Final Technical Report
for the

Cyclotron Institute Upgrade Project

at Texas A&M University

Prepared by the
Cyclotron Institute Upgrade Project Management
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On January 3, 2005 the Cyclotron Institute Upgrade Project (CIUP) at Texas A&M University began with the approval of the CIUP management plan by the Department of Energy Nuclear Physics Office. The CIUP is divided into three major tasks: (1) re-commission the K150 (88") cyclotron, couple it to existing beam lines to provide intense stable beams into the K500 experimental areas and use it as a driver to produce radioactive beams; (2) develop light ion and heavy ion guides for stopping radioactive ions created with the K150 beams; and (3) transport 1+ ions from the ion guides into a charge-breeding electron-cyclotron-resonance ion source (CB-ECRIS) to produce highly-charged radioactive ions for acceleration by the K500 cyclotron. The upgraded facility has been built to extend research capabilities with both stable and radioactive beams and to provide high-quality re-accelerated secondary beams in a unique energy range in the world. Figure 1 shows the layout of the upgraded facility and its major components.

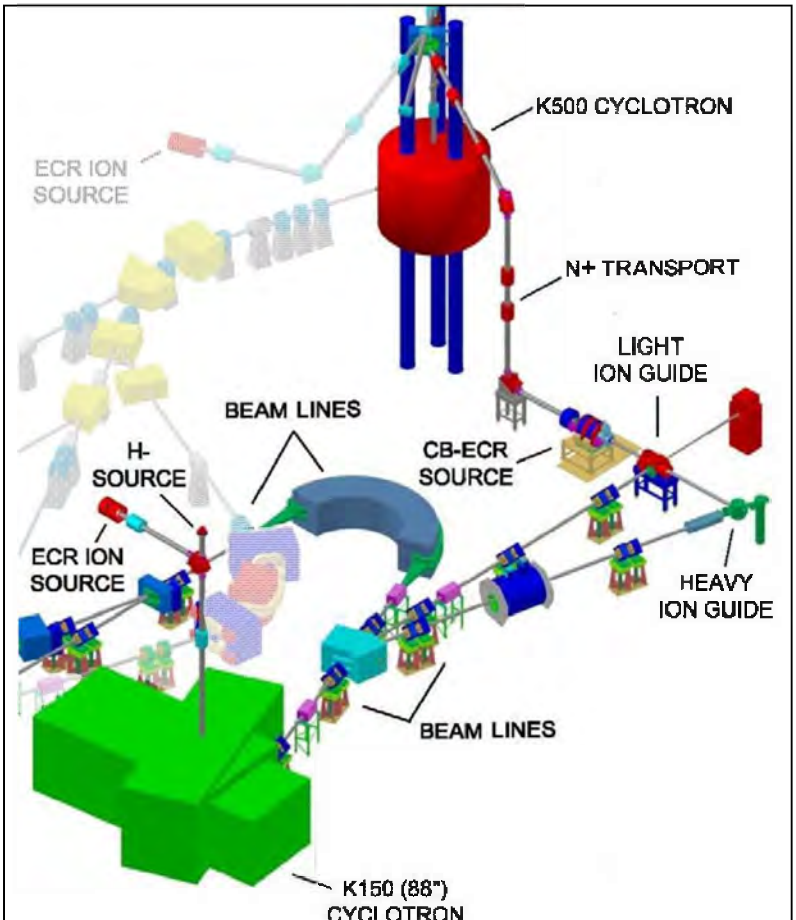

Figure 1. Layout of the Cyclotron Institute Upgrade Project facility. The re-commissioned K150 cyclotron has been coupled to existing beam lines to provide intense stable beams into the K500 experimental areas and will be used as a driver to produce radioactive beams.

Funding in the amount of $5.23M for the upgrade project came from several sources: the Department of Energy ($1.8M), matching support from Texas A&M University ($0.75M), the Robert A. Welch Foundation ($1.0M) and beam time sales for testing electronics components at the Cyclotron Institute ($1.68M). Table 1 summarizes the project expenditures of each major component for Task 1. The funds provided by the DOE were used to cover the costs associated only with Task 1. The remaining costs of Task 1 and the costs associated with Tasks 2 & 3 were paid for by the funds provided by Texas A&M University, the Robert A. Welch Foundation and redirected funds from the Cyclotron Institute's beam time sales. This final technical report will describe the results of the upgrade project of Task 1 where the DOE funding contributed.

Table 1. Task 1 – K150 cyclotron major component expenditures. The funds provided by the DOE were used to cover the costs associated only with Task 1. The remaining costs were paid for by the funds provided by Texas A&M University, the Robert A. Welch Foundation and redirected funds from the Cyclotron Institute's beam time sales.

