# ADVANCES IN SUPERCONDUCTING CYCLOTRONS AT MSU

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## Introduction

Intensive work on superconducting cyclotrons began at MSU in late 1973 (a brief earlier study had occurred in the early 1960's) and continues vigorously at present. One large cyclotron, the "K500", has been operating for a number of years, a second, the "K800", is nearing completion, the first operating tests of its magnet having occurred at the time of the previous conference, and a third, the "medical cyclotron", is now also nearing completion with first operation of its magnet expected just after the present conference. These cyclotrons like other superconducting cyclotrons are all dramatically smaller than comparable room temperature machines; overall weight is typically about 1/20th of that of room temperature cyclotrons of the same energy. This large reduction in the quantities of materials is partially offset by added complexity, but finally, a net overall cost savings of 50 to 70% typically results; as a consequence the superconducting cyclotron is widely viewed as the cyclotron of the future. The thirteen years of experience at MSU involving three of these cyclotrons, together with much important work at other laboratories, gives a rather clear view of the advantages and disadvantages of various design approaches including by now a rather significant period of long term evaluation. This paper reviews highlights of this program.

## The K500 Cyclotron

The K500 is the first of the superconducting cyclotrons to reach what might be described as "middle-age". It produced its first internal beam in Nov. 1981 and its first external beam in Aug. 1982, and has thereafter operated more or less continuously to the present date supporting a frontier program in nuclear science on a 24 hour/day, 7 day/week basis. The experience with this cyclotron evidences the long-range viability of the design approaches used in the cyclotron's various sub-systems and also points to areas where efforts to improve future designs might be particularly desirable.

### Axial Injection from ECR

The Proceedings of the previous conference describe the design of a large, superconducting electron cyclotron resonance (ECR) ion source[1] to produce beams for injection into the K500 cyclotron. Subsequently, in November 1984, a decision was taken to first construct a smaller, room temperature source; the structure selected has a vertical axis with a full iron yoke which also functions as support structure, stray field shield, and X-ray absorber. Both 1st and 2nd stages have a minimum B magnetic field and operate at a frequency of 6.4 GHz. This source came into operation in July 1985 followed by the analysis system in August 1985; in the winter of 1986 the axial injection system was completed and since March 1986 the K500 cyclotron has operated with an axially injected ECR beam.

The beam transport system takes the exit beam from the vertical source, bends it into the horizontal plane, transports it at basement level below the cyclotron, and bends it back to vertical up the cyclotron axis to the median plane. Bending elements are edge-focused magnetic dipoles; five solenoids provide additional focusing. Finally at the median plane of the cyclotron the beam is deflected back into the horizontal plane by an electrostatic spiral inflector of the kind developed at Grenoble[2]. A single gap buncher is located just below the cyclotron magnet.

The operation of the ECR and axial injection system has been very reliable and has greatly improved the overall performance of the K500 cyclotron leading to many new beams of higher energy (described in a following subsection) while eliminating the extensive down time required for replacing cathodes in the previously used PIG sources.

Other papers at this conference give more details about the ECR and the axial injection system[3].

### K500 Beams

Normal Beams. Beams of the elements listed below have been produced in the ECR ion source and extracted from the K500 cyclotron. The highest energy for a given projectile is shown. (The lowest energy used so far is 8 MeV/A.)

| Nucleus | Max. E/A achieved [MeV] | Nucleus | Max. E/A achieved [MeV] |
|---|---|---|---|
| 2 H | 53 | 18 O | 35 |
| 4 He | 54 | 20 Ne | 30 |
| 12 C | 50 | 22 Ne | 35 |
| 14 N | 54 | 40 Ar | 30 |
| 16 O | 54 | 86 Kr | 20 |

Generally, beams can be produced for any energy per nucleon (E/A) which satisfies all of the following conditions:

| | |
|---|---|
| 1) $E/A > 2$ MeV/A | Rf low frequency, h=2 |
| 2) $E/A < 515\ (Q/A)^2$ | Magnet bending limit, 515 MeV |
| 3) $E/A > 200\ (Q/A)^2$ | Coupling resonance limit |
| 4) $E/A < 110\ Q/A$ | Dee voltage limit (75 kV) |

Condition 4) will be replaced by $E/A < 160\ Q/A$ (magnet focusing limit) after upgrade of rf resonators increases their power handling capability. Continuous coverage of the energy band is possible for ions with

A=12 and above by selection of appropriate charge state. Standard values of energy per nucleon (multiples of 5 MeV/u) are used whenever possible. Development of lithium beams from the ECR is scheduled for fall 1986 (lithium beams were frequently run with the PIG source in the pre-ECR operating era).

External beam intensity used in experiments is typically in the range 0.5 to 100 particle nA. In many cases of interest the intensity is not limited by the ion source, but rather by the experiment requirements (usually data processing limits) or by heating of the electrostatic deflector. One tenth of the DC beam injected is accelerated by the cyclotron (phase width = 35 degrees); this is increased by a factor of 3 to 5 by use of the buncher in the injection line. Overall transmission from ion source analyzer output to target is between 1 and 5 percent at present.

Radioactive Beams. Several runs on the K500 have used an internal target to produce radioactive isotopes on the turn preceeding the extraction system. The extraction system can then be used as an isotope separator, the combination of electric and magnetic components allowing the system to both velocity select and momentum select. An intermediate stripping can also be inserted part way through the system to shift the Q/A distributions, which is a helpful step in removing trace components of undesired isotopes such as primary beam residuals. Characteristics of this process are described in a separate paper[4].

Phase Selection. A phase selection system for the K500 cyclotron has been constructed and used in an initial set of test runs. The selection is accomplished using the coupling between the horizontal and longitudinal motions; a slit located on the first turn provides the coarse selection, while two tungsten posts located 120° apart at turn 33 provide the fine selection. Initially this system will be used to prepare sharply defined beams for studies of turn patterns and focusing frequencies; later it will be available to user's who need short pulses for timing measurements.

## Highlights From The K500 Experimental Program

In the years since 1982 the K500 cyclotron has supported a highly productive experimental program, operating as a national user facility providing beam for 3500 to 4000 experimental hours per year. Approximately 90 experiments have been completed as of Sept. 1986, and by the end of 1986, 14 students will have finished experimental theses at the NSCL.

It is not possible in these proceedings to summarize the extensive K500 experimental program in detail; the following subsections briefly outline studies performed in the past year which are likely to have an important influence on the evolution of heavy ion physics.

Observation of High Energy Gamma Rays. Gamma rays with surprisingly high energies (up to 120 MeV) have been observed in heavy ion collisions at K500 energies -- detailed studies of these gamma rays are expected to provide a diagnostic of the collision process with a well understood, weakly interacting probe;

The Meaning of Nuclear Temperatures. Nuclear temperatures obtained via the Boltzmann technique are both smaller than those obtained from spectral slopes and similar for very different systems -- these measurements are expected to be important in clarifying the meaning of temperature in the nuclear context;

High Energy Charged Particles. Measurements of the extreme high energy tails in the spectra of high energy protons and alphas produced in nucleus-nucleus collisions show alpha particles with total energy equal to that of the beam -- this is direct evidence for the presence in nuclei of phenomena that concentrate the total energy carried by a complex projectile on a much smaller number of nucleons;

Circularly Polarized Gamma Rays. Measurements of the circular polarization of gamma rays from nucleus-nucleus collisions show that the attractive nuclear mean field remains important in the Fermi energy domain; this provides an important constraint on the collision process;

Charge Exchange Reactions. A correlation between cross sections for ($^{6}$Li,$^{6}$He) reactions and beta decay strength has been established; this will permit quantitative application of heavy ions to the important field of spin-isospin spectroscopy, a prime area to look for the effects of the meson and excited baryon constituents of nuclei;

Lifetimes and Decay Branching Ratios. Measurements of the lifetimes and decay branching ratios of exotic nuclei with the Reaction Product Mass Separator (RPMS) have yielded the first results from a program that will study the properties of nuclei far from the valley of stability, testing theories of nuclear structure for extreme ratios of neutrons and protons;

## K500 Operating Problems and Improvements

Helium System. Almost all helium system difficulties are associated with impurities in the helium gas which degrade the performance of the helium liquifiers and build up and block the flow in the liquid helium distribution system. At various times we have experienced impurity difficulties due to: a) water, traced to a water cooled heat exchanger in a compressor, b) oil, traced to a faulty compressor oil coalescer unit, and c) neon, present in makeup gas at the 27 ppm level. Possible other sources of contaminants include makeup compressor oil, equipment additions, and refrigerator warmup and maintenance procedures. Quick identification of the contaminating substance always aids in implementing corrective measures; rather sophisticated diagnostic equipment has therefore been added to the helium system. Specific devices include a hygrometer to test for water, an aerosol meter to monitor oil mist concentration, and an optical spectrometer capable of detecting Ne, $N_2$, and $H_2$ below the ppm level.

