were anxious to find out how the cyclotron would perform with the batwings. Just before the Christmas break, we got to look at several proton and oxygen beams with the batwings (Table I). Because we were mainly interested in the beam acceptance into the cyclotron and the internal transmission, all the Dec. 2009 beams were internal beams and were not extracted. The beam buncher was not operational and was not used. We used the CYDE calculations to set up the cyclotron (the main coil and 17 trim coils and the rf frequency) initially for beam tuning. During the beam tuning the trim coils were mostly left set to the CYDE values and only the main coil was adjusted. In order to test CYDE, we did run old run solutions for 20 MeV proton and 7.5 AMeV $^{16}\text{O}^{5+}$ beams, and we obtained very similar beam currents between the old run solutions and the CYDE solutions. The use of the CYDE calculations will allow faster beam tuning in the future, and at this early stages of running K150 we will perform more comparison studies with old run solutions to gain confidence in CYDE.

TABLE I. First look at beams with the batwings (Dec. 2009).

T/A (MeV/u)	Ion	Main Mag (A)	Vdee (kV)	ILC02* (μ A)	Inflector (μ A)	BP=10'' (μ A)	35'' (μ A)
20	protons (Oct./07)	612	73 (w/o batwings)			0.65	0.22
20	protons	613	45	29	10	0.33	0.32
25	protons	669	46	23	8	0.56	0.54
30	protons	742	52	25	9	0.40	0.37
7.5	16 O 5+	1262	53	89	35	3.1	1.9
10	16 O 6+	1186	56	132	62	3.9	3.5
12	16 O 6+	1367	65	130		5.0	4.7
14	16 O 6+	1606	65	110		3.4	2.9
14	16 O 7+	1199	65	22	12	0.74	0.67

The first beam on Table I, the 20 MeV proton, was the first beam accelerated (without the batwings) and extracted 2 years ago, and it is listed only as a comparison. Looking at the beam currents from Table I, the first thing that stands out is how much the internal transmission improved with the batwings. Two years ago it was only 33% from 10'' to 35'' on the beam probe for the 20 MeV proton beam. With the batwings we obtained 85% or better. The exception is the 7.5 AMeV oxygen beam which may be affected more severely by poor vacuum. Next, looking at the cyclotron acceptance as measured by the percentage of the beam current at 10'' from the beam on the inflector, the proton beams averaged 5% and this is consistent with Berkeley, where they typically obtain 2.5 to 5% acceptance without beam bunching. The acceptance for the oxygen beams was slightly better. Lastly, it was observed that the rf dee voltage ran much lower with the batwings, 73 to 45 kV for 20 MeV proton beam, and even for the higher energy 25 and 30 MeV proton beams it ran under 52 kV. This is a good development, but this does not clarify how much higher the dee voltages will be for more energetic beams, such as 55 MeV proton beam. In the constant-geometry mode, the dee voltage scales with the beam energy (actually the total kinetic energy divided by the charge). From the observed dee voltages, namely 45, 46, and 52 kV for 20, 25, and 30 MeV proton beams, respectively, while it was not calibrated it does seem that the three proton beams did not follow the strict constant-geometry mode. And also, while the dee voltage depends mostly on the electromagnetic structure of the center region, the dee voltage does affect the beam extraction. Further beam studies are obviously needed to learn more about the dee voltage requirements.

In the meantime, the beam orbits in the center region were further investigated using the MSU program Z3CYCLONE, this is a continuation of the calculations which was described in the last year's progress report. This year the 3D electric map of the batwings and the grounded inflector housing was calculated with TOSCA, a 3D electro-magnetostatic solver. The magnetic field map was obtained from CYDE, however, because of its coarse polar map, $\Delta r=1'$ and $\Delta\theta=3^\circ$, the averaged magnetic values (over angle) were used in the Z3CYCLONE calculations instead of the actual map. This should not matter for the first few turns as the flutter effect is small inside 5".