K150 Cyclotron Major Component	Component Cost
K150 Cyclotron Electrical, LCW & Deflector Equipment	$265,104
K150 Cyclotron Vacuum Equipment	$328,296
K150 Cyclotron RF System	$154,977
K150 Cyclotron Coil Power Supplies	$818,995
K150 ECR2 & H- Ion Sources, Injection Line, Probes, Inflector Equipment	$375,649
K150 Beam Line Electrical Utility Equipment	$121,538
K150 Beam Line Magnets & Power Supplies	$425,634
K150 Beam Line Vacuum Equipment	$177,805
K150 Computer Control System & Interlocks	$34,929
Labor	$307,037
Total Cost	$3,009,964

Tables 2 and 3 list the milestones and performance specifications for Task 1 as detailed in the CIUP management plan. All items have been completed except for meeting the extracted beam intensity milestone of 0.9 pμA of ^{40}Ar at 13.7 MeV/u from the K150 cyclotron. This milestone should be met in the near future as improvements to the operation and vacuum equipment of the K150 cyclotron are made. A brief synopsis for each area of Task 1 is described below.

The construction of the K150 cyclotron radio frequency (RF) system was completed in Q1 FY07 and commissioned in Q3 FY07. The main components of the RF system consist of the RF power supplies, RF control system, RF driver amps, and RF final amplifier. All components were built in house and spare components were built at the same time. The various machine components pertaining to the running/tuning of the RF system were refurbished for proper operation.

The RF control system consists of low voltage power supplies, the modules needed for the RF signal processing, RF driver amplifiers needed to drive the main RF amp, and controls for driving the various machine components relative to the RF system. The anode power supply provides all the power requirements for the 4CW150,000 power tube used in the final amplifier, as well as the interlock system involved in protecting the power supply, final amplifier, and cyclotron components. The final amplifier tube requires grid, screen, and anode power supplies. The grid and screen power supply chassis are contained inside the main power supply cabinet. The final amplifier cabinet was rebuilt with new components and installed on the back of the cyclotron. The filament power supply provides the 15 volts at 200 amps d.c. for the 4CW150,000 tube filament.

Twenty-three new K150 cyclotron coil power supplies (including the 3000 amp - 180 volt main coil power supply) were installed. The supplies were custom built by Alpha Scientific with cabinets that matched the dimensions of the original power supplies and each supply was placed on the original footprint underneath the cyclotron. All supplies have digital-control and are operational from the new K150 computer control system. The power supplies were commissioned in Q2 FY07 and operate at values consistent with those found in the old 88" cyclotron logbooks.

Table 2. Task 1 – K150 cyclotron major milestones and completion dates (from Table 5.6 of the CIUP Management Plan).

WBS	K150 Cyclotron Major Milestone	Completion
1.4.2	Bid Awarded for K150 Coil Power Supplies	Q3 FY05
1.1.2	K150 Vacuum System Design Complete	Q4 FY05
1.5.2	K150 ECR & Injection Line Design Complete	Q1 FY06
1.1.4	K150 Initial Vacuum System Equipment Procured	Q1 FY06
1.1.7	K150 Initial Vacuum System Commissioned	Q4 FY06
1.4.6	K150 Coil Power Supplies Commissioned	Q2 FY07
1.2.7	K150 Start-up Sub-Systems Restored	Q2 FY07
1.3.3	K150 RF System Commissioned	Q3 FY07
1.5.6	K150 ECR & Injection Line Commissioned	Q3 FY07
1.6.2	Extract First Beam From K150	Q4 FY07
1.7.3	K150 Beam Line Materials Procured	Q2 FY08
1.7.5	K150 Beam Lines Assembled	Q2 FY09
1.8	K150 Beams Transported to Ion Guide Cave & K500 Beam Lines	Q2 FY09
1.6.4	Extracted 14 μA 30 MeV Protons	Q3 FY10
1.6.6	Extracted 0.9 pμA 13.7 MeV/u ^{40}Ar Beam	Incomplete*

*Note: ^{40}Ar ions were accelerated to 13.7 MeV/u and extracted; 0.9 pμA intensity was not met.

Table 3. Task 1 – Performance specifications for K150 cyclotron and beam transport of 30 MeV protons to the light ion guide (from Table 3.1 of the CIUP Management Plan).

