COMMISSIONING OF THE COUPLED CYCLOTRON SYSTEM AT NSCL*

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Abstract

The Coupled Cyclotron Facility at Michigan State University is being completed with the experimental program scheduled to start in July 2001. Beam from either the recently completed room temperature ECR or from the existing superconducting ECR is injected axially into the refurbished K500 cyclotron, sent to the K1200 cyclotron via a new beam line along the median plane and stripped by a carbon foil located inside a dee for injection. First beam through the paired cyclotrons was obtained on 10 October 2000.

1 INTRODUCTION

In the early 1990's the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) explored different options in upgrading facilities to meet anticipated experimental demands for a wider variety and greater intensity of radioactive nuclear beams. Such beams were being made at NSCL by projectile fragmentation where stable ion (primary) beams from the K1200, directed onto a target at the object of the A1200 [1], produced unstable fragments which were then separated and sent on to experimental vaults as a radioactive (secondary) beam. One way to increase secondary beam intensity is to raise the primary beam energy, which achieves a large fraction of the maximum production rate at 400 MeV/u. Raising primary beam energy from the present limit of 200 MeV/u however was rejected on the basis of cost and timeliness for the intermediate term and two other options were explored instead. One was to enhance transmission efficiency with a new higher acceptance particle separator, now also being commissioned as the A1900 [2]. The second option described here was to increase primary beam intensities available from the K1200.

These considerations led in 1994 to the publication of a white paper [3], which included a refurbishment plan of the K500 cyclotron for use as an injector to the K1200. Although the maximum final energy of any accelerated particle remained 200 MeV/u, such a scheme allowed higher intensities overall as well as raising energy limits for the heavier ions. By way of example, in stand-alone mode (direct injection of beam from the ECR into the K1200), the ECR must produce fully-stripped $^{16}O^{8+}$ in order to accelerate that ion to 200 MeV/u. By instead using $^{16}O^{3+}$, source output is increased by roughly a factor of 1000, which more that compensates for losses involved in using a second accelerator stage.

The US National Science Foundation approved this project in 1996. Construction started immediately, resulting in first beam through the coupled system in October 2000.

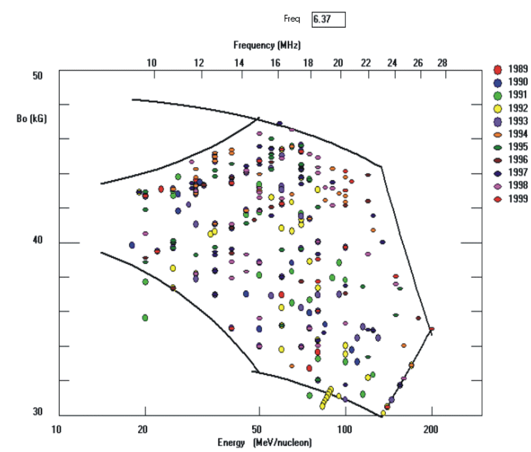

Figure 1: Operating diagram of the K1200 cyclotron showing the beams extracted in stand-alone mode in the central field Bo (kG) vs. energy (MeV/u) plane.

2 ECR AND INJECTION LINE

2.1 ECR's

NCSL presently operates two ECR's, one superconducting (SCECR) and the other (ARTEMIS [4]) with room temperature magnets built from a design based on the AECR at LBNL. The original room-temperature source (RTECR) has been decommissioned. Appropriate beam lines allow either source to inject beam into either cyclotron since stand-alone K1200 operation is still possible after the upgrade. (Stand-alone was retained to be able to continue to provide certain energy/particle combinations that are not available in coupled-mode). Injected beam intensities are controlled by a series of attenuation screens in these beam lines allowing changes in factor-of-3 steps downwards from full beam to about 10^{-7} of that value.

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2.2 Fringe Field Issues

One problem addressed during reconstruction of the injection line into the K500 cyclotron was the effect of non-symmetric fringe fields.