The beam tracking starts from the exit of the mirror inflector (mirror angle was assumed to be 45.7 degrees). With the opening of the inflector oriented toward the dummy dee side, as was the case for the Dec. 2009 beams, the beam emerges from the inflector into the dummy dee through the opening in the dummy dee batwing. The beam then bends around towards the active dee side to start the acceleration (Fig. 4). Two important parameters in the calculations are the rf dee voltage and the starting rf time. The dee voltage needs to be large enough so that the energy gain from the first gap-crossing allows for the beam to make it around the batwing collars. And the rf starting time must be properly synchronized so when the beam gets to the accelerating gap the rf would be correctly phased for acceleration. Additionally, in order to utilize the electric vertical focusing property, the beam needs to go through the RF electric field gap in the falling e-field, namely that the electric field experienced by the beam must be stronger in the first half of the gap crossing than that from the second half. Also, because the magnetic field is not isochronous at the center of cyclotron (it is about 3 to 5% larger than the isochronous value), the particle orbital period near the center is shorter than the rf period, and so it is necessary to start the beam late with respect to the rf and allow the beam to "catch up" with the rf after several turns. For the 20 MeV proton beam, see Fig. 4, using 20 to 40 kV on the dee produces well centered, reasonable looking orbits at the center region. (The 20 kV on the dee translates into about 500 turns inside the cyclotron to reach the maximum energy.) So, the Z3CYCLONE is useful in finding a range of acceptable dee voltages, but perhaps not the optimal dee voltage. The calculations do show that higher dee voltages lead to wider RF phase widths, which in turn lead to larger beam acceptance into the cyclotron.

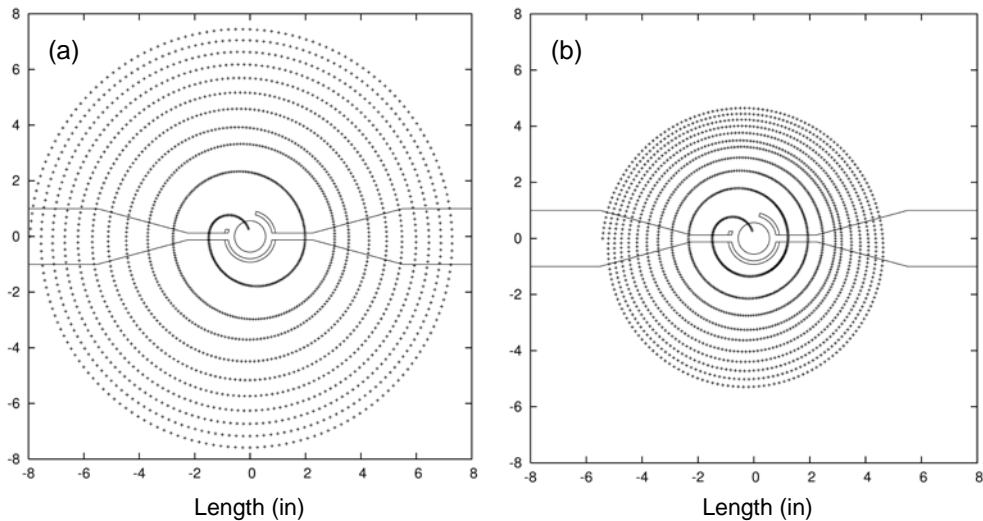


FIG. 4. Simulating 20 MeV proton beam with the dee at (a) 40 kV and (b) 20 kV.

The dee inserts (Berkeley batwings) were installed in Oct. 2009, and then in Dec. 2009 we tested them with several internal beams. The tests showed that the dee inserts work very well: the beam acceptance into cyclotron and the internal beam transmission were very good, and the dee inserts allowed the rf to run at lower dee voltages than two years ago.

H- Acceleration

One of the concerns for the project is the extraction efficiency of high intensity protons from the cyclotron. Poor extraction efficiency may cause radiation damage to and high activation of the cyclotron deflector. One solution is to accelerate H⁻ ions and then strip to H⁺ near extraction. At other cyclotron labs this technique has shown to have extraction efficiencies of nearly 100% and greatly reduces interior activation problems. Ray tracing calculations show that such a system could physically fit into and operate within the vacuum space of the K150 cyclotron. With the deflector pulled back from the extraction channel (but not removed from the cyclotron), H⁻ ions could be accelerated to 38" (extraction channel radius) and then stripped to H⁺. Upon exit, the trajectory of the H⁺ ions would then be steered along the normal beam line with a dipole magnet (Fig. 5).

