STATUS OF THE COUPLED CYCLOTRON FACILITY AT NSCL

P. Miller, F. Marti, D. Poe, M. Steiner, J. Stetson, A. Stolz, P. Zavodszky NSCL, East Lansing, MI 48824, USA

Abstract

The Coupled Cyclotron Facility at Michigan State University was completed in July 2001. It has produced dozens of secondary beam species for the users performing experiments, from about 14 primary beams (O to Bi) with energy in the range 80 to 160 MeV/u. To enhance the yield of rare isotopes, the primary beam is generally a separated isotope with either the largest or the smallest neutron excess available. The facility has two ECR ion sources, feeding two superconducting cyclotrons in tandem, followed by the secondary beam production target and the A1900 fragment separator. The ongoing effort to understand the beam formation process with space charge effects and improve the matching of the ion source output to the first cyclotron is expected to increase the beam output of the facility.

INTRODUCTION

The Coupled Cyclotron facility at the National Superconducting Cyclotron Laboratory at Michigan State University was the result of a five year project to construct a new fragment separator and to refurbish the K500 superconducting cyclotron for use as an injector for the K1200 cyclotron. The goal was to increase the secondary (radioactive) beam intensity by several orders of magnitude and to increase the energy for heavier ions. The maximum energy for ions with charge-to-mass ratio ½ is limited to 200 MeV/u by the focusing limit of the K1200. This project was completed in July 2001. [1]

OPERATING EXPERIENCE

Radioactive ion beam research is predominant. Only 5% of the beam time run for experiments has been using the primary beam alone. Since we need to produce beams of radioactive ions which are distant from the "valley of stability" in the traditional mass chart of nuclei, it is inefficient to use a primary beam derived from source feed material having the natural abundance of isotopes. There is typically a large intensity gain from producing the desired radioactive beam with a primary beam of the isotope with the largest or the smallest available neutron excess, depending on the neutron excess of the desired secondary beam particle. These isotopes have a low natural abundance and relatively high cost in enriched form. For example, the production rate for neutron rich secondary beams of nuclides with mass number below 35 from a primary beam of ^{48}Ca may be 10 times larger than the rate if the primary beam is ^{40}Ar instead, at the same intensity. While it is cost effective to use expensive enriched isotopes as source feed material, doing so adds more importance to the efficiency of the ion source for converting the feed material to ions in the beam. Our consumption rate for ^{48}Ca (metal form) delivered from a miniature internal oven has typically been about 1 mg/hr for intensity of 15 particle nA.

The primary beam species that have been delivered to users are listed in Table 1. The direct beam line from the ion sources to the K1200 has remained operational to allow the K1200 to operate standing alone, for lower energy beams than can be produced by the coupled cyclotrons. The conversion from coupled to stand-alone operation takes a few days and has been done once so far.

Besides the predominant nuclear physics work, a small fraction of the beam time (4%) is used for irradiations of various kinds of samples for specific applications. Several groups have used ions of different masses and velocities to deliver controlled doses of energy to electronic devices or biological samples. The linear energy transfer (LET), the rate of energy transfer per unit length of ion track, can be varied to simulate the effects from various cosmic rays that might be encountered by the final devices. The response of biological molecules to irradiation is different, depending on the LET value. High LET is achieved in practice using heavy ions; the high beam velocity needed to allow the ions to penetrate the dead layer or container is available at a large accelerator such as the NSCL coupled cyclotrons.

The beam list shown in Table 1 gives the average intensity of beam out of the Coupled Cyclotrons used for planning experiment durations. The beam time that is approved by the Program Advisory Committee is based upon the available intensity given there. The secondary beam intensity is estimated from models of the interactions in the production target, the effective acceptance of the A1900 fragment separator and the transmission efficiency to the user's target.