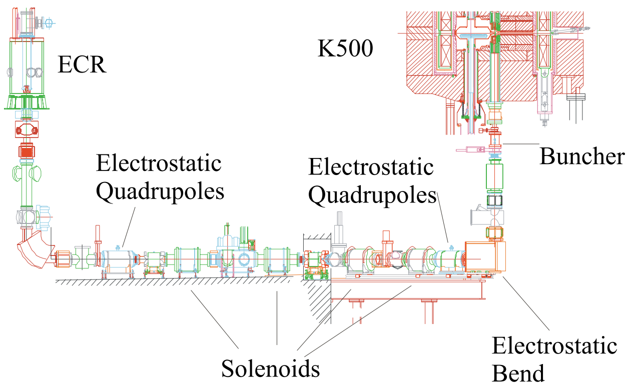

Figure 2: Layout of the ECR to K500 low energy beam transport line.

Beam from the ECR sources is directed vertically down, horizontal, then vertically upwards along the K500 field axis (see Figure 2). K500 fringe field effects are already significant (300-400 G) at this upwards bend. In the previous configuration the bend was produced magnetically. The iron of this magnet and of the shielding on the horizontal beam line produced a significant asymmetry of the vertical field lines, disturbing the K500 solenoidal fringe field. To minimize this asymmetric situation we introduced dummy iron volumes that mimic the iron shielding around the beam line and replaced the 90 degree bending magnet with an electrostatic deflector enclosed in an iron box to reduce the effects of the fringe field. This configuration has provided a more symmetric fringe field thus simplifying the beam tuning by reducing needed steering corrections.

3 K500 CYCLOTRON

3.1 Refurbishment

The K500 cyclotron was completely disassembled. It was necessary to rotate the whole cyclotron in order to direct extracted beam to the K1200 instead of to the experimental vaults as before. Additionally, the magnetic circuit, cryostat and return yoke were modified for greater symmetry to reduce first harmonic effects in the beam chamber area. It became obvious during magnetic mapping that this task was much more complicated than anticipated because small amounts of steel in the yoke had strong effects on the magnetic field. A compromise solution was found between operation at the lowest and highest fields.

The RF amplifiers were also redone to make them more similar to amplifiers and related systems used in the K1200. The main magnet power supply was rebuilt and much better stability was obtained.

3.2 Performance

The K500 cyclotron has shown a much-improved stability compared to its operation before the refurbishments mentioned above. Extracted beam current remains constant without interruption for many hours with little operator intervention. We are presently studying long-term phase stability with non-intercepting probes. Figure 3 shows a probe trace from the K500 cyclotron. This probe consists of a differential wire followed by a main "block". The wire allows us to see the turn pattern at small radii as well as precession signature at larger radii. The K500 is operated in broad phase, multi-turn extraction mode; hence extraction efficiency is typically between 65 and 75%. An interesting but not yet understood observation is shown in Figure 4 where K500 extracted current is plotted as a function of the buncher voltage. By changing the attenuators we can change the beam intensity without modifying the injected phase

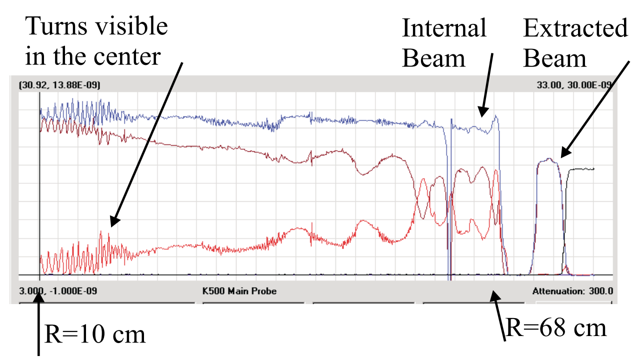

Figure 3: K500 beam probe trace.

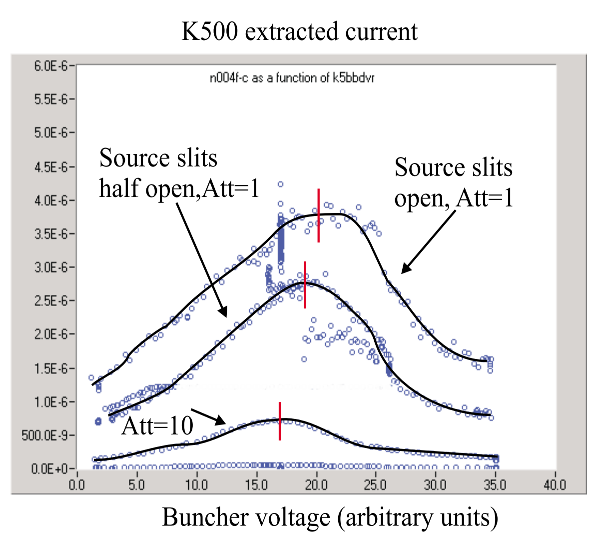

Figure 4: Extracted current from the K500 cyclotron as a function of the buncher voltage for different intensities. The un-attenuated beam from the ECR was 85 micro ampere (40Ar7+).