The cyclotron laboratory in Jyväskylä, Finland (JYFL) has had great success with a multi-cusp negative ion source that was built by them with help from the TRIUMF lab in Vancouver, Canada. The experience of JYFL is that their source LIISA (Light-Ion Ion Source Apparatus) produces over 5 mA of H⁻ at the 5.9 kV extraction voltage suitable for their fixed center region geometry for 30 MeV. This results in a proton beam out of the cyclotron of 60 μ A. The injection line has a vacuum in the region of mid 10^{-8} torr while the cyclotron has a vacuum in the low 10^{-7} torr region. This vacuum results in only

about 5% residual gas losses. The major loss seems to be from matching the beam from the source to the cyclotron inflector. The dose from lost beam in the JYFL cyclotron has decreased by a factor of 10 to 20 for 30 MeV protons over the case from running positive ions. Their LIISA source matches very well with our needs for an ion source.

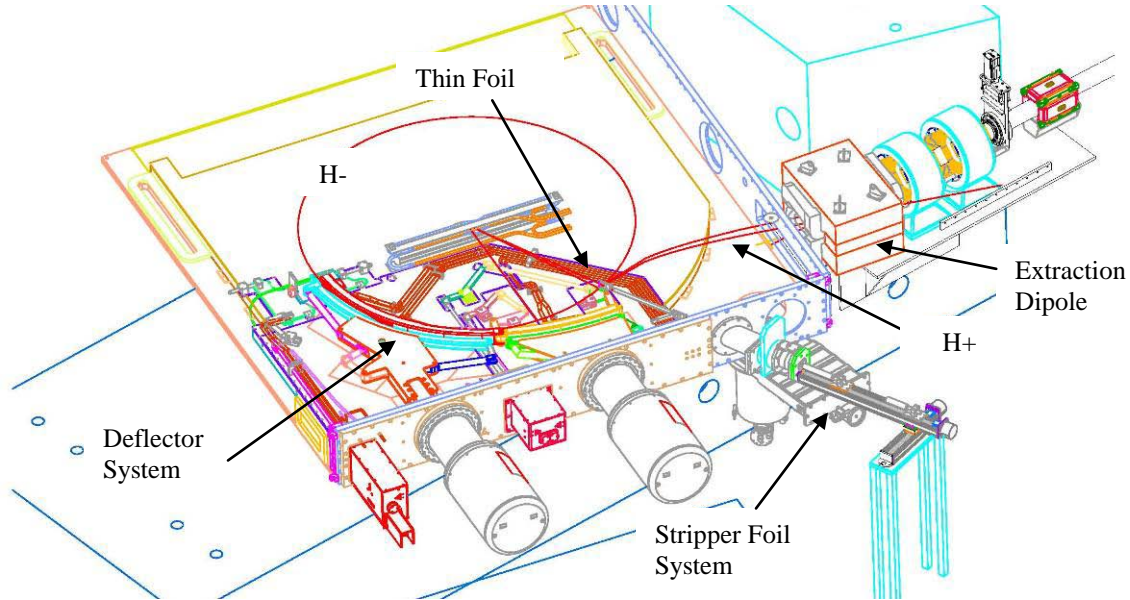


FIG. 5. Illustration of H⁻ extraction from the K150 cyclotron. With the deflector pulled from the 38" extraction radius, H⁻ ions would strip to H⁺ by a thin foil and then exit the cyclotron. A dipole magnet would then steer the beam along the normal beam line leading from the cyclotron.

In April 2009, Cyclotron staff traveled to JYFL to discuss H⁻ cyclotron acceleration, operation and construction of a negative ion source for the K150 cyclotron. Discussions with them lead to the suggestion that we use their prototype (in storage) LIISA source to get started. Quick testing on a test stand showed that their prototype LIISA source could produce a sufficient amount of H⁻ beam for our project. JYFL has offered their prototype LIISA source on loan and then they would sell it to us once it was proved to work on the cyclotron.

For the LIISA source to provide the intensity and emittance needed for the project, a new source extraction system was built by Texas A&M with design help from JYFL. In August, the new source extraction system was brought to JYFL and tested on the prototype LIISA source. Results showed that the ion source produced up to 1 mA of H⁻ ions and with an emittance of less than 8π mm-mrad which is sufficient for our project. After additional testing in September and October, the source was shipped to Texas A&M in late November.