The present most troublesome system impurity is neon[5] which is primarily controlled by sintered stainless steel filters in the liquid distribution lines. The optical spectrometer indicates that neon is gradually removed from the process stream over time, and repopulates when new makeup gas is added. The neon apparently moves through the liquid helium lines as some form of small solid cluster (a "snow-flake") and forms blocks at points where the aperture of the line is reduced (at valves, etc.). A brief, slight change in the temperature of the line removes the block, but the process is troublesome and improved trapping of neon in the makeup gas stream would be quite helpful.

Contact and corrosion problems in the rf system. When the K500 cyclotron was first turned on, the rf resonators were operated individually with peak voltage on the dees in the 90 to 100 kV range. More recently, operation of the cyclotron with beam has been limited to lower voltages by contact failures and overheating of various joints in the dee stems.

The first of these problems involved the sliding contact fingers on the outer conductor of the dee stem shorting planes; after a few months of use, these contacts would tend to fail during high rf current runs. This problem was successfully corrected by introducing specially made contact fingers with silver/graphite contact spheres for the contact surface. Aside from premature failures due to insufficient silver plating and poorly soldered joints, the new fingers have been trouble free in all locations where they have been used including 1) from stem to sliding short in the rf transmitter tuning stems, 2) from dee stem outer conductor to sliding short on the cyclotron rf tuning stems, and 3) for test purposes on one dee stem, at the joint between the dee stem inner conductor and the sliding short, this joint having a higher current density than any other joint in the cyclotron. (The fingers survive steady-state bench-tests at 100 amperes at 60 Hz and 42 amperes at 27 MHz; noting the favorable results from the K500 tests, the K800 cyclotron will use these fingers for all movable rf joints, the extreme K800 operating condition corresponding to 34 amperes per finger at 27 MHz.)

The present limiting K500 rf system problem is associated with overheating of the copper corona rings which electrically join the two sections of the dee stem at the flange where the dee stem insulator contacts the stem. Failures in this joint have been traced to a thermal instability: the ring is cooled by conduction to water-cooled copper flanges through a contact which becomes less effective as the temperature rises. The planned solution is to install stronger contacts and modify the rings to include water cooling tubes to remove heat directly.

Another troublesome rf system joint is at the point where the copper tubes lining the dee stem holes in the magnet poles are assembled to a mating spinning. This is a bolted joint with a helical rf spring contact in the joint to conduct current, a type of joint which is normally trouble free. The difficulty with these particular joints is thought to be due to the fact that the assembly procedure required soldering a number of water cooling tubes between these parts after assembly of the bolted joint; extensive corrosion believed to be caused by the water tube soldering flux was observed in two of these joints and rf energy was detected leaking from the joints. The two joints in which this condition was most advanced were repaired by removing the rf spring ring and soldering the two parts directly together. This procedure appears to have worked successfully; the corresponding joints in other resonators will therefore be similarly modified.

The K500's rf amplifiers have also been impacted by corrosion. The cabinets housing each of these amplifiers are constructed mostly of aluminum, and originally without any protective coatings. Over the years the rf heating and the humidity which occur in the cyclotron vault have speeded an already high oxidation rate for aluminum. As a first order solution to this problem, when maintenance or component replacement occurs, we a) scrape and sand the corroded surface, and b) brush on an iridizing solution. At present, this is working well, but the sheer number of such connections could call for full amplifier box overhaul or box replacement in the future. (Surfaces of the amplifier boxes for the K800 cyclotron are either iridized or composed of materials which oxidize more slowly, such as copper or nickel.)

Lower Gasket Ring Vacuum Leak. A potentially serious K500 problem is associated with a growing beam chamber vacuum leak in a major joint between the cryostat inner wall and the lower magnet pole. This joint is sealed by a double gasket between the rim of the cryostat and the magnet pole, the inner gasket being an indium wire and the outer a rubber O-ring which allows guard pumping. The increasing leak is believed to be due to corrosion (rust) from occasional coil condensation, the rust propagating under the O-ring so that it leaks at an increasing rate. We are still able to operate the cyclotron at present because the seal works marginally when the magnet is on (beam chamber vacuum ≈ $10^{-6}$ torr) even though it now leaks badly when the magnet is off (beam chamber vacuum ≈ $10^{-1}$ torr). Unfortunately, the lower pole gasket was not designed to be easily changed, but modifications to make this change easier are now being planned. One presently favored solution is to build a new magnet support system that allows lowering of the magnet lower pole for the initial fix and for future maintenance of the seals. Fortunately, the corresponding upper gasket is readily accessible whenever the pole cap is raised for access to the beam chamber. To avoid this problem in the K800, a lower pole lowering system has been installed and tested.

Deflector Dust. As reported at the previous conference[6], the electrostatic deflectors in the K500 cyclotron do not run routinely at voltages above about 60 kV, whereas the peak design value was 100 kV (or 140 kV/cm electric field). In an electrostatic test stand these deflectors do, however, operate routinely at 80-90 kV. The difference between operation in the cyclotron and in the test stand is thought to be due to the rather dirty environment which exists in the cyclotron; deflectors removed from the cyclotron generally have coatings of dust and fine particles on the high voltage electrodes, but ones removed from the test stand do not. To address this problem, end caps are being added to the deflector housings to reduce the aperture through which dust particles can enter the deflectors.

Coupler Insulators. The rf power is sent to the dees of the K500 cyclotron through a 3" diameter 75Ω coaxial transmission line. The vacuum window insulators used in these lines in their original form tended to fail after a few months of use. A new design has been introduced which utilizes a "planar" disc insulator of alumina brazed between the inner and outer coaxial conductors and includes a pair of "corona" rings or baffles on the vacuum side. None of the new insulators have failed in over a year of operation.

Deflector Insulators. At the previous cyclotron conference we described electrical and mechanical problems with the insulators which support the K500's electrostatic deflectors[6]. At that time a new "planar end" insulator design was being developed and is now routinely used. The new insulators are made from sapphire cylinders 0.313" diameter x 0.85" long, metallized on each end with a standard Mo-Mn procedure and then brazed in a hydrogen furnace to molybdemum end caps. Grooved insulators appear to perform slightly better than smooth insulators, but the difference is marginal. The new insulators are mechanically rugged, but require cleaning to remove metallization after extended operation at 80-100 kV.

Main coil internal short. A number of years ago a short circuit appeared in the main superconducting coil of the K500. The short is not superconducting and therefore effects the coil only when voltage is being applied for charging or discharging the magnet. At these times the short is evidenced by an imbalance in the potential distribution (and the flux distribution) between the two halves of the coil, the voltage imbalance oscillating with a period of about 3 s during charging and discharging of the magnet as shown in Fig. 1. The observed behavior is consistent with what one would expect if a metal chip were in contact with two layers of the coil in a way which shorts out several hundred turns; as the main field is increased or decreased the current in such a cluster of shorted turns would increase to oppose the flux change until it reached the critical current of the superconducting part of the loop; at this point the loop's resistance would increase, the current in the loop would fall, and, after the temperature of the loop returned to superconducting values, the cycle would repeat. The phenomenon is interesting but has no impact on operation of the cyclotron, the magnet being regularly ramped to whatever field is desired using the full voltage available from the power supply.