Table 1—Primary beam list for the Coupled Cyclotron facility

Particle	**Energy per nucleon [Mev/u]**	**Intensity [particle-nA]**	**Power [W]**
^{16}O	150	100	240
^{18}O	120	100	216
^{36}Ar	150	40	216
^{40}Ar	140	40	224
^{40}Ca	140	15	84
^{48}Ca	90	15	65
^{48}Ca	110	15	79
^{48}Ca	140	15	101
^{58}Ni	140	5	41
^{58}Ni	160	5	46
^{64}Ni	140	7	63

^{76}Ge	130	10	99
^{78}Kr	140	15	164
^{86}Kr	100	7	60
^{86}Kr	140	15	181
^{124}Xe	140	1.5	26
^{124}Sn	120	1.5	22
^{136}Xe	120	2	33
^{209}Bi	80	0.1	1.7

The ongoing R&D to increase transmission efficiency from ion source to the K500 injector cyclotron will be addressed below, and in another paper in greater detail [2]. The transmission efficiency of the cyclotrons and the coupling beam line between them is approaching the theoretical maximum, and seems to be generally understood. The cyclotrons are accelerating a broad phase distribution (30 rf degrees). The extraction efficiency is improved as the quality of the injected beam in improved, that is, as the emittance is decreased, in agreement with numerical simulations[3].

The probe data showing the best extraction efficiency (90%) observed in the K500 are shown in Fig.1. Note that this performance was with a rather high intensity ^{78}Kr beam of 1 μA.

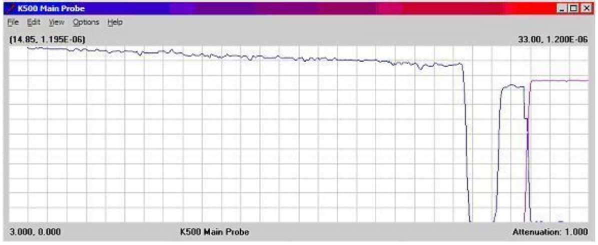

Figure 1: K500 probe trace

Fig. 2 shows probe traces for a ^{40}Ar beam. The extracted current is 1.8 μA of ^{40}Ar^{7+} (12.5 MeV/u) from the K500, and 0.9 μA of ^{40}Ar^{18+} (140 MeV/u) from the K1200. There is some loss of signal from the K1200 probe which varies with the probe radius, due to the increasing range of the particles and the probe geometry.

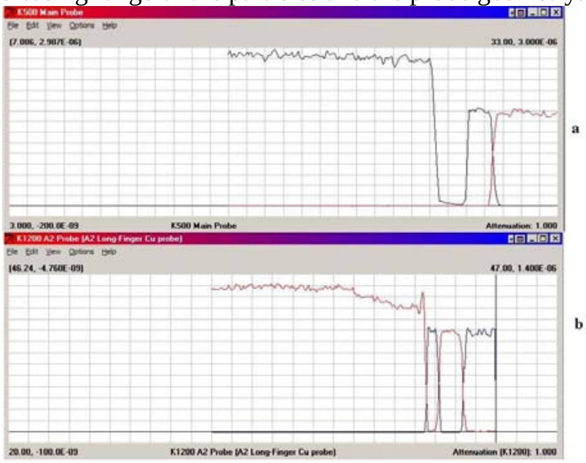

Figure 2: Argon beam probe traces (a) K500 probe, (b) K1200 probe

Operating Statistics

In 2003 the NSCL was running 5561 hours, of which 2136 was Development and Tuning and 3425 h was beam to Experiments. There were 1142 h of Unscheduled off, due to equipment failure, etc., and 2056 h Scheduled off. The Availability was 83%.

In 2004 (first 3 quarters) there has been less running time due to funding limitations. We are performing refurbishment and upgrade projects intended to increase reliability, in addition to maintenance, during scheduled off periods. The total time running was 3621 hours, of which 1570 was Development and Tuning and 2051 h was beam to Experiments. There were 604 h of Unscheduled off, and 2349 h Scheduled off. The Availability was 86%. The graph of the statistics by calendar quarter is in Fig. 3.