In order to receive the beam into the K150 cyclotron, the transport of H⁻ ions was studied with the code SIMION (transport plus space charge effects). The results showed that a double Einzel lens system is needed to first, get the beam through the vertical beam tube of the ECR2 injection line 90° magnet and second, to refocus the beam to the Faraday cup at the mid-point of the vertical injection line. Fig. 6 shows the final layout of the H⁻ ion source and double Einzel lens system. Fig. 7 shows the ray tracing results predicted by SIMION using a double Einzel lens system.

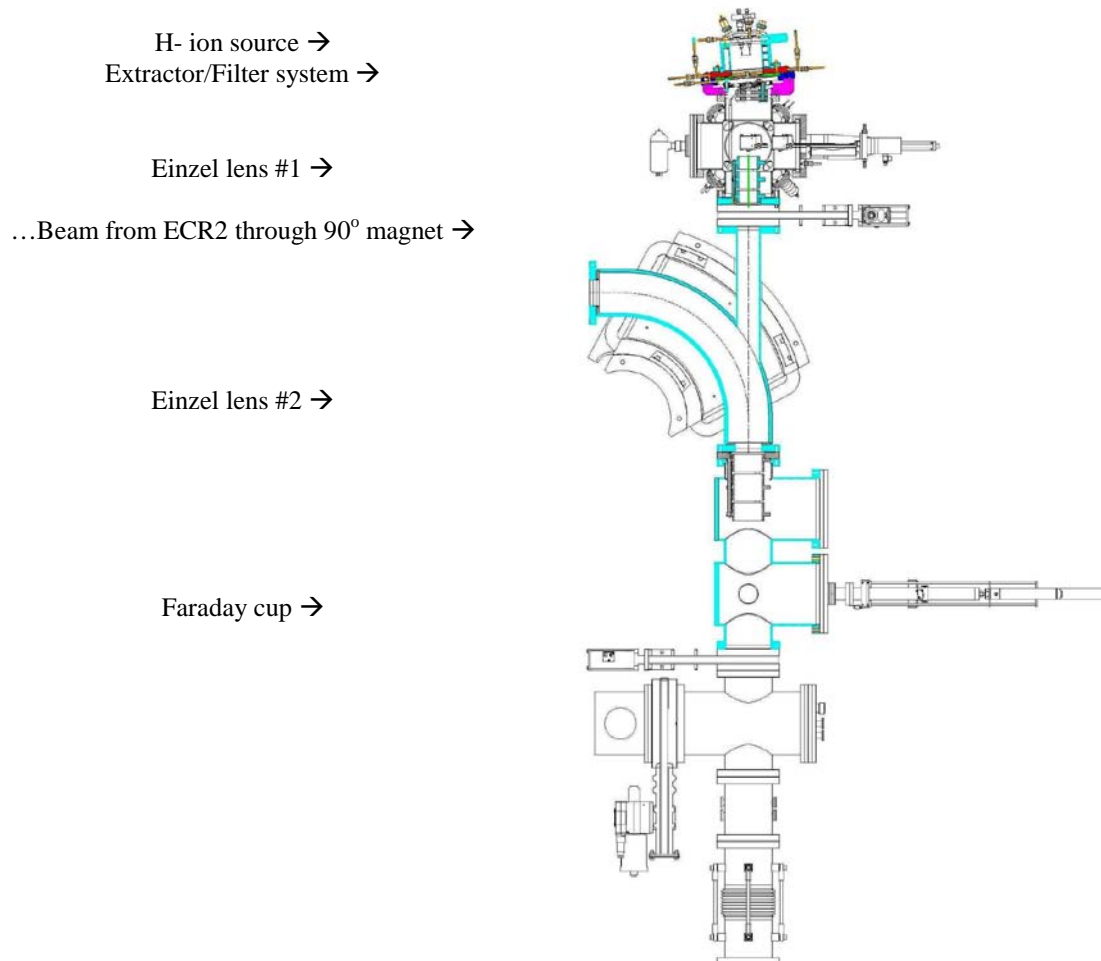


FIG. 6. Layout of the H- ion source and double Einzel lens system. The system fits above and below the ECR2 90° magnet and without any modifications.

During the installation of the dee inserts, the deflector positioning system was modified so that the deflector electrode and shoe could be pulled out to 41". This allows unobstructed extraction of the H- beam with the foil stripper system at 38". Equipment for the foil stripper system was installed by mid March. The exit magnet acquired from surplus was refurbished and installed in February. The pole tips were reshaped and extra steel was added to the yoke in order to produce the magnetic fields for the highest energy H- and D- beams that can be accelerated. The power supply for the exit dipole magnet was installed in January.

