THE MSU SUPERCONDUCTING CYCLOTRON PROGRAM*

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Summary

This paper reports the status of construction and summarizes recent experience with the cyclotrons at the National Superconducting Cyclotron Laboratory, which is located at Michigan State University in East Lansing. The emphasis is on material relating to the operation of the first cyclotron which is not duplicated in elsewhere, such as in other papers in this conference.

Overview of the Laboratory Program

The facilities of the laboratory, which are in different stages of design, procurement, construction and operation are intended to be operated primarily for research in nuclear science with ion energies up to 200 MeV/u. The accelerator system is a pair of superconducting cyclotrons in tandem. The injector cyclotron, called "the K500",[1] has an internal Penning ion source and a magnet with a bending rigidity K=520 MeV and a focusing limit specified by K_F=160 MeV, where the limiting energy per nucleon is either K $(Q/A)^2$ or K_F (Q/A), whichever is smaller.[2] The beam is injected by foil stripping inside the booster cyclotron, called "the K800", which has K=1200 MeV and K =400 MeV. External beam intensity of 10^{11} particles per second is projected with energy 180 MeV/u for mass 60, decreasing to 20 MeV/u at mass 240.

Beamlines using superconducting quadrupoles and benders are also planned (see Fig. 1). The major experimental facilities are magnetic spectrometers (S800, Split pole and RPMS), scattering chambers (60-inch and 120-inch), and two 4π detector arrays, one a wide energy range particle detector and the other a gamma-ray multiplicity detector.

The K800 magnet is currently being assembled (see Fig. 2). The pole tips have a normal spiral pattern like the K500 instead of reversing near the center, as this turned out to be most convenient for injection[3]. The magnet is scheduled to be tested at full magnetic field in May.

A prototype beamline section containing three magnets is being constructed. The superconducting quadrupole will be tested first; a bending magnet will then be assembled and installed.

The prototype transmitter for the K800 rf system has been operated at full output power (250 kW). The anode resonator is being modified to eliminate spurious resonances which prevented operation in some frequency bands. A low power full scale model of the dee and resonator is being assembled to verify the frequency tuning range. The dee resonators will resemble the corresponding structures in the K500. The K500 cyclotron has been operating since October 1982. It is providing beams with energies up to 35 MeV/u to 7 beam lines. The present configuration of

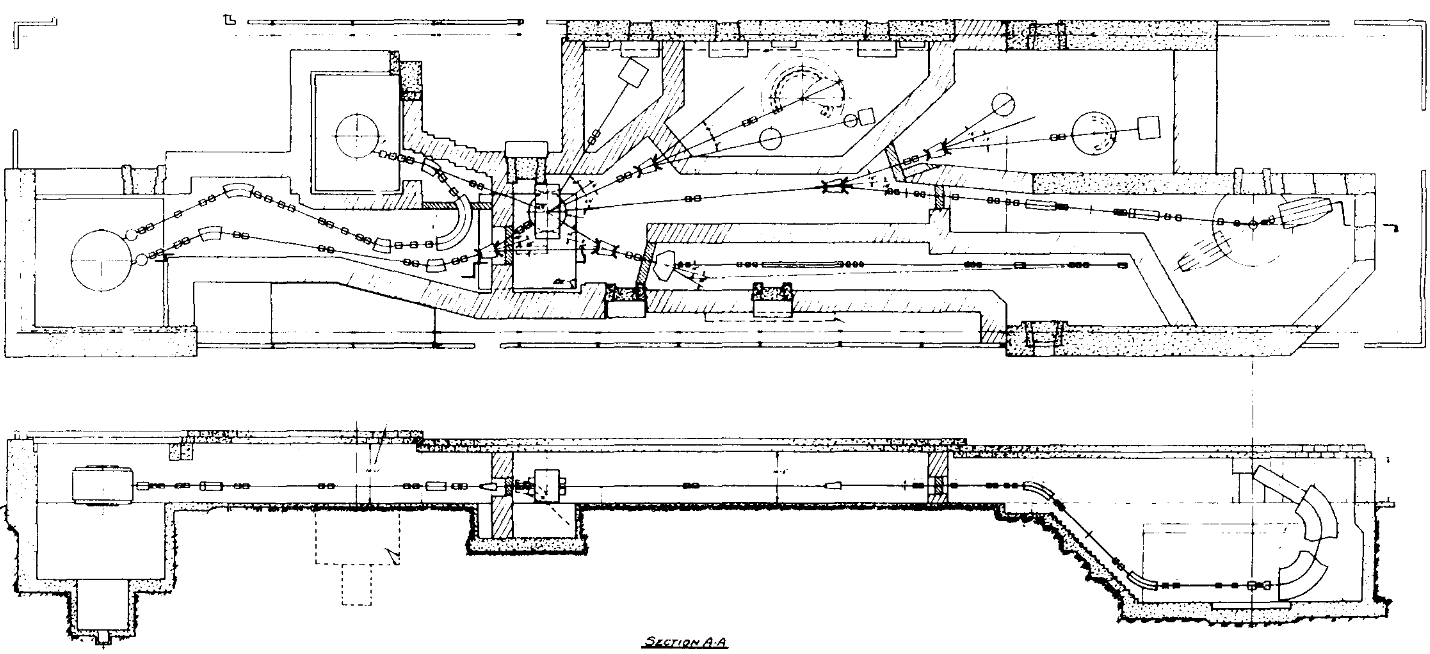

Fig. 1--(top) Floor plan of the beamlines for the K500-K800 coupled cyclotron facility. (bottom) Elevation view through a section marked by arrows labeled "A", showing the K800 at the left and the S800 spectrograph at the right.

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apparatus is shown in Fig. 3. Beam time for a running period (about 2000 hours) is allocated to users by the Program Advisory Committee. We are in the second such running period at present. We plan to continue to operate the K500 standing alone to support user experiments until 1986, when it will be necessary to re-configure the shield walls and begin replacing the present beamlines.

A proposal to acquire an Electron Cyclotron Resonance (ECR) ion source for the facility is being prepared. The advantages of an ECR source are high output of high charge states, long lifetime and high reliability. Such an ion source requires addition of an axial injection line.[4] Since the ECR will provide higher energy than our normal PIG source in either cyclotron by itself and in tandem operation also, we plan to provide an injection line into both cyclotrons as shown in Fig. 4. Higher beam energies can be reached in tandem for A>100 and with the K800 standing alone, for almost all elements. Such a stand-alone mode would be simpler to operate than coupled cyclotrons.

