COMMISSIONING OF THE UPGRADED K500 SUPERCONDUCTING CYCLOTRON

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An element of the Coupled Cyclotron Project (CCP) has been the refurbishing and upgrading of the K500 cyclotron [1]. The K500 was operated from mid-1993 through 1995 to determine the required upgrades, develop beam diagnostics, and measure beam parameters for the injection and coupling beamlines. Many upgrades were implemented during this time including; second harmonic buncher, second harmonic spiral inflector, M4 diagnostic probe, improved extraction optics, and a non-intercepting beam probe [2].

Construction and commissioning of the new K500 injection line took place during most of 1996. During that time, most of the K500 subsystems were disassembled, and only main magnet operation was maintained to verify that the injection line's magnetic shielding and compensation performed adequately. In September 1996, the injection beamline was shutdown and disassembly of the K500 steel began. At that time, the vault had been completely stripped with only the K500 steel, cryostat and injection line remaining. All designs were complete and construction of the subsystems was underway in 1997 [3].

The return yoke's median plane was modified to decrease the azimuthal asymmetry in the magnetic field which had forced the coil to operate off-center. The cryostat outer diameter was also modified to decrease any azimuthal asymmetry. New center plugs were designed to simplify and improve the vacuum, allow use of the inner trim coil (trim coil zero) without steering the injected beam, and improve axial injection by smoothing the field along the vertical injection line inside the yoke.

The inner diameter of the cryostat was stripped and plated. Vacuum leaks through the liner were repaired. Some of the cooling lines on the liner had been pinched, and required modifications and repairs to the cooling lines and liner supports. A second O-ring groove was cut in the lower beam chamber seal for increased reliability. Many of the trim coil fittings and all of the trim coil vacuum feedthroughs were replaced. The pole caps had many cracks in the casting which were identified and welded to reduce leaks into the liner vacuum.

By the end of March 1997 all repairs to the K500 cyclotron were complete and reassembly of the machine started. The vault electrical, lighting and low conductivity water distribution were installed. A new main magnet power supply and trim coil solid state reversing switches were completed. Also, a new adjustable, combined quadrupole/dipole magnet was installed in the extraction line at the return yoke. The main coil was cooled and ramped to full field in August 1997.

The median plane mapper was installed in September 1997. A search coil and NMR probe were used to map the field over the entire range of excitations along with the trim coil fields. Additional steel was added and hill extension steel removed to fully compensate measured imperfections before the final measurements were taken. The median plane mapper was removed in February 1998 and Hall probe mappers were installed to measure the field in the vertical injection line and the extraction line.

The transmitters were constructed in parallel with installation of the cyclotron and the magnetic mapping. In April 1998 they were tested individually into a resistive load to about 50 kW over the required frequency range. This power level is adequate to obtain the maximum 75 kV dee voltage. During the transmitter tests, the upper resonators were mechanically completed, leak checked and low level rf measurements made which were consistent with the design values.

The vacuum system was assembled and tested with blanks over the rf ports to confirm all inaccessible vacuum seals were good, after which the resonators, couplers and cryopanels were installed.

The liner vacuum was about 10 mTorr and the main chamber vacuum reached the low 10^{-7} torr range with the liquid nitrogen and helium cryopanels. This pressure is adequate for good transmission of the heavy ions.

By the end of June 1998, the lower resonators, valley liner sections, coupling/extraction beamline, control systems, and resonator cooling water circuits were finished, and all systems required for commissioning were complete. Shakedown and integration of all the subsystems began immediately with the goal of extracting beam before the National Science Foundation's CCP review in late July 1998 [4].

EXPERIMENTAL RESULTS

The primary commissioning goals were to confirm that the magnetic field maps accurately predict the cyclotron settings for rapid beam changes, and that the full range of ions and charge states for coupled cyclotron operation can be accelerated and extracted.

A low energy beam requiring low rf and magnetic field that generates very little radiation was chosen as the first beam to accelerate. Early in July 1998 a 4.0 MeV/u $^{16}O^{2+}$ beam was accelerated to full energy on the first day attempting to do so. Less than one week later after completing all extraction systems and the roof shielding, this same beam was extracted, again on the first day attempting to do so.

All of the beams accelerated during the commissioning run are listed in Table 1. The beams accelerated range from near the lowest energy to the highest energy, 16 MeV/u, which corresponds to the beam that is accelerated to 200 MeV/u in the K1200 cyclotron. All of these beams confirmed the accuracy of the magnetic field maps since beam was extracted using the predicted settings with very little tuning.

Table 1. Ions extracted from the K500 cyclotron during commissioning.