## The K800 Cyclotron

The K800 is the largest of the superconducting cyclotrons presently under construction in the world and in terms of magnetic rigidity, the 2nd largest cyclotron ever constructed, the bending power of its magnet being exceeded only by that of the 1 GeV synchrocyclotron at Gatchina. (The Gatchina cyclotron magnet weighs 7,800 tons, the K800 magnet 265 tons.) The bending power of the K800 magnet corresponds to an actual "K" value in excess of 1200 MeV; isochronous operation is limited by a "focusing K" of 400 MeV (or 200 MeV/nucleon when Q/A = 1/2).

The K800 design can, in most respects, be characterized as an improved K500 system. Problems which have turned up in the course of operating the K500 as a research facility have hopefully all been adequately addressed and corrected in the K800 design (a number of K500 improvements described in preceeding sections were noted as transferred to the K800). The K800 is however at the same time a much more difficult technical challenge than the K500 due to the larger number of turns, the higher dee voltage, the tighter spiral, and the intrinsic proximity of the operating point to the 3/2's radial stopband. These factors particularly impact the design of the extraction system which at the time of the previous conference was incomplete. The extraction system is however now fully defined and under construction. This and other components of the cyclotron are expected to be completed on a schedule which will allow operating tests of the cyclotron in the Spring of 1987 with first nuclear physics use following in the Summer.

### The K800 Magnet

Operating experience. Beginning with the initial magnet run in May 1984, the superconducting coils for the K800 have been at liquid helium temperature for a total of approximately 12 months and have operated for over 1000 hours for mapping of the magnetic fields and testing of various systems under the influence of the field. The coils have performed solidly with no indications of shorts or winding movements. Following are cryptic descriptions of some interesting, unintended events which have occurred:

November 84' - Technician disconnects foreline of coil insulating vacuum without closing valve - large heat load on helium vessel blows 2 atm rupture disc - leak fixed and coil refilled without problem.

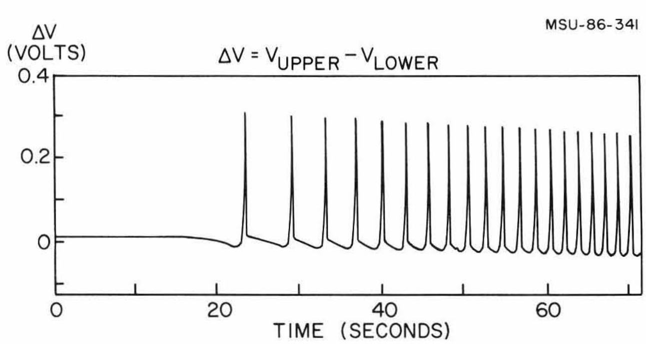


Fig. 1--Voltage imbalance in a K500 main coil pair during a magnet ramp (which started at t=0.)

May 85' - Coil operating at currents of approximately 650 amps when building power failure occurs, turning off refrigerator, magnet power supply, and diagnostic instrumentation - current leads automatically go to full flow as designed - coil current automatically goes into a slow decay mode - power restored in 10 minutes - found liquid helium level to be still above coils and current decaying normally.

March 86' - Transfer line block stops liquid helium flow to coils while operating at full design current (850 amps) - power supply put into full rate ramp down - current leads opened to full helium gas flow - liquid helium level drops below top of windings as current passes 600 amps, and drops several more inches before magnet is fully discharged - coil operated normally after transfer line block cleared.

April 86' - Power supply failure with coil at 850 amps - coil ramps down in the slow decay mode - coil operated normally after power supply repair.

Heat Leak. A measurement of the total heat load generated in the coil cryostat can be obtained by monitoring the helium level after closing off the liquid helium supply ("taking a boil-off curve"). To do this reliably, the cryostat pressure and lead gas flow must be maintained at a constant level; knowledge of the liquid helium reservoir geometry will then yield absolute heat load values. Normal boiloff curves indicate a heat load of 20 watts for the filled coil. As the liquid level falls, the boil-off rate also falls, indicating that much of the heat load is in the upper part of the coil and at the median plane. A drop from 10 watts to 8 watts occurs as the liquid level goes below the median plane of the coil, and, just before the coil runs dry, the boiloff rate is equivalent to a heat load of 7 watts. The heat load carried away by liquid nitrogen cooled shields and intercepts is typically around 175 watts under operating conditions. The observed boiloff rates are not a problem for the laboratory's 800 watt (at 4.5 K) refrigeration system, but are never-the-less 2 to 3 times higher than expected.

A reevaluation of the actual cryostat internal conditions (vs. design conditions) has led to a tentative understanding of this heat load. During the initial running periods, the helium vessel was wrapped with 20 layers of multilayer insulation and the liquid nitrogen cooled radiation shield was in turn wrapped with 30 layers of multilayer insulation. Using a design value for heat transmission that takes into account that some of the multilayer insulation was fairly tightly packed, and noting that the 4 K surface area is approximately 30 $m^2$, a value of 7 watts is calculated for the heat transmitted from the shield to the coil. Openings in the 80 K shield and unshielded penetrations through the median plane of the cryostat account for another 8 watts of heat load on the coil. These losses are then apparently the dominant factor in the larger-than-expected total heat load. In the coming months, as the coil is reassembled following installation of beam extraction elements, effort will be directed toward improving the overall effectiveness of the insulation and thermal shield systems with the goal of significantly reducing the total thermal load on the coil.

K800 Trim Coil Fabrication and Installation. The K800's one hundred twenty-six trim coils use fused dacron insulated, 0.250" square, OFHC, hollow copper conductor. Each coil was hand wound on one of twenty-one different fixtures corresponding to the radial location of the coil on the pole tip. Prior to being mounted on the pole tips, additional coil-to-ground insulation of two layers of fiber-glass cloth was wrapped around each coil. The coils were then mounted on the pole tips and each of the six 3400 lb. pole tip, pole base, and trim coil assemblies were potted with an unfilled, flexibilized epoxy formula chosen for good mechanical and vacuum properties. The potting used a vacuum impregnation procedure with the epoxy cured by resistive heating in the trim coils themselves. Trim coil leads were dressed with additional insulating sleeving and routed through glass laminate clamps to combined vacuum, electrical, and water feed-throughs on the magnet surface.

## Magnetic Field Mapping

Mapping system hardware. Magnetic field maps were taken using the apparatus described at the previous Cyclotron Conference[7] which uses a search coil running radially and read "on the fly" every 0.1". The search coil is calibrated by measuring the absolute field at the center of the cyclotron, and at the center of a dee stem hole, using a $D_2O$ NMR probe. Maps with an angular step size of 0.5 deg, with resolution of 0.001°, covering the entire 360°range are made in less than two hours. Samples of the magnetic field in the edge region were taken using a longer search coil head with the data acquisition program modified to automatically seek the proper angle to insert the longer coil into the cryostat penetrations.

Mapping regime and data processing. Fields with trim coils off were measured from r= -2.5" to +41.5" in 0.1" steps over 360° in 1/2° steps in a 27 point grid of main coil excitations covering the range 400 to 1000 amps for the close-to-the-median-plane main coil section, the "inner" coil, and -400 to +900 amps for the "outer" coil. Fields for all trim coils were measured over 140° in 3° steps for 4 main coil excitations (taking advantage of the fact that the incremental fields from the trim coils are nearly independent of main coil excitation). Processing of the data accounted for: 1) unequal radial and angular spacing; 2) mapper axis of rotation noncoincident with magnet axis; 3) coil center not passing directly over mapper axis; 4) shifts in the angle reference for each map; and 5) possible extra data in some scans. Tests of field quality indicate radial consistency of $<\pm 1.5$ gauss. Angular consistency was degraded from this at large radii due to the relatively coarse spacing (0.35" azimuthal steps vs 0.1" radial).