Performance Specification	Value	WBS	Completion
K150 vacuum	5×10^{-6} Torr	1.1.7	Q4 FY06
Main coil current	800 Amp	1.4.6	Q2 FY07
Deflector voltage	80 kV	1.2.7	Q2 FY07
Dee voltage	60 kV	1.3.3	Q3 FY07
Intensity at K150 inflector	70.0 eμA	1.6.4	Q1 FY10
Extraction efficiency at Faraday cup outside K150	20%	1.6.4	Q3 FY10
Intensity at Faraday cup outside K150	14.0 eμA	1.6.4	Q3 FY10
Transport eff. of focused/collimated beam to light ion guide	71%	2.2.6	Q1 FY11
Intensity at aluminum target at light-ion-guide	10.0 eμA	2.2.6	Q1 FY11

All beam line magnets, support structures, beam boxes, Faraday cups and viewers were built by the cyclotron personnel. The coils for 25 quadrupole magnets and 14 x-y steering magnets were wound with the help of retired cyclotron personnel. The power supplies for the dipole switching magnets and analysis magnets were purchased from Alpha Scientific. The power supplies for the quadrupole and x-y steering magnets were purchased from TDK Lambda. Nine turbo-molecular pumping stations including mechanical pumps were purchased from Pfeiffer

Vacuum Systems for the beam lines. In Q2 FY09, the beam lines connecting the K150 cyclotron to the K500 experimental caves and ion guide caves were made fully operational.

A new radiation area monitoring system was purchased from Ludlum and installed. The system includes gamma and neutron monitors, an air stack monitor and computer control data logger. The gamma and neutron monitors were also installed at locations inside and outside the K150 cyclotron vault and the ion guide cave. The air stack monitor was installed in the vent stack directly above the ion guide cave. All monitors are connected to the data logger in the control room.

The vacuum system of the K150 cyclotron consists of equipment placed externally on the two main sections of the cyclotron (resonator tank and dee tank). The resonator tank has a 35" Varian diffusion pump with a cryogenic baffle backed by an Aerzen roots blower. The dee tank has four Austin Scientific cryopump systems including compressors, transfer lines and VAT isolation valves. These components together provide a vacuum pressure of $1x10^{-6}$ torr which is sufficient for producing high intensity 30 MeV proton beams for the light ion guide experiments.

The dee tank has also been equipped with one large internal cryogenic panel to further improve the vacuum of the cyclotron. The panel has shown to improve the beam transmission efficiency through the cyclotron and is necessary in order to produce high intensity heavy ion beams such as 13.7 MeV/u ^{40}Ar for the heavy-ion guide. The cryopanel has separate channels for LN2 and LHe cooling, although it has only been cooled and beam tested with LN2. With the cryopanel cooled to $74^{o}K$, the improvement in beam intensity was found to be ~21% on average throughout the cyclotron and ~25% at extraction. Further improvement in beam transmission efficiency is expected once the cryopanel is cooled below $18^{o}K$ with both LN2 and LHe.

As detailed in the CIUP management plan, ECR2 and its associated equipment (HV power supply, coil power supplies, analyzing magnet power supply, 14.4 GHz microwave transmitter) were moved over from the K500 to the K150 cyclotron. An injection line including a 90 degree analyzing magnet, two glazer lenses, two solenoid magnets, two steering magnets, power supplies, vacuum equipment and control system were built in order to connect ECR2 to the K150 cyclotron. To aid in focusing the injected beam at the inflector, the center plug of the K150 cyclotron was reconstructed from new iron and the final assembly included a glazer lens, steering elements and an LN2 cryopanel. Construction began in FY06 and ECR2 was commissioned in Q3 FY07. To further enhance the output performance of ECR2, dual frequency heating was added in Q3 FY12 by incorporating at TWTA microwave transmitter. The back plate of ECR2 was rebuilt to allow dual microwave guides.

A negative-ion multi-cusp (H-) ion source was added to the K150 injection line. The ion source was purchased from the University of Jyvaskyla, Finland and was started up with their help. The H- ion source will be used for the production of high intensity proton (and deuteron) beams for the light ion guide. With the deflector pulled back from the extraction channel (but not removed from the cyclotron), H- ions are accelerated to 38" (the extraction channel radius) and then stripped to protons with a thin foil. Upon exit from the cyclotron, the trajectory of the proton beam is steered along the normal beam line with via a dipole magnet. This technique has improved the extraction efficiency to nearly 100% which in turn has greatly reduced interior activation of the cyclotron and neutron sky shine through the injection line hole.