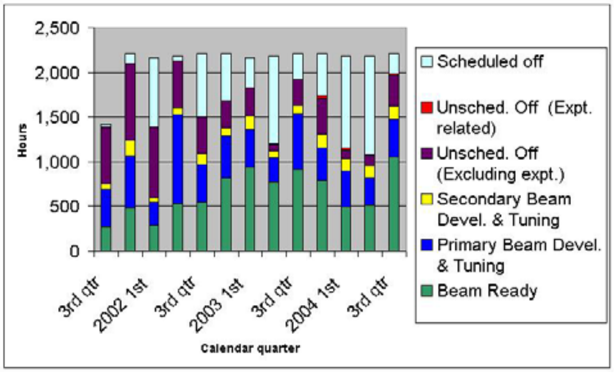

Figure 3: operating statistics

A1900 Separator Performance

The A1900 fragment separator [4] was modified since its completion in 2001 by adding devices (fixed and movable slits and energy absorbers, or “wedges”, detectors) to enhance its performance, such as the beam purity, in specific situations. One example is the movable slit system installed at Image 1 this year, which is used to help separate neutron deficient nuclei from the much more abundant ones in the range of charge states coming from the target. (See Fig. 4) With the background ions eliminated from the detector downstream by the use of the additional slit and wedge, the detector counting rate becomes low enough to allow detection of the rare neutron deficient isotopes, such as ^{45}Fe.

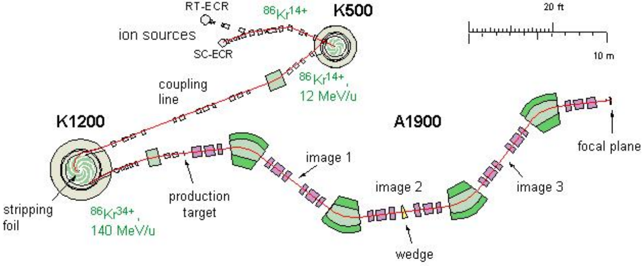

Figure 4: A1900 Plan view

Experimental End Station Equipment

A gas catcher designed to stop rare ions in He gas and accelerate them to kV energies is being developed and tested. It works in conjunction with the LEBIT (Low energy beam transport) beam line that transports the ions to a 9.4 T ion trap for precision mass measurements. Other end station equipment that has been completed recently includes SeGA (the segmented Germanium array of gamma-ray detectors) and MoNA , the Modular Neutron Array, as well as a large vacuum chamber for the S800 spectrograph target area. Devices that are currently being tested and commissioned are the HiRA (High Resolution Array for charged particles) and the superconducting Sweeper magnet for neutron-charged particle coincidence experiments.

ION SOURCES AND BEAM INJECTION

Ion Sources

The primary ions are produced by two ECR ion sources, one superconducting (SC-ECR) built in the early 90’s [5], and the other (ARTEMIS) with room temperature magnets [6] built from a design based on the AECR-U at LBL. A variety of methods are available for introducing the feed material, depending on the available form of the element and its properties: gas feed, internal miniature oven (< 1400 C), inductively heated oven, and sputtering.

The inductively heated oven achieves temperatures above 2000 C in a 6 mm diameter cylindrical sample-holding crucible that can be positioned a few mm from a radial port in the wall of the plasma chamber. The heating power can be varied to more than 1 kW. It is supplied by radio frequency current in a copper coil that induces currents in a thermally insulated rhenium cylinder, which, in turn, radiates heat efficiently to the crucible inside. Beams of iron and nickel have been produced.

A project to build a duplicate of the ARTEMIS on an off-line test stand was started in August 2004. This ion source will allow off-line beam development when the production source is not available, development of beam diagnostics, and study of beam properties and test the results of optics model calculations intended to improve the performance of the facility. This project is scheduled for completion in summer 2005.