Penetrations in the cryostat allowed measurements to be extended to 56" at certain angles. These data were matched to the 0"-41.5" data allowing for all the effects listed earlier for the 360° fields. These edge fields were measured at 19 main coil excitations.

Analysis of the data led to these conclusions: 1) the pole tips were symmetrically placed within about 0.002"; 2) the first harmonic in the field was less than 10 gauss everywhere in the acceleration region; 3) the coil position which minimized decentering forces also minimized the first harmonic in the field in the acceleration region (some excitation dependence of the first harmonic remains); 4) we can reliably design shims with the computer and obtain field changes which closely match the calculated change.

The magnetic field measurements have been used as a base for further optimizing our magnetic field calculation procedures. Presently, our $B_{avg}$ calculations agree with the measurements within ±200 gauss and the same is true for the azimuthal field modulation. (The former is obtained with a POISSON calculation involving >20000 points in the lattice and the latter by reducing the nominal (21.4kG) saturation field of the iron by 3% and slightly modifying the effect of the pole tip edge chamfer.)

## Radio Frequency System

Amplifier Status and Testing. The K800 RF amplifiers are now fully fabricated, and are currently being connected to the rf control console. The control hookup work is scheduled to be completed in October, 1986 after which the amplifiers will be calibrated, tested, tuned, and then 'run in' by operating each amplifier into a 300 kW water cooled load. By December 1986 all these tests should be complete.

Prior to shutting down for installation of the final controls, one of the amplifiers was tested extensively with very encouraging results. Harmonic distortion into 50 ohms was highest at 14 Mhz, but even at this frequency was 18dB below the fundamental. Throughout most of the 9 to 27 Mhz band, the harmonic level was well below -28dB. (The observed distortion was in fact expected on the basis of the design calculations and is caused by the foreshortened cavity design). The amplifier delivered 240 kW to the water-cooled load without difficulty at 27 Mhz. Noting that our expected power need at 27 Mhz is 180 kW, the system appears to have a comfortable power margin. Final confirmation of the design will come as we bring the cyclotron cavities on line in early 1987.

Cyclotron Resonators and Dees. The K800 resonators are similar in layout to the K500 resonators, namely a basic half wave system composed of two quarter wave, shorted coaxial lines running up and down from each of the dees. The vacuum system is terminated by large cylindrical insulators at the point where the lines leave the top and bottom of the magnet and tuning is accomplished by a "sliding short" which moves up and down in the "airside" region beyond the insulator to change the electrical length of the quarter wave stubs. Principal differences relative to the K500 are 1) because of the greater thickness of the magnet, the insulators must be depressed into the magnet rather than sitting on top, 2) copper spinnings are used more frequently in the K800, giving improved electrical characteristics, improved strength, and improved cooling, 3) because of the greater resonator size, the airside outer conductor is a 12 sided array of flat panels rather than a 6 sided array as in the K500.

Principal sub-elements of the resonators include: sliding shorts, sliding short drives, air side outer conductor panels, air side outer conductor spinning, vacuum side outer conductor weldment, air side inner conductor weldment, vacuum side inner conductor spinning, and the dee. Assembly of each sub-unit includes welding or brazing flanges, final machining, and installation of water cooling circuits. After completion, each assembly is vacuum leak checked.

The sliding short is perhaps the most complicated subunit; it is fabricated from formed plates which fit the dodecagonal outer conductor and the circular inner conductor. Inner and outer conductors are contacted by spring-loaded fingers of the type described previously. Each water cooled short base is moved through its design 12 foot range of travel by a screw-driven servo unit.

The dee proper consists of a formed copper skin supported on an aluminum frame with a soldered-in-place water cooling tube circling the inside of the dee near its periphery. An offset has recently been introduced in the stem attachment point as described in the next subsection in order to achieve a more optimum voltage distribution on the dee. This offset and other features of the dee show clearly in Fig. 2, which gives a perspective view of one of the two mirror image halves which go to make up a complete dee.

Low Power Model with Offset Stem. The original location of the attachment point for the K800 dee stem was based on the expectation that the principal use of the cyclotron would be as the second stage of a double cyclotron system, i.e. that the inner radius of the dees would be at 1/3 of the K500's extraction radius (3 to 1 coupling ratio). More recently, developments in ECR sources make it clear that the K800 will most (if not all) of the time be working with a beam axially injected at the magnet center (this point is discussed more extensively in a later section), i.e. that the inner radius of the dees will need to be nearly at r=0. With this revised dee configuration, calculations and low-power-model measurements showed that the balance between the dee voltage in the central region and that at extraction would be significantly improved if the connection of the dee stem to the dee was made closer to the central region (farther from the extraction radius). Noting the complex geometry of this offset dee connection, and the uncertainties inherent in computer models of such complex situations, a full scale mock-up of the revised dee and dee stem was constructed. This structure was designed to operate at the high frequency end of the cyclotron tuning range (27.5 MHz) where the voltage gradient along the dee is most severe. Results showed the frequency to be 2.5% higher than calculated (using the NSCL program RESON), and the voltage at extraction was approximately 4% lower than calculated. The net improvement in the voltage balance was however 17% relative to the previous design and the offset stem design was therefore selected for the K800 dees.

Rf Liner Fabrication. The rf liner for the K800 is both the final section of the resonator outer conductor and a vacuum barrier separating the high-quality, organic-free, beam chamber vacuum from the "dirty" trim coil vacuum. The liner is then a very intricate component -- in essence a thin copper skin shaped to just clear the intricate array of spiral pole tips and valley shims which constitute the pole tip, without taking up undue space and with 1)water cooling adequate to withstand significant rf power dissipation and 2) strength adequate to withstand atmospheric pressure loading in at least one direction.

Fabrication of this pair of intricate elements is fortunately now nearing completion. The main 84" diameter copper covers are made of .094" thick copper sheets formed and silver brazed together around special fabrication fixtures. All seams are helium leak tight to maintain vacuum separation, and the 35" deep, 84" diameter, copper can that is formed is brazed to an iron ring that carries the assembly joint vacuum seals. Figure 3 shows one of the liners in place on the magnet.

## Extraction System

Layout of System Elements. The principal difference between the final K800 extraction system and previous versions[8] is that the second electric deflector (E2) is reduced to one-third of its former length, which allows a mechanically important section of the cryostat wall to be left intact in the space occupied by the last third of the previous E2, thereby alleviating a problem of inadequate wall strength in that area. To make up the lost deflecting power, a passive magnetic dipole (B1) replaces the middle third of E2. The central field of this dipole element is 4 kilogauss, i.e. nearly six times the strength (at 200 MeV/nuc) of the electrostatic element it replaces. The layout of these and other extraction system elements is shown in Fig. 4.

The focusing bars M2-M8 have gradients ranging from 7.5 to 12 kilogauss/inch, with central field strengths of two to three kilogauss. Maximum E1 and E2 field strengths are 124 kilovolts/centimeter (this compares with 140 kV/cm required for maximum design energy in the K500). The magnetic elements B1, M1 and M2, which are close to the internal orbits, each have two compensators to eliminate first and second harmonic field perturbations. B1, unfortunately, cannot have perfect three-sector compensation because an exact 120° duplicate would interfere with the electric deflector

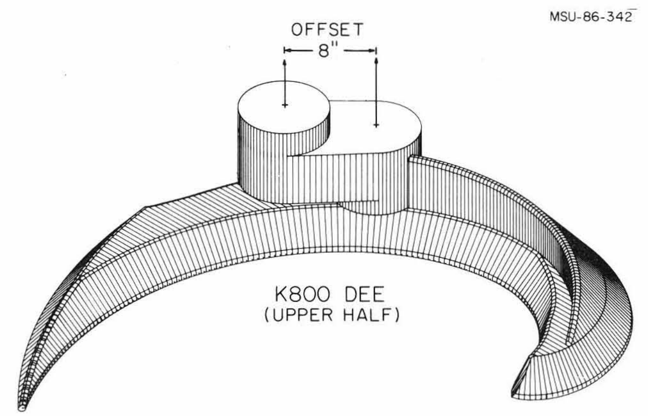


Fig. 2--Perspective view of a K800 dee. The beam space is a 1" gap between this dee half and a symmetric mirror image lower dee half.