space. When plotting curves for various levels of attenuation they generally scale normally, obtaining the same bunching gain for all voltages. But when working at the highest intensities, with attenuation factors of 10 and 1 (no attenuation), behaviour is abnormal; the curves are not proportional increasing current. The possibility of space charge effects had been explored but our models did not show any significant effects at these intensities.

4 COUPLING LINE

4.1 General Description

The coupling line transports the beam from the K500 to the K1200 with tuning enough flexibility to match the K500 extracted beam to the required phase space at the entrance of the K1200. For purpose of matching we have implemented an emittance measurement system. The coupling line consists of a superconducting dipole, nine superconducting quadrupoles and several room temperature steering magnets. Two pairs of defining slits in each plane are available to reduce the beam halo and better define the beam, thus reducing losses in the K1200.

4.2 Emittance Measurements

The emittance measuring system consists of two pairs of Parallel Plate Avalanche Counters (PPAC) that determine the (x,y) position of every ion with an error of less than 1 mm. By using two stations separated by approximately 3 meters we can precisely determine the transverse phase space of the beam. The limitation of this system is that it works with low intensities. We have to attenuate the beam in the injection line with the maximum level of attenuation available (10^7). As the attenuators sample the beam, this measurement is valid as long as space charge forces are not an issue.

Recent measurement have indicated a larger emittance (10π mm mrad) than can be injected in the K1200. We use the defining slits to cut down the beam emittance. We are in the process of building a slit system for the ECR injection line that will limit the phase space injected in the K500. Further studies in this area are necessary.

4.3 Energy Measurements

It is important to determine the beam energy to be able to match the injected beam to the closed (accelerated) orbit of this corresponding energy. Any error in this measurement will put the stripper foil in the wrong place and consequently the beam will be off-centered. The energy is determined by the time of flight between the first PPAC of the emittance measuring system and a third PPAC located approximately 11 m downstream. In most cases, the measured energy is approximately 1% below the nominal calculated extraction energy.

5 K1200 CYCLOTRON

5.1 Injection Channel

The injected beam path inside the K1200 cyclotron is shown in Figure 5 The arrow at the top points to a dipole just outside the figure. The dipole quadrupole combined magnet has a tapered pole shape and a single coil [5]. The quadrupole field is then determined by the bending needed. The matching must be done with quadrupoles upstream in the beamline.

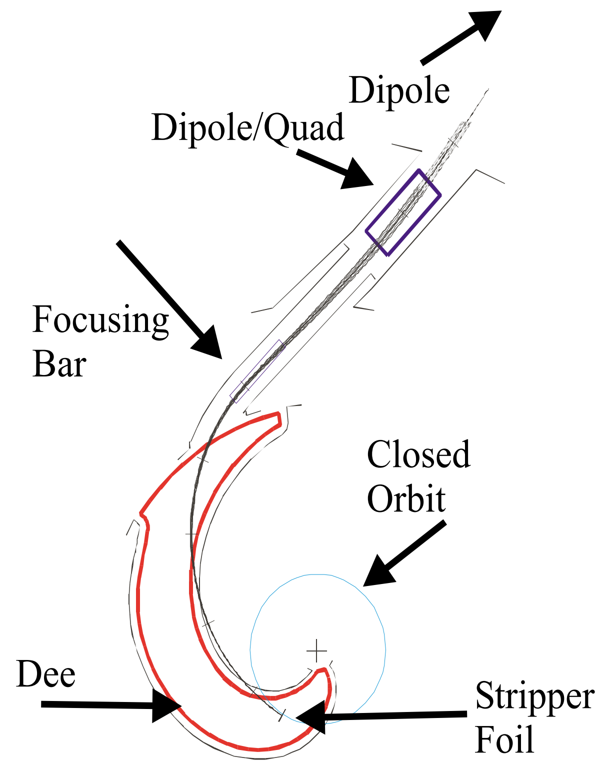

Figure 5: Injection channel path. A dipole is situated just outside the top of the figure. The thick red line indicates the dee profile