The ECR ion source is planned to have a fairly large confinement volume relative to other such sources now in operation. The main coils will be superconducting coils, oriented to a vertical axis. The hexapole magnets will probably be superconducting coils also, although permanent magnet designs are still under study.

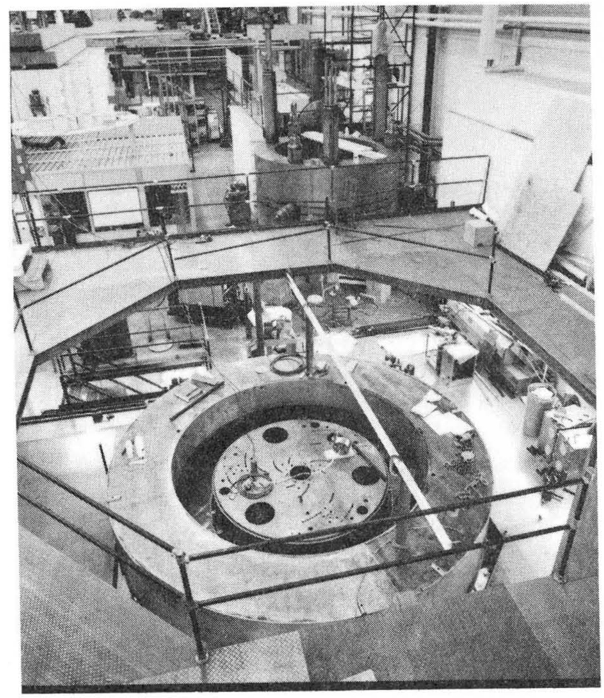

Fig. 2--Photograph of the K800 magnet during assembly of the yoke (foreground) and leak testing of the cryostat containing the superconducting coils (top).

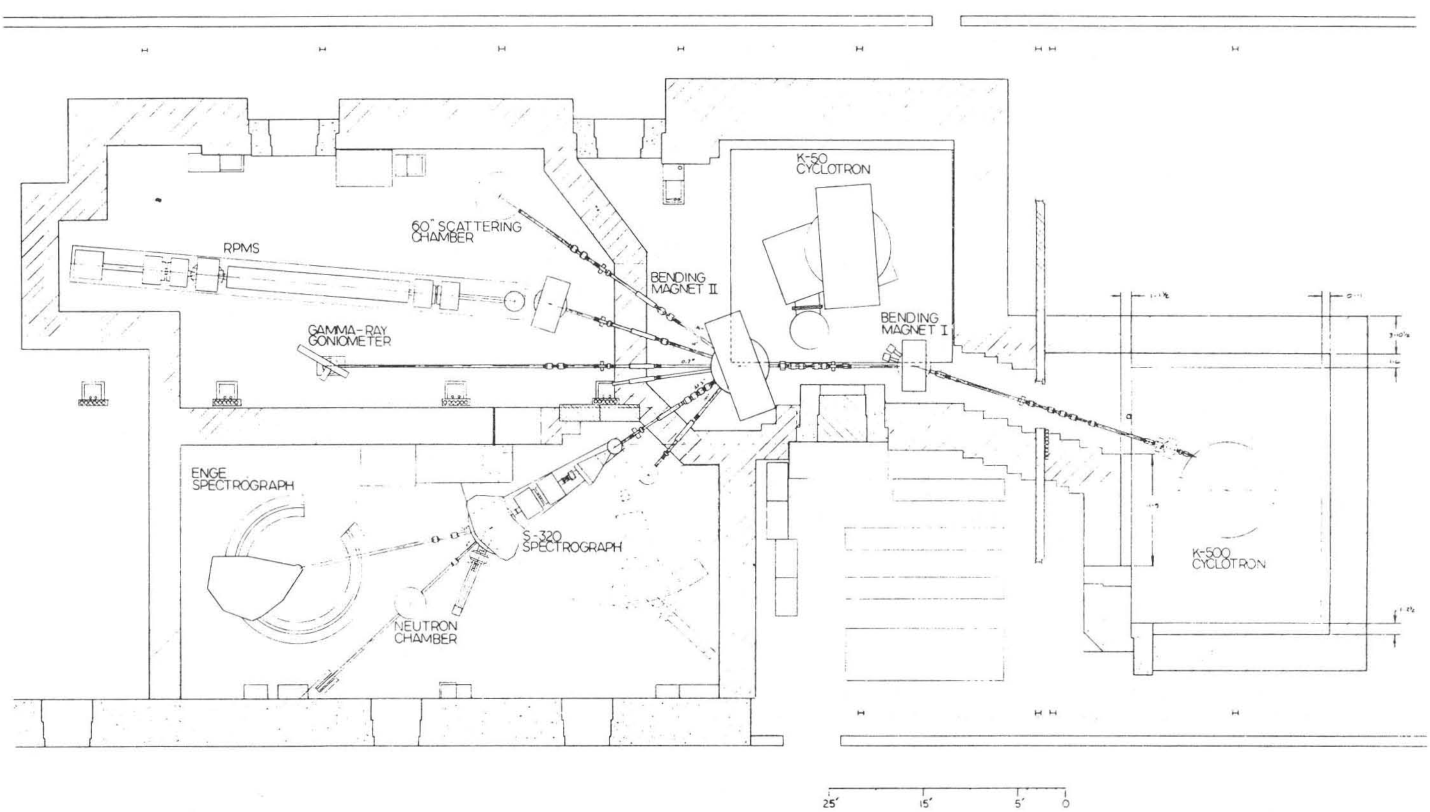

Fig. 3--Floor plan of the beamlines presently in operation with the K500 cyclotron. There is a target station for production of radionuclides in Bending Magnet I in addition to the others labelled on the drawing.