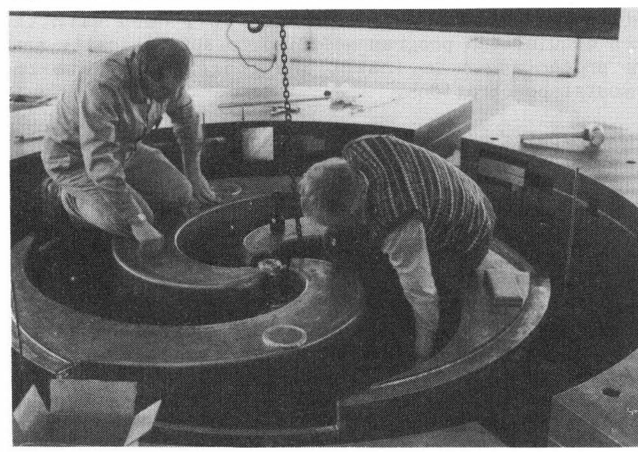

Fig. 3--Photo of a K800 liner in position on the lower magnet pole.

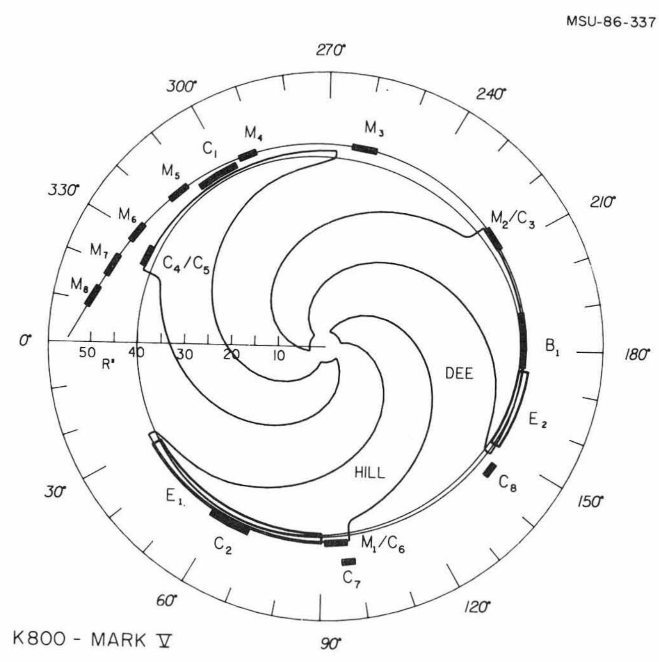


Fig. 4--Polar coordinate drawings showing the location of K800 extraction system elements. Symbols are: E-electrostatic deflector; M-magnetic focusing cluster; B-magnetic dipole; C-imperfection compensating element.

E1. Its compensators (C1 and C2) are therefore single element bars placed at a larger radius, and a "wing" is added to B1 to give its fringe field the same shape as the field of the compensators over the last inch of internal orbit space.

The external field of B1 generates a significant displacement of the last internal orbit by decreasing the average field of the main magnet. M1 and its compensators largely offset this effect by generating a positive peak at the extraction radius. A second function of M1 is to prevent radial defocusing of the extracted beam by the M2 compensator at the end of E1. This is done by making another, smaller peak on the outer side of the large one. Figure 5 is a plot of the M1 field and the external field of C6, a compensator identical to M2, and shows the cancellation of the gradients.

At lower main-magnet excitations, the focusing power of the extraction system is adjusted by removing elements. Figure 6, for example, shows the radial and axial envelopes for the 200 MeV/nucleon beam and indicates that satisfactory focusing is obtained for this field with M3 not in use.

Extraction System Fabrication. The electrostatic and magnetic deflectors required for the extraction system have been laid out using a Computer Assisted Design (CAD) system. The main design layout work is now

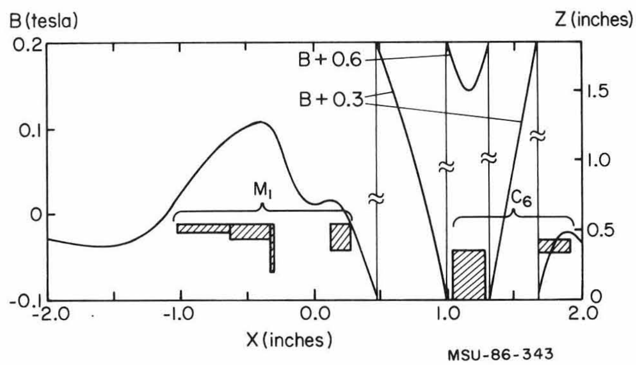


Fig. 5--Right ordinate--cross section through the pair of elements M1/C6 (which are identical to M2/C3 and C4/C5); left ordinate--the magnetic field produced by these elements.

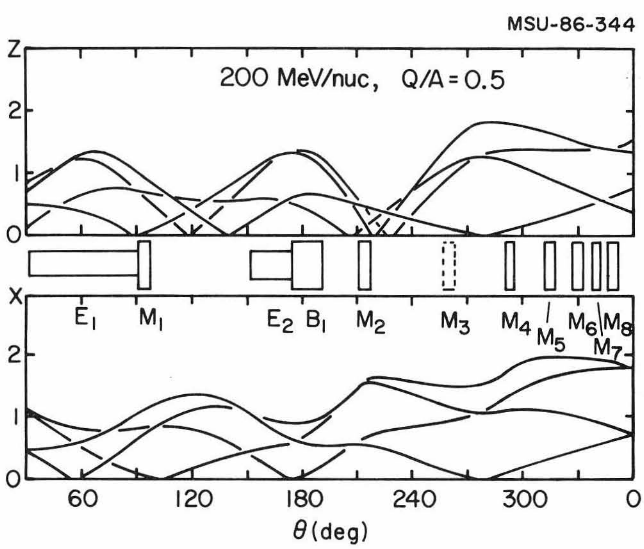


Fig. 6--Extraction orbit behavior for Q/A=0.5 rays in the 200 MeV/nuc field.

complete (Sept. 1986) and drawings of component parts are being prepared. The inner and outer wall of the cryostat are now being machined to incorporate entrance and exit channels for the beam, and drives for the deflectors and beam probes. In some locations this includes replacing segments of the inner wall with heavier sections to accommodate the loss in wall strength caused by the cutouts for the deflectors and magnetic channels. Some machining of the helium vessel will also be required to make room for beam channels; the helium vessel in previous operating cycles was found to be completely leak tight (pumps on the insulation space could be left valved off, giving a significant operating advantage in that the insulating vacuum was immune to power failures); fortunately, the remachining which is required for the beam channels will leave previous welded seals undisturbed except for one small area; this area will be rewelded with extreme care to preserve the fully leak tight status of the vessel.

## Vacuum System

The beam chamber of the K-800 superconducting cyclotron is maintained at high vacuum by two types of pumping systems, cryogenic and turbomolecular. The cryopumps which are mounted inside of each dee are the primary pumping system, but three external turbo-molecular pumps serve for the initial pumpdown and pump away gasses evolved when the cryopanels warm up. The effectiveness of pumps external to the cyclotron is limited by the conductance of the penetrations through the magnet yoke; thus each of the 550 liter/second turbo pumps yields a net pumping speed for air of only 110 liters/second in the beam space, or a total of 330 liters/second from the three external pumps combined.