Except for Einzel lens #2, the source and all its equipment were fully installed by early February. Two experts from the JYFL lab came to TAMU in February to help with start-up, and optimize the ion source and beam transport system. Testing showed that the ion source and transport system worked properly. A beam current of ~1.5 mA of H- ions was measured at the H- Faraday cup, and ~0.5 mA was measured at the ECR2 Faraday cup. Einzel lens #3 was installed in March and improved the transmission between the two Faraday cups from 30% to 60-70% as expected.

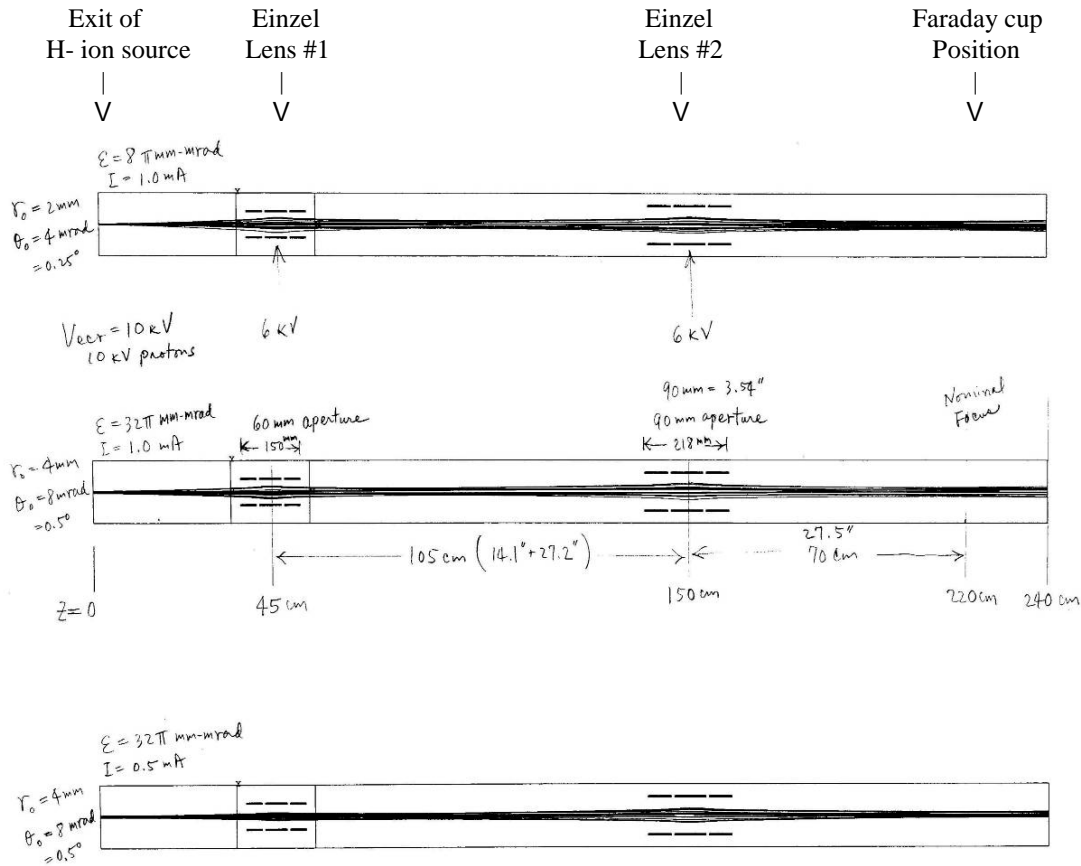


FIG. 7. Simion calculations for various assumptions for the emittance and current of the H- ion source. The diagrams show the position for the double Einzel lens system.

In order to deflect H- ions into the center region of K150 cyclotron, the inflector power supply had to be replaced with a negative high voltage supply. The main magnetic field of the cyclotron was reversed by crossing over the buss bar leads from the main supply to the cyclotron coils. The “crossing buss bar” was installed and tested in late March 2010. The magnetic fields from the trim and valley coils are also reversed, in order to accelerate H- ions. However these supplies can switch between positive and negative potential so no modifications were needed.