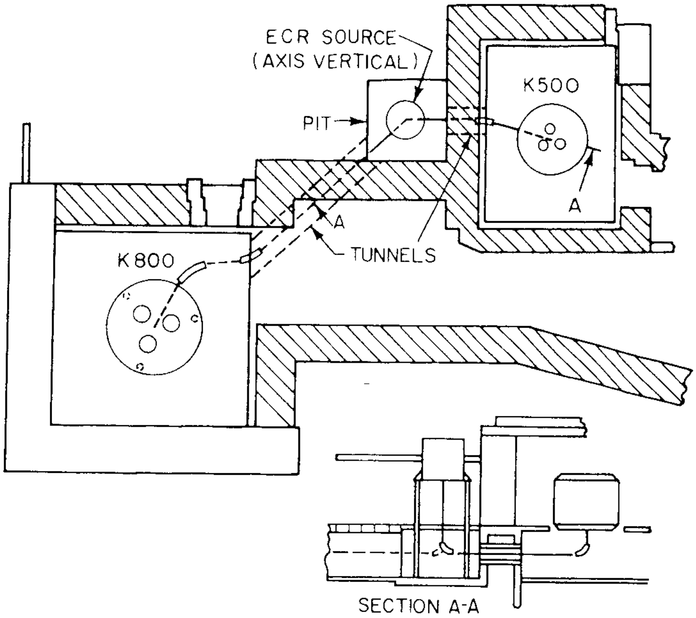

Fig. 4--Plan and elevation views of the proposed ECR ion source installation with tunnels to accomodate the injection beamlines.

Laboratory Construction Plan

The work schedule for the laboratory is based on the following concepts:

1) Concentrate construction efforts on the K800 cyclotron, the ECR source and the beam line and particle detector that will be used initially with the K800;
2) Continue the K500 experimental program until experiments start with the K800;
3) In two years (1986 and 1987) disassemble the K500 beam transport and construct new beam lines and shielding.

The first item represents the construction tasks needed to begin utilization of the K800. The tasks are:

a) finishing the K800 cyclotron;
b) constructing the ECR source and axial injection lines;
c) constructing the beam line prototypes
d) constructing the 4 π detector and the 120 inch target chamber;
e) constructing a beam line from the K800 to the 120 inch chamber located nearby. This work will be carried out in 1984 and 1985.

The change-over to the new laboratory configuration is estimated to begin in January 1986. The K500 program will stop and the shield walls will be relocated. The new beam transport system will be installed and will be tested with beams from the K500. The S800 spectrograph will be constructed. The coupling line from K500 to K800 will be installed during this period also, followed by testing of coupled operation of K500 and K800.

The planned time schedule for significant events is given by the following table of milestones:

May 1984	Operate K800 magnet at full field
June 1984	Operate K800 amplifier over full frequency range at full power
March 1985	Operate ECR magnet at full field
April 1985	Operate K800 magnet with trim coils and magnetic extraction elements in place
May 1985	First ECR beam test
December 1985	First rf tests with all dees in place
January 1986	First K800 internal beam
April 1986	First K800 external beam
June 1986	K800 experiments in progress in 120 inch chamber/shut down K500 program
December 1986	All shield walls in new configuration
September 1987	Beam transport system complete/first tests with K500 beam
October 1987	First beam tests of S800 spectrograph
October 1987	Begin three month shutdown to complete K500/K800 coupling line and to connect K800 to full beam transport system. Move 120 inch chamber.
January 1987	Test coupled operation
March 1988	Begin experimental program with coupled cyclotrons

K500 Cyclotron

Magnet

The magnet yoke and poles were manufactured from low carbon steel casting. The median plane penetrations for extraction elements, probes and beamline are unsymmetrical, which produces an unsymmetric magnetic field at the coil. The resulting horizontal force on the coil is approximately 4 tons at maximum current (700 A) when the coil is centered. At the chosen operating location (coil .035 ± .015 inch

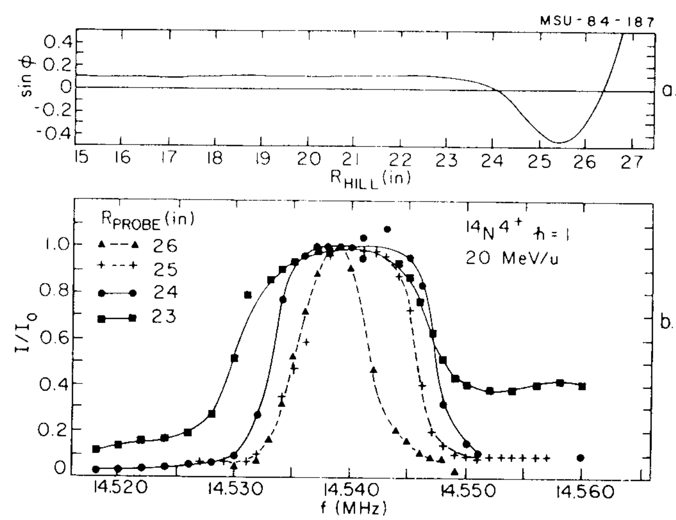

Fig. 5--a. Calculated phase curve for 20 MeV/u $^{14}N^{4+}$ beam. b. Measured resonance de-tuning curve: internal beam intensity (arbitrary units) as a function of the radio frequency at 4 values of probe radius. The cut-off frequencies vary with radius in a manner consistent with Fig 5a. The off-resonance background current may represent $^{14}N^{1+}$ ions in unstable orbits.

off center) the maximum force is 1 ton. The amplitude of the magnetic first harmonic attributable to this centering error is less than 10 gauss.

The accuracy of the magnetic field trimming process (1 part in 5000) is demonstrated by comparing the radio frequency to the value predicted by the field trimming program. Such accuracy is obtained without recourse to phase measurements on the beam. Fig. 5 is an example of the variation of internal beam current as the frequency is changed (first harmonic, 535 turns). One observes some variation in the settings of the magnetic bump and trim coil currents required to optimize extraction. Changes in the temperature of the pole tip iron may be induced by the water cooled trim coil windings, and this effect is being studied further to try to explain the variation in the control settings.

Vacuum system

The beam chamber is pumped by 3 liquid helium-cooled panels coated with activated charcoal. Each panel is surrounded by a radiation shield consisting of a copper box with a chevron baffle top cooled by liquid nitrogen to approximately 100 K. This radiation shield serves also as a pump for water vapor. There are three turbomolecular pumps installed on pipes above the cyclotron. They are needed for rough pumping, for regenerating the charcoal on the cryopumps and for pumping helium (see Fig. 6).