The cryopanels are located in the lower half of each of the three dees. Each helium-cooled panel presents 900 square centimeters of pumping surface which, taking account of the transmission to the panels, leads to a net pumping speed for nitrogen of about 2500 liters/second. Each cryopanel includes a layer of charcoal granules epoxied to the surface to enhance the pumping for neon, helium, and hydrogen which would otherwise have a low sticking probability. The cryopanel is enclosed in a shroud, cooled by liquid nitrogen, to shield the panel from high temperature sources of radiant energy. A small reservoir for each of the cryogens, helium and nitrogen, is housed in the dee stem just outside the dee, and heavy copper thermal buses conduct heat from the cryopanel and its shroud to these reservoirs.

A continuous supply of liquid helium and liquid nitrogen is delivered to the cryopanels via vacuum-jacketed cryolines in the interior of each lower dee stem. Following the K500 design, these lines emerge at the shorted end of the dee stem which is at ground potential and are connected to the general cryo-distribution system. The cryopanels and shrouds are instrumented with sensors for temperature monitoring during operation. The estimated total pumping speed for the three cryopanels and the turbo-molecular pumps of about 8000 liters/second is expected to result in a vacuum of about $10^{-7}$ Torr in the beam region.

## Control System

The K800 controls will be a sub-system of the overall NSCL Phase II control system. This system can be characterized as a modified copy of the Fermilab Linac control system. The basic structure is a distributed, intelligent data base, system, with the multi-node structure connected by ARCNET, a token passing ring network. The ARCNET link permits passing commands or readings and data base alteration as needed. An ARCNET to ETHERNET gateway will be used to interface the control system to the central laboratory VAX system.

Local control nodes are M68010 single board microprocessor systems. All local control nodes operate with the same core program; the general program is tailored to the requirements of a specific complement of devices by using a table driven data base stored in nonvolatile RAM and specific device driver software. Each local control node can be directly accessed via a dedicated local console consisting of an alpha-numeric keyboard, 5" CRT screen, multipurpose knob and several switches.

General system control is from multiple main console nodes, which include a centralized master station for program development, initial load, and archival storage. Each main console is managed by a multi-tasking operating system servicing several CRT screens, a keyboard, a mouse, a collection of adjustment knobs, and a bank of meters. All main consoles are basically identical and are user configurable within the generic capabilities of the console. The primary control CRT is touch sensitive; other screens are used for dedicated display of interlocks, graphical displays, control menus, parameter lists and data logs. An operator at any console can select any desired set of major subsystems for control (provided the subsystems are not already under the exclusive control of some other console), can save and recall complete sets of value settings for all parameters, can save and recall user configured console control arrangements, and can change parameter settings via knobs, touch screen, keyboard or mouse buttons.

Interlocks will be managed by separate programmable logic controllers. Control system computers will have "read only" access to interlock status in the programmable controllers, and will have a mechanism to request that interlocks be reset. (The read-only access protects interlocks from unintentional changes by control system computers.)

## Cryogenic System

The 800 watt helium refrigerator-liquefier from Cryogenic Consultants Inc. has been operated since Sept. 1982. The system utilizes liquid nitrogen precooling and incorporates 3 reciprocating expanders, the third acting as a wet expander which can be bypassed by a J.T. valve. The design allows for expansion of capacity by adding a turbine expander and also includes intermediate temperature tap points appropriate for controlled coil cooldown. An additional feature, a cold gas compressor, is being added to maintain a lower helium boiling pressure in the cyclotron coils when the refrigerator is running at maximum capacity. Three oil flooded screw compressors can supply up to 80 grams/s of room temperature helium at a pressure of 18 atmospheres. Liquid nitrogen, brought in by tanker truck and stored in two 3600 gallon tanks, is used as well for operating liquid nitrogen cooled shields and intercepts in coil cryostats and transfer lines. A comprehensive cryogen distribution system is being build in stages. The design makes extensive use of Invar 36, a material with a very low thermal expansion coefficient. The Invar 36 has been used in unshielded, multi-layer insulated transfer lines up to 65 feet in length (these lines were used in the K800 magnet testing and mapping phase to supply cryogens to the magnet).

The final crogenic distribution system uses counterflow coaxial subcooling lines for controlled liquid transfer and employs liquid nitrogen cooled shields to minimize the 4.5 K heat load. One of 4 main distribution boxes is in operation and a second is about to be completed by a local shop. The system in its final configuration will be capable of supplying cryogens to the main coils and cryopumps of the two cyclotrons as well as to an ECR source and to approximately 70 beamline magnets.

## Medical Cyclotron Studies

Two medical cyclotron projects are underway at the NSCL, one involving construction of a K100 superconducting cyclotron for neutron therapy, the other, a study of a K250 superconducting synchrocyclotron for proton therapy. The neutron project is in an advanced state with first operation of the magnet expected in Nov. 1986 and first beam in the cyclotron expected in Feb. 1987. This cyclotron will then be moved to Detroit and installed in the radiation oncology center of Harper Hospital, one of the city's largest medical facilities. The proton project is in contrast in an early design stage with possibilities for funding construction of a first such machine in a state of initial exploration.

## The K100 cyclotron for Harper Hospital

At the previous conference the design concepts for a hospital based superconducting cyclotron were described[9]; shortly after the conference, in Sept. 1984, the project became official and the pace of work accelerated considerably. An updated description of the design was given at the 1985 Accelerator Conference[10], describing particularly a new mounting system for the cyclotron and a new, invertible, helium vessel design. This cyclotron as mentioned above is now nearing completion with installation at the hospital expected in early 1987.

System Concept. Many project details have changed significantly in the two years that the project has been in process, but major features remain the same as previously described[9,10] namely:

1) the cyclotron will mount on a ring type gantry and will be able to move in a full 360° arc about a supine patient.

2) the cyclotron will use a third harmonic, three dee rf system operating at 105 Mhz to accelerate deuterons to 50 MeV in a magnetic field of 4.58 tesla at the center and 5.4 tesla max. on the hills.

3) the deuteron beam will produce neutrons in an internal, thick beryllium target located 185 cm from the rotation axis of the isocentric mounting system and giving an estimated dose rate of 0.6 gray/min for a 10 μamp beam.

4) the cyclotron will be extremely simple with no frequency adjustment, no trimming coils, and no extraction system so that the overall system should be exceptionally reliable.

A central element of the cyclotron design which has changed significantly since the previous conference is the design of the superconducting coil. The coil is now a high current density, fully impregnated design, with a batch-fill helium system which includes thermal conduction elements designed to allow the coil to continue to operate until the liquid supply in the vessel is fully exhausted. The helium vessel includes a special array of vent pipes[10] which allow the vessel to operate as an atmospheric pressure, pool boiling system, which can never-the-less be fully rotated without spilling liquid helium. The coil structure involves a number of novel design features whose performance will be interesting to observe as the magnet is brought into operation for the first time.

Construction Status. Fig. 7 shows a model of the cyclotron and gantry system. Specifications require that the gantry be stiff enough to support the 50 ton combined load of cyclotron and counterweight with maximum deflections such that the axis of the beam always intersects a sphere of 3 mm diameter at the system isocenter, irrespective of the position of the cyclotron in the 360° rotation range of the system. The two large rings of 166" O.D. and 126" I.D. are the major element responding to this specification. Stress calculations predict that the shift in aiming point due to deflection of these rings will be less than ±0.050". The rings are supported by a system of 8 rollers one of which is driven by a 1 hp gearmotor, and the complete system is mounted on a precision base plate that measures 180" x 120". A floor allowing access around the treatment couch has been designed. This floor will be pushed out of the way by the gantry when the cyclotron is positioned at angles below the horizontal. (Many features of the combined floor and support system can be seen in Fig. 7.)