E(MeV/u)	Ion
4.0	$^{16}O^{2+}$
4.0	$^{40}Ar^{5+}$
4.0	$^{136}Xe^{17+}$
4.0	$^{238}U^{27+}$
4.4	$^{84}Kr^{8+}$
16.1	$^{16}O^{3+}$

The majority of the commissioning time was devoted to quantifying the system performance for the 4.0 MeV/u $^{16}O^{2+}$ beam due to its reduced demands while breaking-in all of the cyclotron systems. The best overall transmission from the ECR to extracted beam on a given day is shown in Table 2. The 29 % transmission from the ECR ion source to the spiral inflector is caused by an aperture (4 mm inner diameter by 89 mm length) placed just before the spiral inflector to produce a clean, well centered beam inside the cyclotron. Without the aperture over 90 % of the beam can be transported from the ECR ion source to the spiral inflector. The capture efficiency with the first harmonic buncher was 27 %, which was within design values for a long bunch. The extraction efficiency was 47 % during this run, but during subsequent runs a maximum extraction efficiency of 67 % was obtained. The overall transmission from the source to extracted beam was 3.7 %. While this is lower than the design specifications, individual improvements have already been made as stated above and further improvements are expected as the overall performance is better understood. The emittance was measured using slits and wire pickups or phosphor viewing screens on both the injected beam and the extracted beam, but further refinements will be required before these values can be reliably determined.

Table 2. Transmission of 4 MeV/u $^{16}O^{2+}$ (data 10/8/98)

	Fraction of beam transported
ECR to Spiral Inflector	29 %
Spiral Inflector to Internal	27 %
Internal to Extracted	47 %
TOTAL ECR to Extracted Beam	3.7 %

One of the highest energy and power beams planned for CCP operation is the 16 MeV/u $^{16}O^{3+}$. This beam pushes the rf, deflector and magnetic fields to their maximum levels, requires the most cooling on extraction elements and generates the highest radiation levels. A high power beam was accelerated to full energy and stopped internally by the water cooled main probe. The maximum current demonstrated was 7.3 eµA with a beam power of 630 W, and could have been increased to 21 eµA by removing attenuation in the injection line if the power level on the probe and radiation limit on the roof could handle it. The maximum internal current required for CCP operation with this beam is 7.8 eµA, which shows the K500 can exceed the highest required currents and powers. Because the deflector was not water cooled the beam was extracted at lower power levels with ~50 % extraction efficiency.

Vacuum attenuation due to electron pickup or stripping places fairly stringent requirements on the K500 vacuum system. All of the 4 MeV/u beams exhibited some attenuation in general agreement with theoretical predictions. The worst case, as expected, was the $^{238}U^{27+}$ which was attenuated roughly 17% in the injection line at ~$2x10^{-7}$ torr, and 40% in the K500 at ~$8x10^{-7}$ torr. These levels of attenuation, which will be improved with leak checking and longer pumping, were considered acceptable for the worst case beam. During later runs after extended pumping and repair of leaks, the injection line vacuum was ~$5x10^{-8}$ torr and the cyclotron was in the low 10^{-7} torr range.

During a nuclear physics run with both cyclotrons operating, their rf systems were integrated and the dee voltages of the K500 and K1200 cyclotrons were phase-locked. This test confirmed the ability to operate the coupled cyclotrons with stable phase-locked rf.

A few of the 4.0 MeV/u beams were stripped to higher charge states using a 200 $\mu g/cm^2$ foil in the extraction channel where the high magnetic field acts as a spectrometer. The charge states generated were in good agreement with the predictions. Lifetime tests were planned in the high magnetic field, but no failures were observed because the beam size/density and corresponding lifetime were much larger than they will be at the foil inside the K1200.

An issue that remains to be resolved is the vertical motion of the beam at extraction. Observations of the motion, which may have degraded the extraction efficiency and increased the extracted emittance, indicate the vertical position of the superconducting coil is responsible. Since the coil will need to be realigned after the CCP shutdown when cryogenics are reconnected, it was decided to complete this study once operation is resumed.

FUTURE WORK

Commissioning studies were completed in December 1998 and the K500 cyclotron and injection lines were placed in standby. Afterwards the new anode power supply (K500 Phoenix) and EPICS control of the magnet power supplies were completed. The only significant modifications that remain to be completed before operation resumes are the high power deflector and M-channel upgrades. Also, improved extraction diagnostics will be implemented in the coupling beamline to measure the beam functions such as emittance, energy and energy spread. The schedule calls for the K500 to resume operation in early 2000 for coupling beamline and K1200 cyclotron injection studies. Full CCP commissioning through the A1900 fragment separator is scheduled to begin in January 2001.

References

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