With the ion source set at -10 kV, H- acceleration at 20 MeV was tried as a first test. The main, trim and valley coil power supply voltages were reversed and set to the current values from the 20 MeV proton run in December 2009. After several hours of optimization, beams of $\sim 10 \mu\text{A}$ of H- were stripped and extracted from the cyclotron on to the Faraday cup after the exit dipole. This first test showed that the H- acceleration system was working properly.

Lower proton energy was tried first to allow time for the RF system to condition and to keep the secondary radiation level as low as possible in the cyclotron vault. After the RF system had time to condition, 30 MeV H- ions were then accelerated. As with the 20 MeV tune, the starting currents for the main, trim and valley coils were set to the 30 MeV proton values from the test run in December 2009, but with the power supply voltages reversed to reverse the cyclotron magnetic field. After a couple days of optimization, steady beams of $14 \mu\text{A}$ of H- were extracted and measured on the exit Faraday cup. Fig. 8

shows the reading on the current meter for the exit Faraday cup. The optimized parameters for the H- ion source are shown in Table II.



FIG. 8. Beam current of $14 \mu\text{A}$ of 30 MeV protons measured at the Faraday cup at the exit of the K150 cyclotron. H- ions accelerated to 30 MeV were stripped to protons at the extraction radius.

TABLE II. Optimized parameters for the H- ion source for 30 MeV H- acceleration.

BM1:	0.94 A @ 0.32 V
Puller:	+8.82 kV @ 56 mA
Plasma Electrode:	+4.03 V @ 2.18 A
ARC:	79.9 V @ 21.70 A
Filament:	3.99 V @ 146.1 A
Source Bias:	-10.0 kV @ 0 A
Einzel #1:	-7.49 kV @ 0 A
Einzel #2:	-6.28 kV @ 0 A
Einzel #3:	-4.18 kV @ 0 A
Ion Source Vacuum:	$1.3 \text{ E-}5$ Torr
Injection line Vacuum:	$9.2 \text{ E-}7$ Torr
Leak valve @ 3 full turns open,	pressure on regulator set at ~ 37 psi

While the beam was stopped on the exit Faraday cup of the K150 cyclotron, secondary radiation levels from neutrons were measured in the cyclotron vault and at the injection line above the K150 cyclotron. Levels of ~ 1 Rem/hr were measured in the vault and 2 – 3 mRem/hr were measured at the injection line. These are very low values with regard to the safety of the staff working around cyclotron facility. Fig. 9 shows the reading by the RAM system at the injection line.



FIG. 9. Secondary radiation levels of 2 – 3 mRem/hr were measured at the injection line above the K150 cyclotron while 14 μ A of 30 MeV protons were stopped on the exit Faraday cup of the K150 cyclotron. H⁻ ions accelerated to 30 MeV were stripped to protons at the extraction radius .

Charge Breeding ECR Ion Source

The CB-ECRIS was delivered in September 2007 and was assembled by Wayne Cornelius of Scientific Solutions of San Diego in October 2007. All of the equipment needed to complete the CB-ECRIS has been procured and installed including both coil power supplies, the turbo pumping systems, microwave transmitters and control equipment. CB-ECRIS was installed completely and turned on for a short period of time first, with the TWT transmitter and plasma was created successfully. During Q4 FY09, a section of n⁺ transport system following the CB-ECR ion source was installed and allowed analysis of the beams produced by the CB-ECR ion source. With 100 watts of RF power from the 14.4 GHz transmitter and an extraction voltage at 10 KV, first results of the CB-ECR ion source were obtained.

One of the milestones in the upgrade project is the commissioning of the CB-ECRIS This ion source will be used to further ionize low charge-state (1^+ mainly) radioactive ions to higher charge-states (charge-breeding) for acceleration by the superconducting K500 cyclotron. The frequency used to ignite the plasma was 14.5 GHz and the extraction voltage varied between 7 kV to 10 kV. The source was initially tested as a conventional ECR ion source by injecting neutral gases: oxygen and argon. After running for few weeks the source became unstable and was inoperable due to the appearance of a large and oscillating drain current. It was found that the insulator between the plasma chamber and the steel from the injection side coil had developed significant damage from a sparking track. After the insulator was removed and examined, it was replaced with one redesigned to have a longer path from high-voltage to ground. The source has since operated in a more stable fashion. Fig. 10 shows a scan for high charge-states for argon with low microwave power. To test the charge-breeding capability of the CB-ECRIS we chose to inject a beam of stable 1^+ ions into the plasma chamber from a commercial ion gun made by HeatWave Labs and capable of producing 1 μ A of 1^+ current from the alkali elements, Li, Na, K, Rb and