The label “Focusing bar” points to a passive element built in a similar way to our extraction focusing bars. It is a conical cluster of three bars that produces a field gradient at the beam path. These focusing elements are needed because of defocusing gradients seen by the beam when traversing the superconducting coil and hill-valley transition regions. Due to this high gradient, beam tuning is quite sensitive. Beam also experiences transverse forces due to the RF field in the gap region. Consequently beam position at the stripper foil is phase dependent, and even initial tuning must be done with RF phases and voltage close to final values.

5.2 Stripper Foil Mechanism

The stripper foil mechanism [6] is probably one of the most complicated devices we have installed during the upgrade. Its purpose is to position a thin stripper foil at the matching point inside the dee with an accuracy of 0.3 mm and also allow a large reserve supply (31) of foils for immediate use. A foil loader system to replace reserve foils under vacuum has been designed and is under construction. When installed, the foil loading will be done by moving the mechanism to a “loading position” and lifting the whole platter to the median plane.

The limited space available inside the dee made the design and construction a challenging project. A pair of hydraulic cylinders moves a platter in two directions to position the foil and another pair moves a bicycle chain where the foils are attached. A ramp brings the foils from their horizontal, off the median plane position, to a vertical position, and later back to horizontal when no longer needed.

Our estimates of RF electrical currents inside the dee were not correct and thus temperatures were higher than anticipated, melting some plastic hoses of the mechanism. A copper shield that covers a large fraction of the dee was then retrofitted. This shield provides then a path for these currents. We now monitor the temperature and RF pick-up inside the dee. We have now used it for many weeks at 140 kV dee voltages with no problems.

5.3 Centering Problems

The original plan for injecting the beam to the stripper foil was to tune the dipole in the coupling line indicated by the top arrow in Figure 5 and the dipole/quad combined magnet in conjunction with the focusing bar in the injection path. By moving the foil to a smaller radius the beam is not stripped and continues in a path that will be intersected by a TV-viewer probe downstream. We pre-calculate the position of the stripper foil and the position of the un-stripped beam at the probe path. By moving the foil and looking at the shadow on the probe we can measure the beam radius at the foil azimuth as well as its width. Although this method works, it proved too slow and time consuming. The adjustment range of the three magnets was not adequate for everyday tuning. We then decided to modify trim coil 5 to provide a first harmonic contribution as well as an overall average field. It was necessary to rewire the leads and connect two new power supplies. Trim coil 5 was selected because its peak field occurs at the radius of the stripper foil. This first harmonic bump displaces the closed orbit to match the injected orbit and adiabatically brings the beam back to a centered, accelerated orbit. As a significant bump (50 G) is necessary to correct a 6 mm off centering, the possibility exists that the stable region in phase space is reduced significantly. Figure 6 shows the stable region behaviour for a 50 gauss bump with six different azimuthal phases. Although reduced with respect to the unperturbed field, the stable region is still large enough (more than 2.5 cm minimum size). The effect on the closed orbit at the approximate azimuth of the stripper foil is shown in Figure 7.

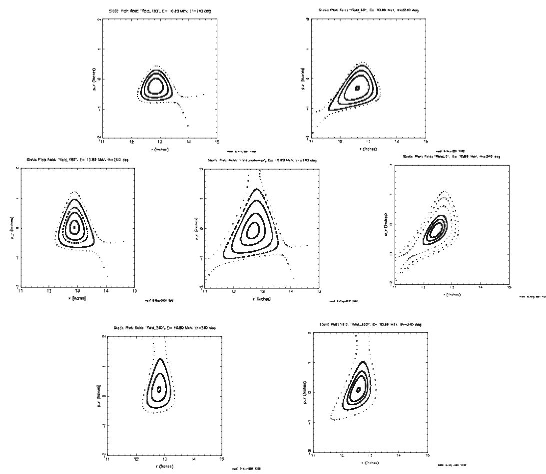

Figure 6: Static phase space plot for the perfect field (center) and for six different bumps in trim coil 5. All of them have a 50 gauss amplitude, but with azimuths changing by 60 degrees.