A project to build a new fully superconducting ECR (SuSI) is scheduled for completion in 2006. This project is described in another paper in this conference. [7]

ARTEMIS Permanent Magnets Demagnetization

The hexapole magnet for ARTEMIS that provides a radially increasing field to confine charged particles in the plasma chamber consists of six identical permanent bar magnets made of neodymium iron boron material. Due to a problem with electrical insulation breakdown, the plasma chamber was recently removed from the ion source. When the field of the hexapole was measured it was found, unexpectedly, to be asymmetric and weaker than when the source was assembled, indicating that some loss of magnetization had occurred. The cause of this problem is still being sought. There were two instances when the temperature of the cooling water supply increased from the usual value of 29 C to 40 C due a problem with the controls for the main water system for the laboratory. Around the same time experiments were being performed with an electrostatic quadrupole substituted in place of the usual focusing solenoid at the beam exit from the ion source, and the field from the axial confinement solenoids of the ARTEMIS was increased beyond the previous value typically used. A new hexapole has been ordered. The controls for the ARTEMIS will be modified to prevent overheating if the water supply temperature rises above normal. A special temperature regulation system for the water to the plasma chamber will be installed to provide a lower supply temperature than is provided by the main water system.

Matching beam from ion source to K500 cyclotron

The transmission of beams through the coupled cyclotrons has reached the expected values. The losses at extraction from the cyclotrons are between 10 and 30 percent. The transmission through the coupling beam line between the cyclotrons is close to 100 percent. The beam losses are directly influenced by the emittance, according to computer simulations, and the empirical evidence is qualitatively in agreement. At present there are no continuously adjustable slits installed in the injection beam line, only fixed diameter apertures (3 sizes remotely selectable). To optimize the matching of the beam to the cyclotron, one key element needed is adjustable width slits to improve momentum resolution and to help select spot size and angle range transmitted. From the three beam viewers in the injection line we can see that the entire transverse phase space area occupied by the beam has a very irregular intensity distribution, and the cyclotron accepts only a fraction of this area. When the injected phase space is limited appropriately the transmission of the coupled cyclotrons is excellent. We conclude that future improvements in beam intensity will come from improvements in brightness of the beam delivered from the ion source to the cyclotron. This is the area that is receiving attention with beam simulations. An electrostatic quadrupole triplet has been substituted temporarily for the focusing solenoid immediately after the ion source. This was predicted to reduce beam blow-up from space charge force in the (un-analyzed) multi-charge state beam exiting from the ion source. In some situations the charge density on the beam axis is enhanced when an intense charge state is focused before the desired charge state is. This situation does not arise with electrostatic focusing. The best intensity for several test beams has been obtained recently while in this configuration, and the transmission through the injection line and the rest of the system was also better. This implies that the brightness of the beam was improved.

It has been possible to transmit beam at intensity up to a maximum of about 25 µA to the inflector at the center of the K500. At that intensity the optimum tuning of the buncher is already affected, as was predicted to occur at about 100 µA, due to space charge effects on the longitudinal motion. It is expected that some gain in transmission at these high currents may be achieved with a buncher placed closer to the K500 midplane, inside the yoke of the magnet.

EQUIPMENT IMPROVEMENTS

Deflector performance

Each cyclotron has 2 electrostatic deflectors as part of the beam extraction system. The deflectors in the K1200 produce a maximum working field in the gap of 130 kV/cm. The gap is 6 mm. We have been running at 110 kV/cm or lower because of voltage holding difficulties, especially with an intense beam. In the K500 the requirement is 73 kV/cm, using a 7 mm gap. Because of the necessity to dissipate some beam power on the leading edge of the septum of the first deflector (called E1), that deflector is water cooled. The second deflector is not cooled directly.