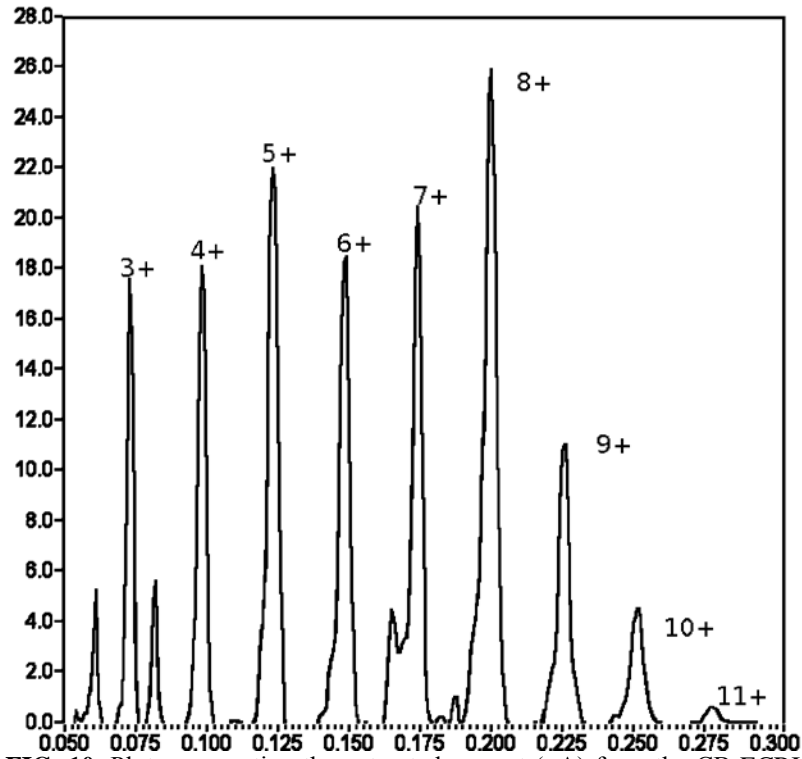


FIG. 10. Plot representing the extracted current (μA) from the CB-ECRIS with argon versus Q/M . The peaks are labeled with the corresponding charge-states.

Cs. Details of the ion gun can be found on the company website. The critical feature for high efficiency charge-breeding is the capture of the injected ions by the plasma. For this to happen the injected ions should be within a few volts of zero velocity as they encounter the plasma. Since the potential ΔV of the plasma with respect to the plasma chamber is on the order of a few volts and indeterminate, the extraction voltages V_{ext} of the ion gun and of the CB-ECRIS were tied together through a single high-voltage supply with ΔV applied to the ion gun via a low-voltage, remotely adjustable supply floating at V_{ext} . Fig. 11 illustrates the injection system. The ion gun is mounted on the left-hand flange in the figure.

We conducted ion transport simulations using the SIMION code, a software package designed to calculate the trajectories of ions moving through electric and magnetic fields. The code was used to visualize the trajectories of the ions at the entrance in the plasma chamber as well as to estimate voltages to be applied to the Einzels A and B. The solenoid magnetic field from the injection side coil was considered during the simulations, and we could observe that it does provide extra focusing to the injected beam. In Fig. 12 we present a comparison for Rb^+ injected beam with the solenoid turned on and turned off. ΔV used in this simulation was 40 V.

In tests of detecting the Rb^+ beam on the extraction side of the CB-ECRIS, without the ECR plasma ignited, it was found that the voltages used for the Einzels A and B differ from the SIMION simulations within $\pm 10\%$. Einzel A has a narrow range of voltages whereas voltages for Einzel B span a larger range for the 1^+ beam at the extraction side to still be detectable. When the microwave transmitter

is turned on, the Einzel A voltage must be decreased in order to detect the Rb^+ beam again. Higher charge states of Rb have not yet been observed, and further investigations and tests are underway. For the next series of experiments we will inject a $\text{Na } 1^+$ beam, Einzel A will be eliminated from the injection scheme.