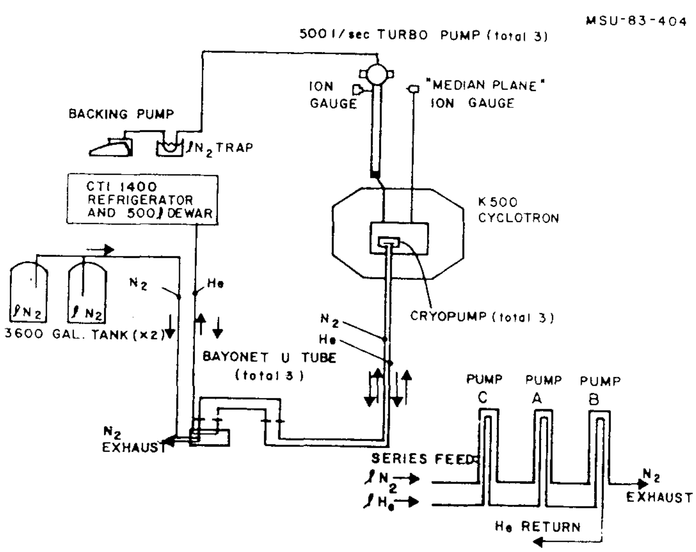

Fig. 6--Schematic diagram of the K500 cyclotron pumping system. There are three turbomolecular pumps (one is shown) connected to a common backing pump and trap. These pumps and the ion gauges are mounted on pipes to remove them from the strong magnetic field. Liquid nitrogen and helium are supplied to the three cryopumps via concentric transfer lines in the lower dee stems. The cryopumps are fed in series as shown.

The prototype cryopump was installed in dee "A". A mechanical design change in the next two resulted in higher operating temperature for the radiation shield and consequently for the helium panels also. The pumps were found to consume more liquid nitrogen than the coil and refrigerator combined. The pump heads were redesigned incorporating 1.) an unbroken copper heat conduction path between the radiation shield and the nitrogen; 2.) a small liquid separator; and 3.) welds of similar metals throughout, i. e. stainless steel to itself, not to copper. The latter was done by making some parts from bonded copper-stainless steel plate. The "B" and "C" cryopumps were successfully rebuilt in September 1983, and they now perform even better (i.e. require less liquid nitrogen) than the prototype("A"). Consequently we have been running with the "A" cryopump bypassed. The liquid nitrogen consumption of the K500 facility (coil, refrigerator, cryopumps and dry gas supply) has been reduced from 44 g/sec to 16 g/sec by this and other smaller improvements. Fig. 7 is a cross section view of the cryopump cold head.

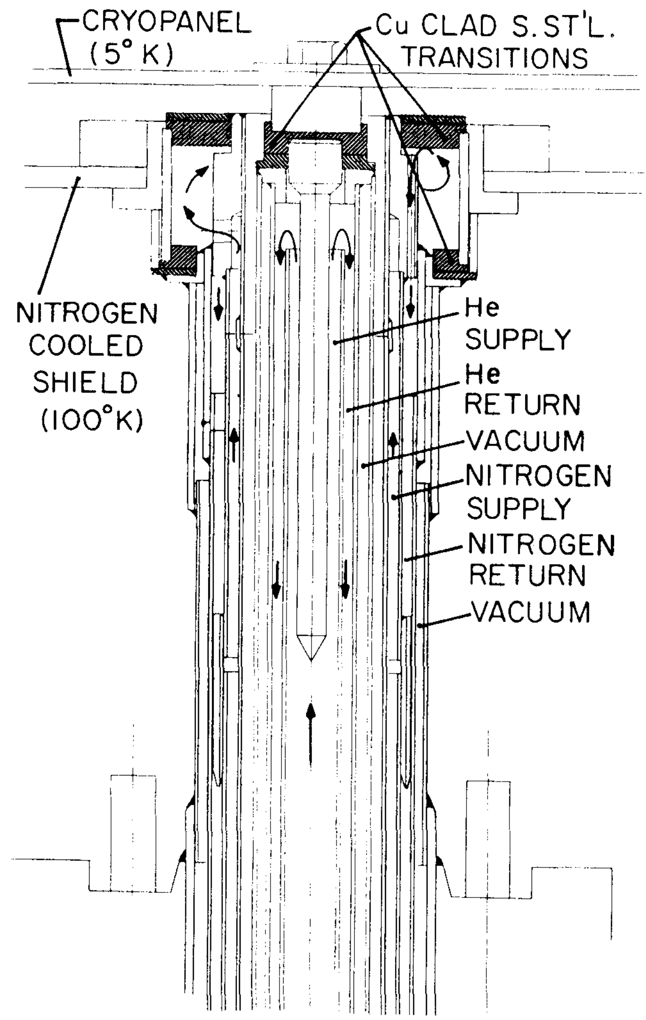

Fig. 7--Detail of the cryopump cold head inside the dee. The cryogenic supply and return pipes are vacuum insulated from each other everywhere except in the short section shown here. Copper clad stainless steel transitions have been added to improve heat transfer and to avoid welding problems at assembly.

With no gas flowing to the ion source the pressure in the cyclotron is 1×10^{-6} torr. This base pressure is influenced by small leaks. The pumping speed of the cryopumps is about 2000 liter/sec. measured by flowing gas into the cyclotron through the ion source and observing the ion gauge. When the ion source is in operation the pressure is 7 to 20 x 10^{-6} torr. Fig. 8 depicts a strip chart record of the cyclotron pressure during operation.

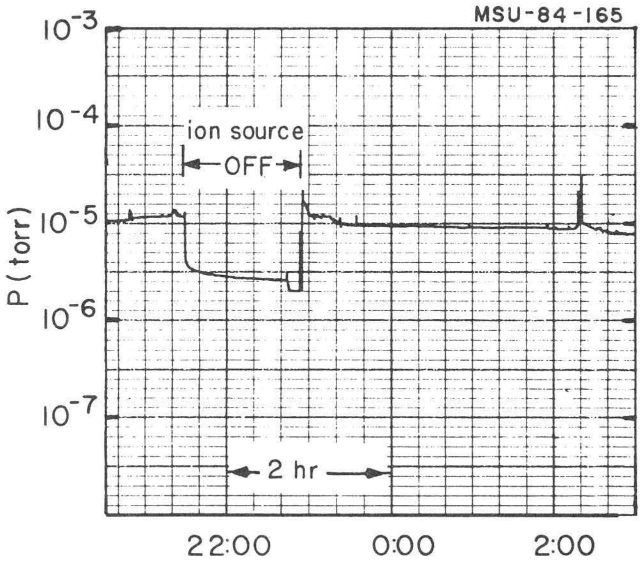

Fig. 8--Strip chart record of the pressure measured by the "median plane" ion gauge during a run of the cyclotron.