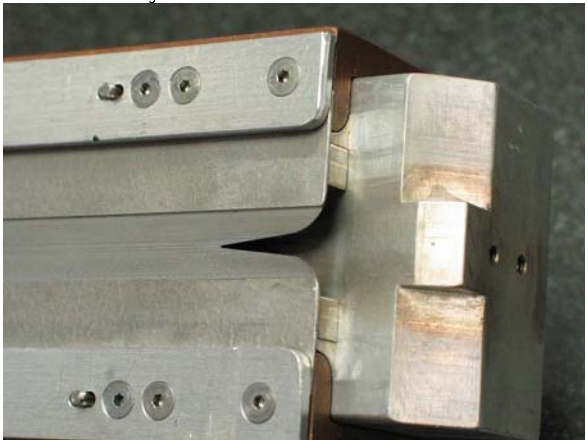

Figure 5: K1200 E1 deflector with short notch in septum

We have observed an increase of dark current and of sparks when the voltage is increased or when the beam is present. This limits the upper range of beam energy to about 160 MeV/u at present. The limited space between the internal beam and the superconducting magnet cryostat constrains the mechanical design of the deflector, which must be moveable to adapt to the shape and position of the extracted beam orbit for different beam particles and energies [8]. The improvements in performance that have been realized are the result of small changes in shape or materials. The insulators that support the cathode are fluted ceramic cylinders with metal buttons brazed to each end. The ceramic BeO has generally been the most reliable. We have used insulators made of aluminum nitride, but they seem to be more susceptible to flashover failure that is not recoverable by conditioning (see Fig. 6)

Figure 6: Aluminum nitride insulator with marks from flashover tracks, which are electrically conducting. The insulator body diameter is approximately 1 cm.

When a deflector will not hold the necessary voltage, due to a run-away current or too-frequent sparking, we usually are able to restore good operation by flowing oxygen into the deflector while the voltage is applied. This procedure results in a glow discharge that in many cases has a healing effect. A low flow rate of oxygen gas (<0.5 cc/m) can be maintained in the K1200 while the beam is running without any detectable loss of beam intensity. This has been done when the deflector dark current was found to rise toward an unacceptable value when the gas flow is shut off. In the K500 cyclotron the loss of beam is unacceptable when the vacuum is degraded by flowing oxygen gas.

The deflector septum design for E1 in both cyclotrons was modified to (1) improve the mechanical stability at high temperature induced by beam heating, and (2) increase the power dissipation from the septum. Instead of using a uniform thin sheet of tungsten (0.25 mm thick) for the septum, a thicker septum (0.63 mm) which has been machined to the required 0.25 mm near the midplane was clamped to the housing. The new septum is considerably stiffer, but still as able to bend to follow the contour of the housing and can be slid into position without removing the clamping strips. Calculations show that conduction of heat to the housing accounts for about a third of the power dissipated in the septum at maximum power, the balance being radiation. Conduction through the original septum was negligible.

We employ a test stand in a separate magnet from the cyclotrons to test each deflector assembly before it is installed in the cyclotrons. The vacuum chamber is pumped by a cryopump. The magnetic field is 0.7 T.

Stripper mechanism performance

The beam is injected into the K1200 cyclotron in the midplane on a path through the "C" dee, and strikes a stripper foil inside the dee at a position to match its path to the equilibrium orbit for the injection energy. The position of the stripper foil varies by several centimeters (in radius and azimuth), depending on the injection energy and charge to mass ratio. The foil is supported on a stainless steel plate that can be moved by hydraulic master-slave cylinders connected to the control system [8]. (See Fig. 8) Each foil is mounted in a frame that supports it on 3 sides; one vertical edge is unsupported because that is where the beam strikes, and there is no room for a support since the radius gain on the first turn is comparable to the spot size, a few mm. The foil frames are now made of tungsten (0.375 mm thick) and are cooled by radiation. There are 31 foils installed on a chain that can be advanced by two additional hydraulic cylinders mounted on the plate. The spent foil automatically falls on its hinge to a horizontal position out of the way of the beam as the new foil advances into the working position. The two cylinders that move the chain have experienced premature failure of the rubber piston and shaft seals. We have recently discovered that the temperature of these components is above 70 C, due to heating from small stray radiofrequency currents. This problem will be addressed by improving the cooling of the affected components, and by changing the seal material.

Figure 7: Photograph of the stripper foil mechanism installed in the K1200 cyclotron. Several foils are visible, attached to the chain that transports them into position for use.