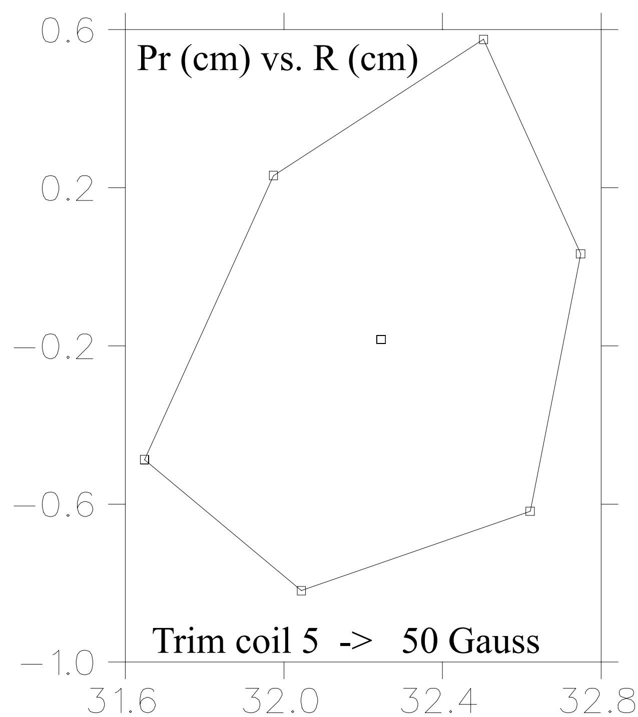

Figure 7: Closed orbit displacement induced by the trim coil 5 in the K1200 cyclotron. The first harmonic magnitude is 50 gauss and rthe azimuth varies 60 degrees betwen points.

5.4 Extraction Issues

Superconducting cyclotrons of the compact type have limited space in the extraction region between the coils to place the electrostatic deflectors. One of the concerns we had at the beginning of the upgrade was the improvement of the electrostatic deflectors at high beam power. Due to the short range of heavy ions a very high power is deposited on the deflector septum in a small area. A new deflector and septum design has been tested up to 1 kW of lost power [7].

5.5 Performance

The first nuclear physics experiment was finished on June 4th, 2001, with the more complete experimental program expected to start in July. The system performed smoothly running with a beam attenuation factor of 30 and delivering 4.1 x 10^{10} particles/second. We have not increased the intensity to the design values yet to avoid activating the components before a thorough check has been performed. The radiation safety system is being verified at the same time.

We show in Figure 8 a beam probe trace of the extraction region of the K1200 cyclotron. The probe measures the internal beam for radius below 40.5 inches, and extracted beam for radius between 40.5 and 42 inches. For larger probe radius the beam is read by a Faraday cup in the external beam line (purple curve). The extraction efficiency is in the 60-70% region. The overall efficiency for the whole system is at this point approximately 2%. There are several areas that can be improved and will be addressed as time allows.

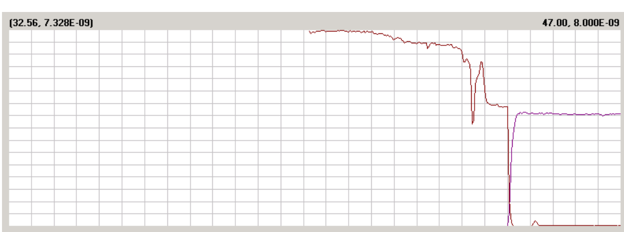

Figure 8: Beam probe trace from the K1200 cyclotron in the extraction region (red curve) and on the Faraday cup outside the cyclotron (purple). Scales are 0 to 8 nA (vertical), and for probe radius 20 to 47 inches (horizontal).

6 CYCLOTRON SETTINGS

The settings for the two cyclotrons, main coils, trim coils, extraction element positions, etc, are calculated with a new program NORTIC [8]. The injection path and associated magnet settings are calculated with the program INJORB [9]. The only parameters normally adjusted by tuning are the injection and extraction first harmonic bumps, and small adjustments to the extraction elements.

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