Transport of the negative ions from the ion source through the cyclotron required various equipment to be installed along with the ion source itself. The equipment included the exit dipole magnet with power supply, remote controlled carbon foil stripper system, computer control system, gas system, three Leybold 1000 l/s turbo pump systems, Faraday cup, beam line isolation valves, two beam line chambers, three Einzel lenses, x-y steering magnet, high voltage platform with isolation transformer and Glassman brand power supplies for the ion source puller, high voltage platform and Einzel lenses and TDK Lambda brand power supplies for the ion source arc and filament. In order to deflect H- ions into the center region of K150 cyclotron, the original inflector power supply was replaced with a negative potential 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 magnetic fields from the trim and valley coils are reversed in order to accelerate H- ions. However, those supplies can switch between positive and negative potential so no modifications were needed.The H- ion source system was fully installed by Q2 FY10 and the milestone of 14 μA 30 MeV protons extracted from the K150 cyclotron was met in Q3 FY10.

Following the Berkeley design, a set of dee inserts or "batwings" made from titanium with mounting mechanisms were constructed and installed on the K150 cyclotron. From the mirror inflector at the center of cyclotron, the acceleration process starts with the help of the Berkeley designed dee inserts. One dee insert is attached to the active dee and the other to the dummy dee. The dee inserts are installed around the inflector housing and provide a well-defined electric field near the center of the cyclotron. The horizontal gap between the two dee inserts is 0.25 inches, and the extent of the dee inserts along the dee lip is only a few inches. The nominal gap between the dee and the dummy dee is 2 inches long.

To reach the project milestone of 12 eμA (0.9 pμA) of $^{40}Ar^{14+}$ at 13.7 MeV/u extracted from the cyclotron, four areas of the operation must be optimized simultaneously 1) ECR2 output must be maximized by employing two frequency heating, 2) the cyclotron vacuum must be improved to its highest level by adding LHe to the cryopanel, 3) the correct trim coil parameters, inflector position and vertical position of the beam must be verified and 4) the deflector must be conditioned to hold high voltages.

In Q3 FY12, ~1 eμA of $^{40}Ar^{14+}$ at 13.7 MeV/u was measured at the extraction radius of the cyclotron, but not extracted from the cyclotron because the required deflector voltage was much higher than what the deflector could hold at the time (60 kV at that time). 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 $^{40}Ar^{13+}$ it would have been 95-97 kV. We did extract 12 MeV/u $^{40}Ar^{16+}$ with 70 kV on the deflector, and then 12 MeV/u $^{16}O^{6+}$ with 75 kV. We conditioned the deflector up to 81 and 80 kV on two separate occasions to extract 14 MeV/u $^{18}O^{7+}$ and 15 MeV/u $^{20}Ne^{9+}$ beams, but we could not push it any higher, and the 12 MeV/u $^{40}Ar^{13+}$ 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 $^{40}Ar^{13+}$ from the cyclotron.

In Q1 FY13, after a week of conditioning, the deflector held at 88 kV and we were able to extract the 13.7 MeV/u $^{40}Ar^{14+}$ (q/A=0.350) beam. We started the beam development by injecting $^{40}Ar^{16+}$ and $^{20}Ne^{8+}$ (q/A=0.400) beams and extracting them with 78 kV on the deflector. Next, we injected $^{16}O^{6+}$ (q/A=0.375) and then extracted the beam with 83 kV on the deflector. The extraction efficiency ranged from 40 to 60% for these beams. The injection efficiencies were around 12%, and the internal transmissions to extraction radius were around 75%.

The extracted current for the $^{40}Ar^{14+}$ beam was only 150 enA out of 4.7 eμA, a 3.2% throughput from ILC02 to FC02. At the same energy, $^{14}N^{5+}$ (q/A=0.375) beam yielded 5.4% throughput, which seemed to indicate somewhat higher vacuum attenuation effects for the argon beam. With the goal of extracting 0.9 pμA of ^{40}Ar beam from the cyclotron, if we could get 77 eμA out of ECR2 (equaling the AECR-U output for $^{40}Ar^{14+}$), with 3.2% throughput we could achieve 2.5 eμA or 0.18 pμA. Or, with improved cyclotron vacuum, we could get 4.2 eμA or 0.30 pμA, which is 1/3 of 0.9 pμA, using 5.4% throughput number we obtained for $^{14}N^{5+}$ beam. Obviously any improvement in the injection, the internal transmission, or the extraction, which we will work to improve, will help the final beam intensities. Of course we were originally thinking of using more intense $^{40}Ar^{13+}$ (120 eμA vs 77 eμA for the 14+ from AECR-U) with 10% throughput to achieve the 0.9 pμA goal. But Ar^{13+} would obviously require higher deflector voltages than we used for the Ar^{14+}. In the meantime, we will continue to work with Ar^{14+}, striving to increase its beam intensity: improve ECR2 output, the injection through the inflector, and the internal transmission with better vacuum.