Ion source

The Penning ion source[5] used in the K500 is designed with a compact body as required by the small orbit radius on the first turn and the dee-to-ground gap of 10 mm minimum. For greatest beam intensity we use tantalum cathodes, but we have found hafnium (metal) cathodes to be beneficial for beams that will run with nitrogen and carbon monoxide support gas. The hafnium cathodes last up to 50 hours, and the arc can be restarted if it is extinguished even after 10 hours of use. The arc power supply is pulsed at a rate between 100 and 400 Hz and with adjustable duty factor and peak current up to 7 A. Low duty factor (<15%) and high peak current produce conditions for the greatest beam output of the desired high charge states. The peak current capability of the power supply will be increased to more than 15 A in the future. The average input power is 300-800 watts with Hf cathodes and 1-2 kW with Ta cathodes.

Beams of Li and B have been made by feeding a solid material (LiF and BN respectively) into the arc using pellets behind the ion source slits which are gradually sputtered by ions propelled back by the rf dee potential.

Pulsing the arc power supply creates a time structure in the beam that is troublesome in some experiments, such as those limited by accidental coincidences. This time structure is compared to the pulsing waveforms for the ion source in Fig. 9. The rise time of the beam pulse is often more rapid than shown in Fig. 9a and is influenced by adjustments of gas flow and power supply controls.

Rf system

The radio frequency accelerating potential is applied by three transmitters, each connected to the resonator for one dee by a coaxial transmission line and a variable capacitor. The vacuum window is part of this capacitor assembly, called the "coupler". Each station (transmitter, line and resonator) can be operated independently of the other two. There is capacitive coupling among the three resonators in the

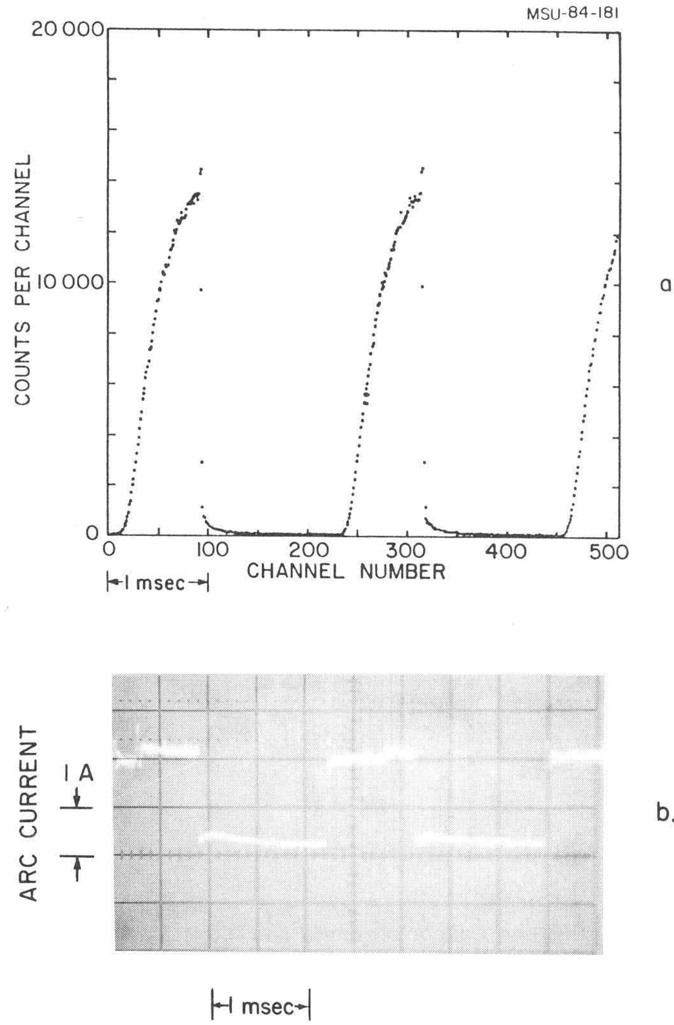

Fig. 9--Effect of pulsing the ion source power supply current, shown in (b.) on the time structure of the beam represented by the gamma ray time spectrum in (a.) measured by a fast scintillation detector installed in a view port. The beam is $^{14}N^{5+}$ at 35 MeV/u.

central region where the dees converge.[6] This coupling is tuned out by "neutralizing loops" connecting the resonators, which are adjusted to cancel the net coupling whenever the operating frequency is changed. The required n x 120° phase relationship for the dee voltages is controlled by adjusting the phase of the low-level drive signal to each transmitter.

The half-wave resonator for each dee is positioned vertically and is symmetric about the median plane of the cyclotron. Variable capacitor trimmers (servo controlled by phase feedback) tune the resonator frequency by approximately ±1%; the sliding short planes do not move during operation, as the contact fingers are clamped for reliability. The gold plated fingers on the outer conductor of the shorting planes will soon be replaced with silver-graphite because the present fingers are marginal and subject to rapid wear.

The coupler insulator (rf vacuum window) has had a number of failures because excessive voltage appeared across the coupler during transients from dee sparking or mistuning. An arc formed at the insulator and made a leak. A forward/reflected voltage interlock installed recently seems to protect the insulator by extinguishing the arc. A new design for the coupler is in progress with a disc insulator expected to withstand a higher voltage (see Fig. 10).

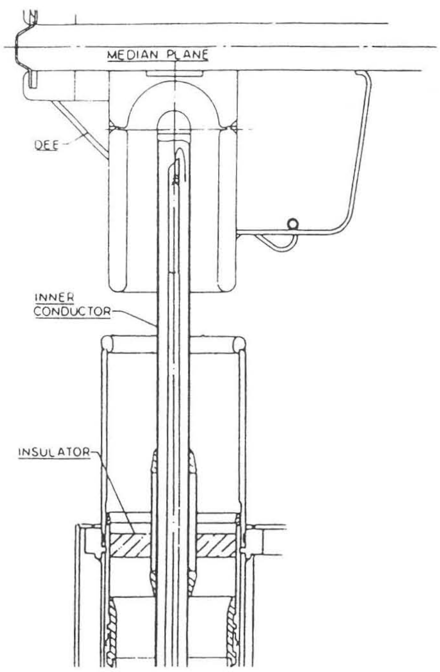

Fig. 10--Detail of the variable capacitor for coupling the transmission line to the dee. This drawing shows the new style of coupler insulator.