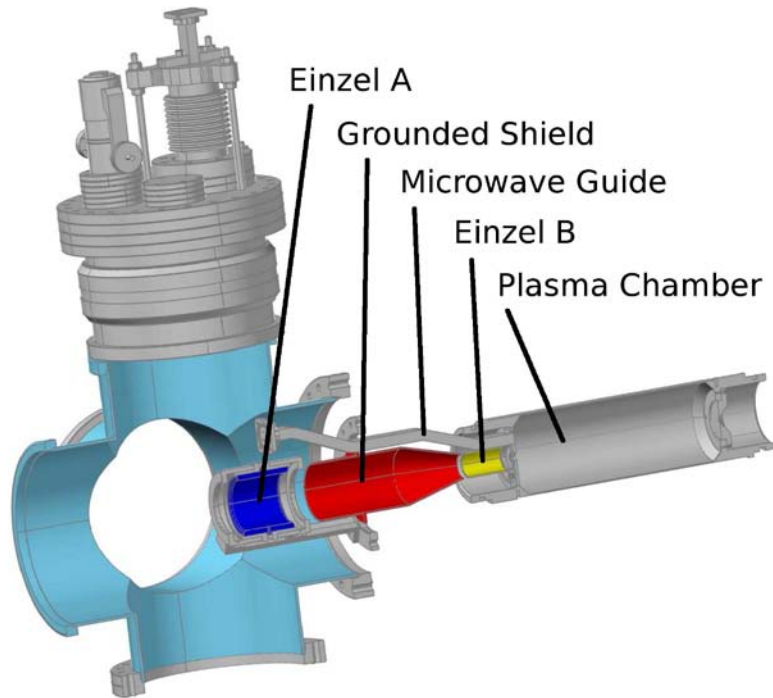


FIG. 11. The injection system of the CB-ECR. Einzel A, grounded shield, and biased tube are respectively highlighted blue, red, and yellow. The microwave guide and the plasma chamber are shown in gray.

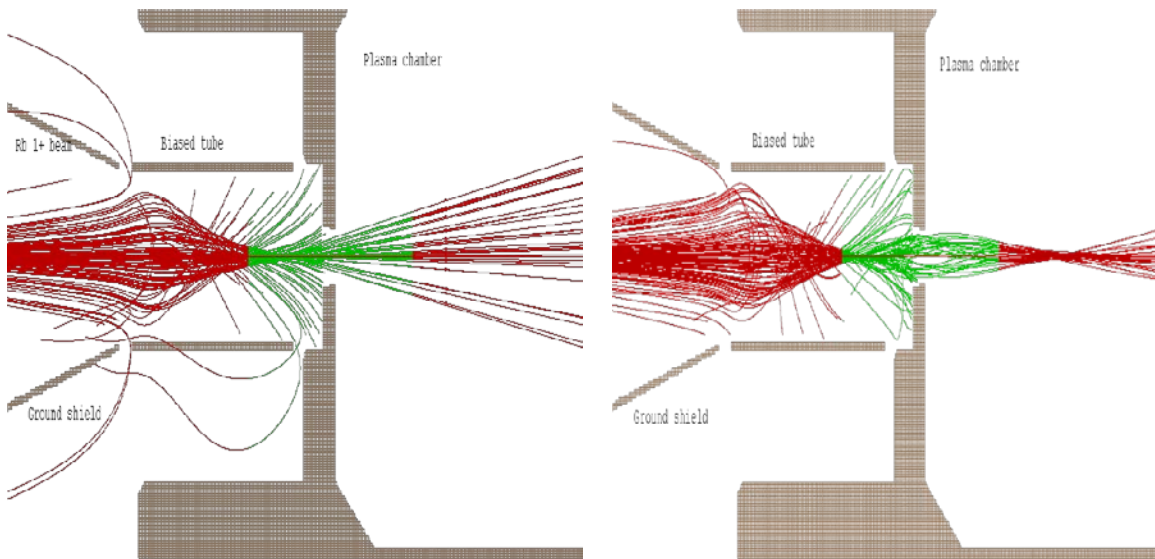


FIG. 12. SIMION simulations for the Rb^+ beam. In the left panel the magnetic field was turned off and in the right panel the magnetic field was turned on.