The main superconducting coils are constructed as a close packed, carefully ordered, epoxy impregnated winding. The conductor is wound in a true helix around a double wall bobbin, the bobbin outer wall fabricated from special, high nickel, 316 stainless steel, the inner wall being of copper. The stainless steel provides strength and vacuum integrity for the He vessel, the copper is a conduction element to cool the potted coil even when the helium level is low. The 0.031" by 0.055" superconducting wire is wound under tension onto the copper bobbin, with the winding tensioner set for 9,000 psi. Individual layers of wire are wound dry, but each layer of wire is preceeded by a layer of epoxy saturated paper, the paper serving as both a convenient method of applying the epoxy and as an additional back up insulator against the estimated 40 volt layer-to-layer quench potential. (The formvar insulation on the superconductor was found in the winding process to have substantial bare spots so that the additional layer to layer insulation is especially valuable.) At the end of each layer, tapered insulating wedges 360° in length were fed into the winding to fill the voids which would otherwise exist at the beginning and end of each layer. At the end of the winding the the final turn is tied down by fitting it into a premachined groove in the insulating plates which form the ends of the coil cavity and inserting a prefabricated insulating clamp.

The initial cool down of the coil will be accomplished by filling the helium vessel first with liquid nitrogen and then with liquid helium. Thereafter, if the heat leak is in reasonable accord with design expectations, the vessel will be maintained at 4.2 K by weekly 100 liter refills. The batch-fill, potted-coil design is thought to be particularly adapted to the environment of an average hospital, where the skills required to procure and batch transfer helium are likely to be much more available than skilled refrigerator operators would be.

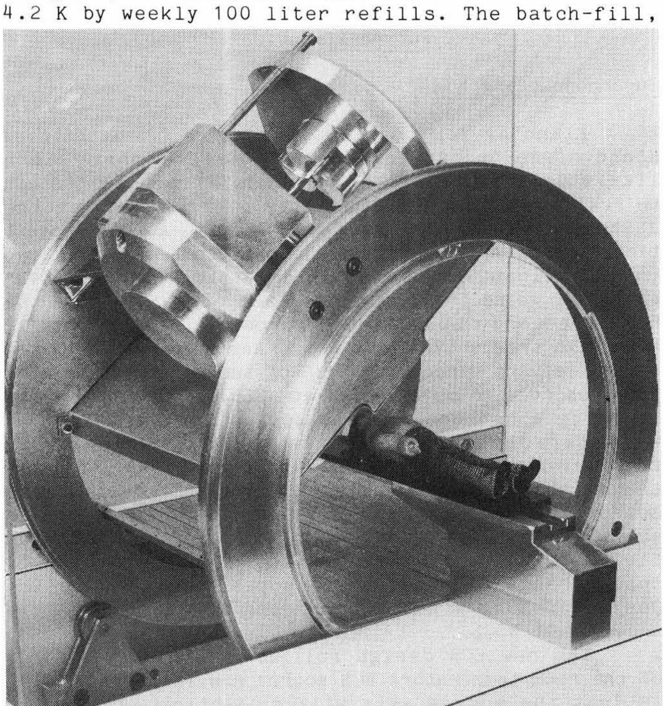

Fig. 7--Model of Harper Cyclotron showing cyclotron, and patient table and the isocentric gantry.

At the present time (Sept 1986), winding of the main coils is complete and the bobbin outer wall has been welded in place and leak checked. The vent tube assemblies are now being installed on the helium vessel, after which, the conventional processes of insulating and installing the nitrogen shield and the outer vacuum jacket will proceed, yielding at the end a completed cryostat ready for testing.

## Medical Cyclotron rf System

The rf system for the medical cyclotron consists of three mechanically coupled dees operating in the 3rd harmonic mode ($\omega_{rf}=3\omega_o$) with dees in the valleys of the magnet. The operating frequency of the system is 105 Mhz, which will be supplied by a commercial 25 kw FM broadcast amplifier. Each dee has two quarter-wave stems going up and down through the magnet in the fashion of the K500 and K800. The dee stems each have an adjustable short which will be permanently clamped in place once the system is tuned. The rf return currents flow through copper plating on the pole tips and through a water-cooled copper plate in the bottom of the valley. At 105 MHz, the dee stems are quite short (≈5") and do not reach out of the magnet; the dee stem holes through the yoke will therefore be blocked with plugs behind the shorts for added neutron shielding. Coupling of the rf drive will be through a special coupling loop on one of the six dee stems. The dees themselves will be made from 1/2" aluminum plate to reduce residual radioactivity.

A low power model has been built and tested to confirm the system design. This model is now being modified to test the coupler design. The central region geometry has been tested in the K500 where it operated successfully with 40 kV across a 4 mm gap between the ion source and the dee (with the source in operation).

## K250 Medical Synchrocyclotron

In the United States, considerable attention has recently been directed toward the development of accelerator systems optimized for radiation therapy with protons. An informal group, PTCOG[11], has been organized and has had a number of meetings. A number of different accelerator systems have been described at these meetings, including a variety of proton synchrotron designs and a high field synchrocyclotron, the latter a system which is under study at NSCL.

System Concept. The design energy goal for a proton therapy accelerator is generally taken to be 250 MeV (the magnet K value required to produce 250 MeV protons is 285 MeV; in the fashion of other MSU cyclotrons, we name the cyclotron based on the Q/A formula for energy). Beam currents of a few nanoamps are marginally adequate and tens of nanoamps are comfortable for even the largest tumors. Synchrocyclotrons are used in present proton therapy programs, but the machines are older, massive room temperature machines which are located in physics laboratories and are overall poorly matched to a hospital environment. Such a cyclotron would also be inordinately costly to reproduce in present conditions. If the synchrocyclotron is redesigned as a superconducting high field device, the mass and cost are greatly reduced and an overall system with many appealing features results. One likely arrangement for such a system has the 70 ton cyclotron mounted on a gantry in a fashion similar to the neutron system. Systems in which the cyclotron is fixed and the beam feeds to one or more beam swinger systems are also quite attractive.

The features of the high field synchrocyclotron which are most questionable are 1) can a proton beam be extracted from a 5 tesla magnetic field (none of the present superconducting cyclotrons attempt to do this), and 2) can a reasonable system for varying the energy of the output beam can be achieved in a synchrocyclotron system (synchrotrons of coarse meet this requirement with ease). A strength of the synchrocyclotron is that it easily exceeds the intensity requirements (by orders of magnitude if desired).

Extraction Studies. As in room temperature synchrocyclotrons, beam extraction from the superconducting synchrocyclotron is based on the regenerative process invented by Tuck and Teng, and perfected by Lecouteur. The main difference in the two situations is in fact simply a change of scale.

To obtain an approximate quantitative picture of the behavior of an actual regenerative extraction system, the fully saturated iron approximation has been used to obtain the magnetic field of a rather simple set of regenerator bars. The regenerator used has a constant angular width of 30° and starts just inside the $\nu_r = 2\nu_z$ coupling resonance (n=0.2) in the unperturbed field. The regenerator constitutes in effect a powerful field bump that drives $\nu_r$ into the $\nu_r = 2/2$ stopband while simultaneously depressing the values of $\nu_z$. The main difficulty with regenerative extraction is the potential loss of vertical stability as a result of the coupling resonance. Although the regenerator gradient depresses the value of $\nu_z$ well below the resonant value for particles close to the equilibrium orbit, the rapidly increasing radial amplitude produced in the extraction process drives $\nu_z$ into the resonance thereby making the vertical motion unstable. This phenomenon therefore limits the maximum radius-gain per turn that can safely be achieved. Figure 8 is an r vs Θ plot of the last five axially stable turns of the central ray of the extraction trajectory; the Fig. shows the characteristic "node" at Θ=65°, and also that a radius gain per turn of about 0.5" can be achieved near Θ=110°. This radius gain is comfortably adequate for inserting an iron bar magnetic channel of the form used in the K800's extraction system as indicated schematically by the dashed outline in the Fig. We therefore conclude that extraction from a high field 250 MeV synchrocyclotron is a reasonably straight forward design problem. Detailed studies of specific magnetic channel geometries are in progress.