The design peak dee voltage at maximum beam energy is 100 kV. We have mainly operated at lower energy where the required voltage is usually less than 75 kV. Beams have not been run at maximum voltage because of perceived reliability problems associated with high voltage operation, namely coupler failures, contact finger failures on the short planes, anode power supply reliability and more frequent sparking of the dees. Deflector voltage-holding also limited extraction of these beams. The rf system has been run several times producing dee voltage in excess of 90 kV for tests. The weaknesses will be corrected in the future. The dee voltage required in the K500 for coupled operation of the 2 cyclotrons has already been achieved.

Probes

The K500 has two probes both of which can measure internal and deflected beam intensity. They intercept the beam and measure its electric current directly. This total beam current signal has been the most useful output for tuning purposes. Both probes can measure radial current density also. They are shown in Fig. 11.

The main probe moves on a spiral track along one hill. It is equipped with a 3-finger head for axial position sensing and a wire differential current probe for radial profile measurements. Some of its outputs are illustrated by the current vs. probe radius measurements pictured in Fig. 12 a) and b). The other probe, called VP, has a 2-jaw (overlapping) tip for radial differential and total current sensing, and it moves radially. Its total travel is 4 inches,

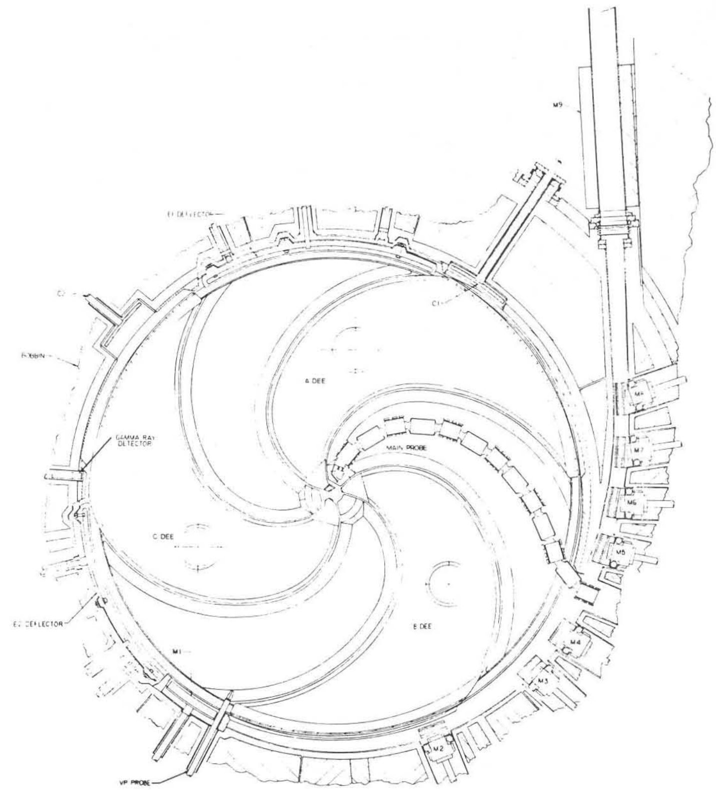

Fig. 11--Top view through the median plane of the K500 cyclotron showing the probes and the extraction elements E1, E2, M1-M9, C1 and C2.

encompassing the extraction region. A typical current plot from the VP probe is Fig. 12c.

A gamma-ray timing detector in a second view port has been used to measure the phase width of the internal beam and the beam turn-on waveform when the ion source arc was pulsed. When the detector is removed, the view port can also be used for measurement of dee voltages by bremsstrahlung endpoint with an external x-ray detector, as well as for visual observations.

Extraction system

The separation of an extracted beam from the internal beam is optimized at the entrance of the first electrostatic deflector by manipulation of the magnetic bump to produce a first harmonic in the field. This bump is produced by varying the currents in the 3 sectors of the outer trim coil. There are two deflectors, called E1 and E2, followed by 9 passive magnetic focussing channels[7], called M1 to M9. All of the elements except M9 can be moved radially by motors, and E1 and E2 have angle control also. There are two iron compensators (C1 and C2) for first harmonic compensation. Channel M4 is not installed because it would over-focus the beam at low magnetic field (<32 kG), and there is enough radial focussing without it at higher field. Fig. 11 shows the positions of the extraction elements in relation to the rest of the accelerator. Note that the deflected beam can be measured by both probes (VP after M1, main probe before M5).

One of the electrostatic deflectors is pictured in Fig. 13. The deflector housings are smaller than conventional cyclotron deflectors because of the