The foils used have been the evaporated amorphous carbon type that are commercially available [9]. The required thickness is between 200 and 500 μg/cm^2. Typical foil lifetimes are 1 day for Xe beam, 3 days for Kr and 10-20 days for Ar.

Experimentally we see that the equilibrium thickness increases for heavier projectiles. The stripping charge state distribution has been measured for each element and energy by using the bending magnet in the coupling beam line between the K500 and K1200 as a spectrometer to analyze the charge states. We have foils of various thicknesses installed on a target ladder upstream from the magnet; the intensity is measured on a Faraday cup downstream as the field of the dipole magnet is adjusted to select each charge state. Some significant deviations of the stripping efficiency from that given by an empirical formula for equilibrium thickness foil have been seen. These measurements show that in certain cases of nearly fully-stripped ions, the intensity is greater with a foil thickness below the equilibrium value. We have not determined how practical it will be to exploit this higher intensity in practice.

ACKNOWLEDGEMENT

This work was supported by National Science Foundation grant PHY-0110253.

REFERENCES

[1] F. Marti, P. Miller, D. Poe, M. Steiner, J. Stetson, X.Y. Wu, "Commissioning of the Coupled Cyclotron System at NSCL" Proc. 16th Int'l. Conf. on Cyclotrons and their Applications, East Lansing, F. Marti, Ed, AIP Conf. Proc. 600 (2001)64-68.

[2] J. Stetson, F. Marti, P. Miller, M. Steiner, P. Zavodszky "Comparison of Electrostatic and Magnetic Solenoid Focusing of Mixed Species Heavy Ion Beams at NSCL/MSU", paper at this conference.

[3] H. Blosser, D. Johnson, F. Marti, "Numerical Study of Efficiency of Multi-turn Extraction in the K1200 Cyclotron", Proc. 15th Int'l. Conf. on Cyclotrons and their Applications 98, Caen, E. Baron & M. Lieuvin, Eds., Inst. of Physics Pub., (1998)454-457.

[4] D.J. Morrissey, NSCL Staff, "A New High-Resolution Separator for High-Intensity Secondary Beams" Nucl. Inst. & Meth. in Physics Research B 126 (1997) 316-319.

[5] T.A Antaya and S. Gammino, Rev. Sci. Instr. **65** 1723 (1994).

[6] H. Koivisto, D. Cole, A. Fredell, C. Lyneis, P. Miller, J. Moskalik, B. Nurnberger, J. Ottarson, A. Zeller, J.DeKamp, R. Vondrasek, P.A. Zavodszky and Z.Q. Xie, in *Proceedings of the Workshop on the Production of Intense Beams of Highly Charged Ions*, Catania, Italy, 24-27 Sept. 2000, eds. S. Gammino and G. Ciavola, Italian Physical Society Conference Proceedings **72**, 135 (2001).

[7] P. A. Zavodszky, B. Arend, D. Cole, J. DeKamp, G. Machicoane, F. Marti, P. Miller, J. Moskalik, J. Ottarson, J. Vincent and A. Zeller, "Innovative Design Principles of SuSI – Superconducting Source for Ions at NSCL/MSU", paper at this conference.

[8] J. Bonofiglio, S. Alfredson, S. Hitchcock, F. Marti, A. Rodriguez, G. Stork, "Stripper Foil Mechanism for the K1200 Superconducting Cyclotron", Proc. 16th Int'l. Conf. on Cyclotrons and their Applications, East Lansing, F. Marti, Ed, AIP Conf. Proc. 600 (2001)117-119.

[9] Obtained from ACF Metals, Tucson, AZ, http://www.techexpo.com/firms/acf-metl.html.

[10] S. Alfredson, F. Marti, P. Miller, D. Poe, G. Stork, "Electrostatic Septum for Kilowatt Heavy Ion Beams", Proc. 16th Int'l. Conf. on Cyclotrons and their Applications, East Lansing, F. Marti, Ed, AIP Conf. Proc. 600 (2001)133-135.