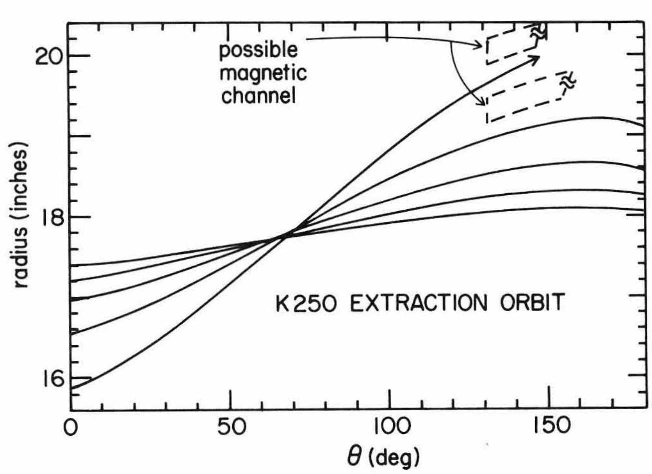


Fig. 8--r vs. Θ successive extraction orbits (just prior to the onset of the axial instability).

Beam Transport and Analysis. The primary beam transport problem is the need to spread the dose over large tumor volumes (large in both transverse dimensions and in depth) with a dose uniformity of no worse than 5% and with minimum dose outside the tumor volume. Two main methods are available for the transverse spreading, namely, passive spreading by multiple scattering and active spreading using a deflecting element to scan a small beam spot over a large area. The longitudinal spreading requires changing the beam energy - this can be done by a variable absorber or by changing the energy of the accelerator. A possible third type of system involves focusing the beam to a line and moving the patient relative to this line as at the meson facility at SIN. In general, passive systems have the advantage of reducing the risk of local over exposure of the patient should the deflecting element fail to function, but the beam is utilized less effectively in the sense that much of the beam will be stopped in slits and collimators as the axially symmetric distribution produced by the scattering is shaped to match the tumor. The synchrocyclotron tends to match best with a scattering type system in that it easily produces more intensity than is needed (treatment times of about two minutes are considered ideal - times less than one minute are considered to be too fast), and energy variation in the output beam from the cyclotron would be quite difficult and energy variation by absorption is of itself a major scattering process.

A major cost issue in either a scattering or a scanning system is the distance from the last beam element to the patient - if this distance is large, the equipment required to rotate the beam transport system in an isocentric pattern becomes large and costly and the cost of the treatment room is also greatly increased. Scattering systems which place the scattering foil in front of the last 90° bending magnet are therefore very attractive. A likely beam spreading method for such a system has been developed[12] which gives excellent uniformity at the tumor, convenient energy variation, and primary beam defining elements are relatively far from the patient so that effective shielding of secondary neutrons can be accomplished.

## Future Directions

### Superconducting ECR

Planning for the K800 cyclotron has identified stand alone operation with an ECR ion source as a likely dominant mode of operation, if ion sources can be realized having the capability of producing charge states of Q=40-50 for very heavy ions. At the present time, the only ECR design philosophy that has resulted in significant new gains in intensity versus Q, over the usual gains from well optimized operation are the high frequency sources at Grenoble[13]. Unfortunately, very high frequency microwave transmitters are quite expensive, and direct purchase of such a transmitter is not presently to be expected at NSCL. We are therefore starting construction of a source for the K800 which will be able to operate over a wide range of frequencies from the 6.4 GHz of our present transmitters up to as high as 30 GHz, so that the source can be reconfigured when, or if, we are later able to obtain transmitter(s) of higher frequency. The field strengths required in the higher end of this design range dictate use of superconducting coils. Design of such a superconducting magnet is presently underway at NSCL.

The new ECR design follows the general features of the room temperature ECR source now in operation[14], in that the source axis will be vertical, the magnet will include a complete iron return yoke, and both stages will have a minimum B geometry. A major difference will be that the hexapole field will be produced by independently tunable superconducting coils instead of by permanent magnets as in the present room temperature source.

In addition to opening up the exploration of high frequencies (when transmitters become available), the wide magnetic range of the new source will allow investigation of alternate resonance modes, such as the recently reported 2B mode[15]. The strong, tunable hexapole will also make it possible to investigate important radial confinement issues.

At present, design of the magnet for the new source is in progress, with first operation of the source at 6.4 GHz scheduled to coincide with the initial operation of the K800 cyclotron in the spring of 1987.

## K500/K800 Coupling vs. Stand Alone

Continuing rapid progress in the development of ECR sources opens to question the wisdom of proceeding with implementation of the originally planned coupling of the K500 and K800 cyclotrons. The purpose of coupling is to provide the K800 with ions of higher charge than can be obtained directly from an ion source (the charge state is increased by passing the K500 beam through a stripping foil at the K800 injection point). This process is expensive by virtue of the cost of the rather complicated beam transport system which must connect the two cyclotrons, and overall reliability for a two accelerator system is obviously reduced compared to a one accelerator system. The appeal of coupling the two cyclotrons then disappears as the charge states which can be produced in the ion source approach those which result from stripping of the K500 beam.

The central uncertainty in deciding whether or not to couple is an assessment of the improvement to be expected in ECR sources in the next few years. In the past few years, ECR's have made quite impressive advances - trends also indicate likely further gains by going to higher rf frequencies and by going to larger sources. Figure 9 indicates the impact of possible further ECR improvements on the K800 operating regime. One curve in this Fig. is based on those ions for which electrical currents from existing ECRs are at the 1 μa level, a second curve raises these assumed charge states by a factor of 5/4's, and a third curve raises the assumed charge states by a factor of 5/3's. For comparison, two other curves are also included, one the original goals of the coupled cyclotron project, the other, the energy which results from coupling the K500 and K800, with the K500 injected from an existing ECR. (The limits for this last curve are due to the injection process and would not be changed by using a higher charge state in the K500.) The judgement as to whether to couple then comes down to an evaluation of which of the ECR curves to assume for the near future and of the incremental value of the expanded research regime which would be derived from coupling versus the cost of coupling (in both money and reliability). Given these issues, and the need for additional information on further ECR improvements, a decision has been taken at NSCL to defer coupling until additional data becomes available, while maintaining all designs in a coupling-compatible state, so that coupling can be implemented later without undue difficulty, if, or when, future developments give a clear cost effectiveness justification for such an action.

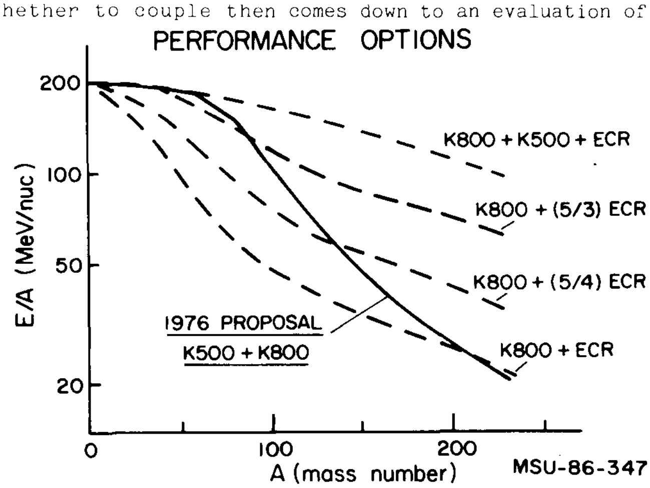


Fig. 9--Energy/nuc versus mass number for several combinations of cyclotrons and ion source (see text).

## Acknowledgments

Virtually every member of the 200 person NSCL staff has contributed significantly to the projects described in this paper and the neutron therapy project has also involved a number of staff members from Harper Hospital. The long list of authors is then not in any sense a listing of all those who have worked on these projects but rather simply a list of those who have contributed to the writing of this paper. The authors acknowledge with pleasure the contributions from all those who have worked on these projects, with a special acknowledgement to J. Parker for invaluable assistance in the preparation of the manuscript.

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