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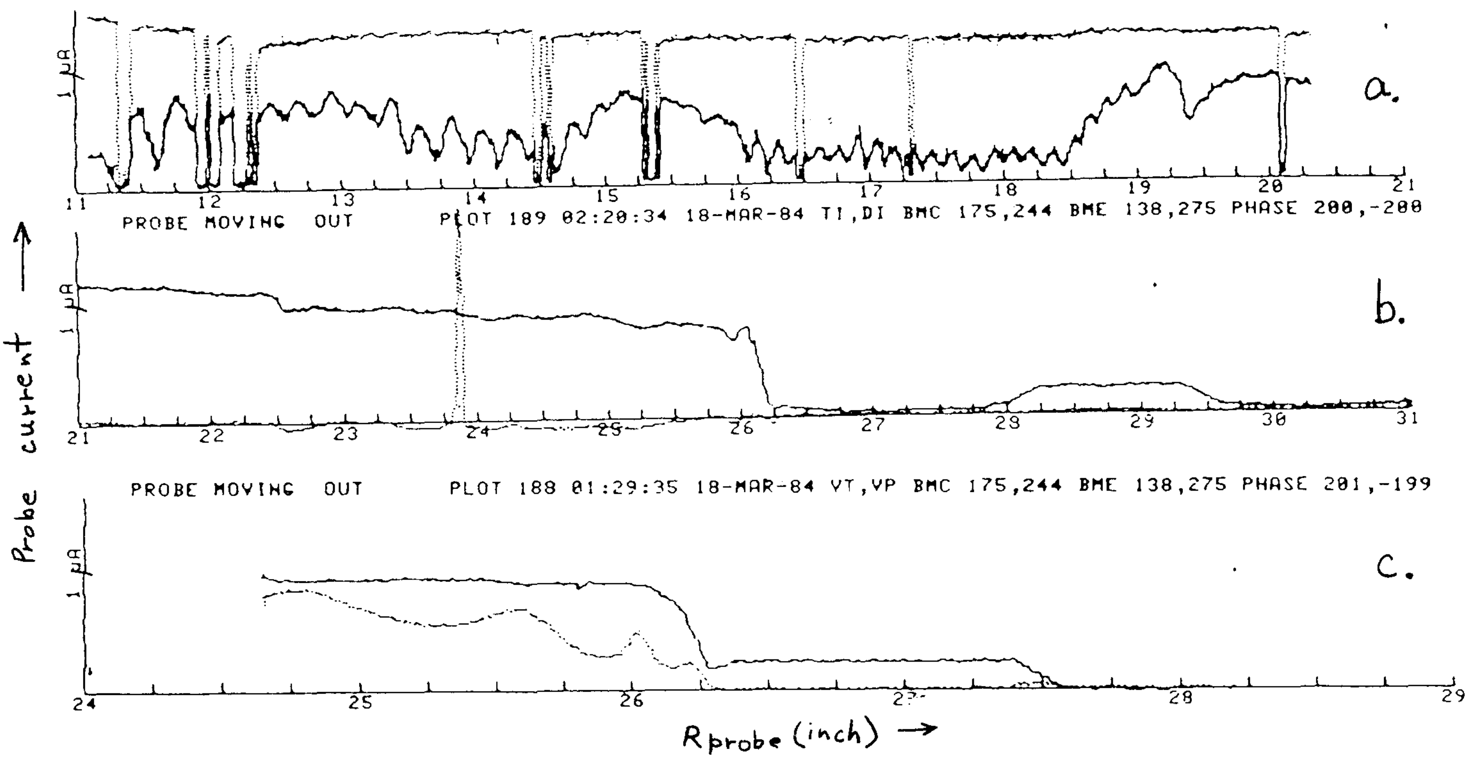

Fig. 12--(a) Main probe trace (total beam current--upper curve, center finger current Z2--lower curve) for probe radius between 11 inches and 20.5 inches; (b) Main probe trace (total beam current) for radius between 21 and 31 inches; (c) VP probe trace (total beam current-upper curve, differential probe current--lower curve) for probe radius between 24.5 and 28.3 inches. In (b) and (c) the deflected beam appears in the total current as a plateau at about 1/3 the level of the internal beam current. In (a) the axial oscillation pattern appears in the Z2 trace. Sparking of the dees causes the beam to dissappear briefly at irregular intervals during the tace. The beam is 25 MeV/u $^{7}Li^{2+}$.

narrow magnet gap and the radial barrier presented by the cryostat of the superconducting coil. The working gap (7 mm) and cathode dimensions are typical. The deflectors have not maintained more than 100 kV/cm reliably, short of the design requirement of 140 kV/cm. Successful model tests suggest, however, that the electrodes will support the needed electric field strength, and experiments and calculations to improve the insulator performance are in progress. This is consistent with the success that the Milan group has reported with a deflector of similar dimensions for their cyclotron.

Extraction efficiency varies between 25% and 50% in a reproducible fashion, with the high efficiency occurring at high magnetic field. The variation is attributable in part to changes in orbit shape, i.e. greater scalloping occurs at low magnetic field. The deflector shape is not variable, so its transparency varies. The beam losses after the two deflectors are negligible, as demonstrated by comparing the current of the deflected beam on the probes to that measured on the beam stop outside in the beam line.

A deflector test stand is being used to test parts and whole deflectors in magnetic field and vacuum. Sapphire insulators seem to be a promising substitute for polycrystalline alumina. They are already being used in the K500 because of their resistance to spark damage and the ease with which we can apply a metal coating for soldering terminations.

We were surprised by a measurement of the beam energy on one occasion which gave a result of 20 Mev/u when the cyclotron was being tuned for 22 Mev/u. This was explained by the use of a larger than normal magnetic bump amplitude for extraction which resulted in a large precession of the beam. Calculations with the orbit programs have confirmed that this can occur, i.e. a considerable fraction of the original beam phase space can survive the extraction process.

Phase I Facilities and Operation

Facilities

The K500 is supplying beams to 7 targets. There are two experimental vaults in addition to the one for the accelerator and switching magnet. The North Vault contains two magnetic spectrometers (S320 and Enge Split Pole) and the Neutron Chamber. The South Vault houses the 60-inch Scattering Chamber, the Reaction Product Mass Spectrometer and the Users Line, which has a goniometer for gamma-ray detectors installed. There is an irradiation station on the 0-degree port of magnet BM1.

The beamlines are instrumented with surplus magnets obtained from other laboratories and with magnets from the MSU 50 MeV facility, generally equipped with new vacuum chambers and, in some cases, new pole tips. The 4-inch aluminum beam pipes from the old facility were re-used, substituting indium wire for the rubber O-ring seals. Cryopumps, ion pumps and a turbomolecular roughing system are used. New slits with bellows sealed movable jaws were installed for beam alignment. These together with televised beam viewers are the major diagnostic probes used in tuning the beamline.

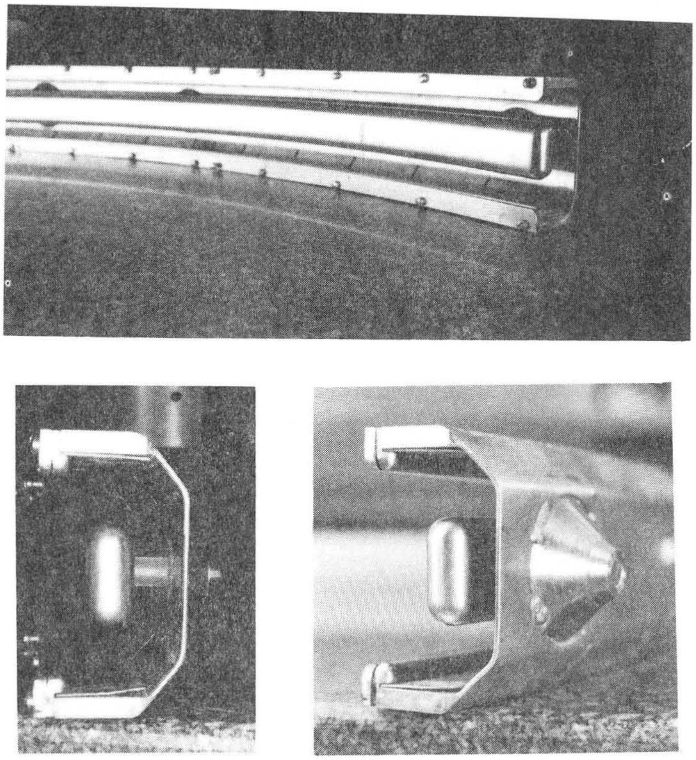

Fig. 13--Photograph of the electrostatic deflector E2 with the tungsten septum removed to expose the cathode and sapphire insulators.

Scheduling of experiments alternates users of the North and South vaults. The data room is adjacent to the control room for the cyclotron and beamlines. Independent computers and electronic racks for two groups are provided.

Operating Statistics

The availability of the beam, expressed as ion source operating hours per week, is shown in Fig. 14. The ion source is generally turned off when the beam is unavailable for any reason. Operation on a 7 day per week schedule was begun in March 1984. During the second running period the following beam species have been delivered:

Ion	E/A [MeV/u]	Ion	E/A [MeV/u]
4 He 1+	22,20,15	12 C 4+	35
6 Li 2+	25	14 N 4+	30,25,20
7 Li 2+	30,20	14 N 5+	35
12 C 3+	25,20,15	22 Ne 5+	22

Past Problems and Solutions

Cryopumps

As suggested above, we had pumping problems that were solved by lowering the temperature of the liquid nitrogen portion of the "B" and "C" pumps. After this was repaired we received an unfortunate surprise when we cooled the pumps with the dee cooling water turned off. The water lines pass through the inner conductor of the dee stem as do the cryogenic lines for the pumps. Since the water was not flowing, it froze and

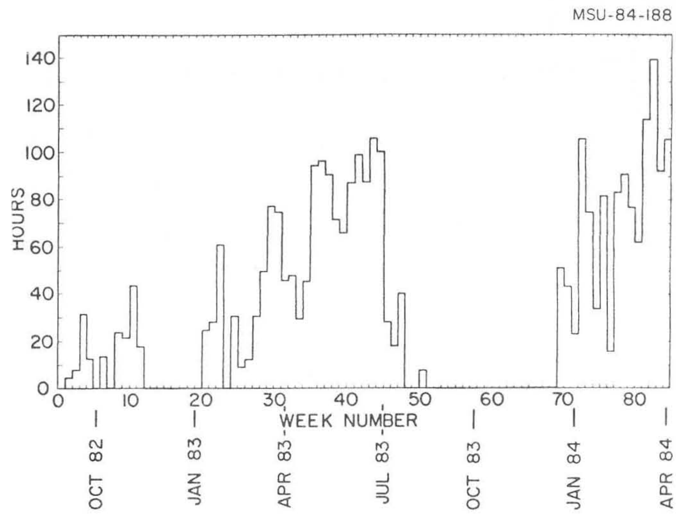

Fig. 14--K500 beam availability (hours per week).

burst pipes in "C" and "B". The repair of this damage required disassembly of these dee stems and took a month to complete. Interlocks have been installed to turn off the cryogens if the water flow stops for more than 10 minutes or if the insulating vacuum fails. The 10 minute delay is a convenience for maintenance and leak checking. The water had been off for 8 hours when the freezing damage occurred.

Vacuum seals

The seals in the beam vacuum chamber were designed to use C-seals wherever possible. These are spring rings plated with a soft metal that seal against grooved flanges in a fashion similar to O-rings. They are compact and relatively inexpensive compared to other non-organic seals. We have found them difficult to use, particularly in larger sizes. The success probability was worst (about 50%) when sealing to the 16-inch diameter alumina dee stem insulators.

We have had success using indium wire seals as a substitute for C-seals even though such a retro-fit is more complicated than a joint originally designed to use indium. As a result of the K500 and beamline experience with indium we are planning to use it extensively in the K800 vacuum system.

The dee stem insulator seals mentioned above are exposed to radio frequency currents and are not particularly well cooled in the K500. The C-seals on 4 of the 6 insulators were replaced with copper rings having indium wire inserted in grooves on both sides. After 5 months of operation we detected two small leaks on these seals, but they are not big enough to require immediate repair. In the K800 the water cooling can be directed to the seal area.

Rf system

The outer fingers on the sliding short planes in the dee resonators have burned out sporadically. Often only one of the six strips in a short plane is affected, and a repair can be made quickly. If the spark detector fails to indicate this condition the failure propagates to other strips and the panels that touch the fingers are damaged as the rf system continues to run.

When new, fingers can carry the currents required for full excitation of the dees. If the current-carrying capacity is degraded enough for one finger to fail, the failure is likely to propagate to the neighbors, resulting in failure of the entire strip. Three causes for failures are: 1. Wear of the gold plating; 2. Dirt; and 3. Excessive temperature of the panel. The fingers are clamped by rubber-backed pressure plates to insure adequate force. We think that the temperature is not high enough to induce failures. High-quality air filters were installed on the blowers for the resonators, but this has not eliminated the failures. The replacement of the fingers with high capacity silver-graphite tipped ones will be made in the near future.

A possible problem with the rf system at very high power is overheating of parts of the rf resonator, specifically the panels that comprise the outer conductor and a ring on one of the inner conductors. Adding water cooling lines has been considered and will be done during a shut down period if further testing shows that this is needed. The K800 rf system is being designed with a better distribution of water passages to avoid this difficulty.

Conclusion

We have found the K500 superconducting cyclotron to be very stable during operation. The magnet characteristics are highly reproducible and allow accurate prediction of many power supply settings for new beams as well as those already developed. Scheduled experiments have been completed close to the scheduled completion times. Several modifications to improve performance of the cyclotron have been made or are under way.

The construction of the K800 is proceeding vigorously with the goal of producing the first beam in 1986. Modification of the construction plan to include an ECR ion source has been proposed and will significantly enhance the capabilities of the accelerators.

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