APPLICATIONS OF SUPERCONDUCTING CYCLOTRONS*

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ABSTRACT

Development of superconducting cyclotrons originated in response to needs of nuclear physics laboratories for compact, less costly accelerators for heavy ions. These same features are significant in a number of more applied situations and, as a consequence, the superconducting cyclotron is being adopted as the accelerator of choice in a number of applied areas.

This paper reviews two superconducting cyclotron application projects which are presently under construction and a number of others in the design study phase. One of the construction projects is under the direction of the author and much of the text is devoted to a description of this device, a K100 medical superconducting cyclotron to be used for neutron therapy at Detroit's Harper Hospital. At the time of writing (April 1989) this cyclotron has just come into operation. The second active construction project is a K12 superconducting cyclotron for production of short-lived medical isotopes -- this cyclotron is presently in the final assembly process at Oxford Instruments with first beam tests expected at an early date. Active design studies for other applications of superconducting cyclotrons likely to follow in the future include a K250 superconducting synchrocyclotron for proton therapy, a K1600, 400 MeV/nucleon superconducting cyclotron for heavy ion therapy, small or medium sized superconducting cyclotrons for wear research, and possible very small superconducting cyclotrons as neutron sources for airport based luggage inspection systems.

INTRODUCTION

The superconducting cyclotron has come of age as a nuclear physics research instrument with K = 500 MeV(1) cyclotrons operating at Chalk River, East Lansing, and Texas A&M; a K = 1200 MeV cyclotron also operating in East Lansing; and superconducting cyclotrons in an advanced state of construction at Milan, Munich, and Orsay/Groningen.(2) Typically, superconducting cyclotrons are enormously lighter (by a factor of 10 to 20) than room temperature cyclotrons of the same energy and are significantly less costly (by a factor of 2 to 3).

The advantages which have lead to the wide use of superconducting cyclotrons in nuclear physics research also have compelling weight in various "practical" applications of cyclotrons. This paper will review the current status of these practical applications and foreseeable future developments.

A first applied superconducting cyclotron, a K = 100 MeV unit for cancer therapy, is at this time nearing completion. Beam was accelerated to full energy for the first time in April 1989 and in a few months the cyclotron will be moved to its final site in the Radiation Oncology Department of Harper Hospital, a large Detroit, Michigan medical center.

Another superconducting cyclotron of K = 12 MeV is under construction in England at Oxford Instruments Ltd.(3) The objective of this project is to provide a source of short-lived medical isotopes appropriate for use with Positron Emission Tomography (PET) scanning units.

Studies of larger superconducting medical cyclotrons have been in process for some years at NSCL/MSU and by the EULIMA (European Light Ion Medical Accelerator) group in Nice.(4) The MSU work has dominantly centered on design of a superconducting synchrocyclotron of K=250 MeV, the characteristics of this accelerator being well matched to the medical specifications of a cancer therapy system based on proton radiation. At Nice the cooperative European EULIMA group has been studying the characteristics of an accelerator matched to medical requirements of a

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^{12}C based cancer therapy system with oxygen and neon beams available with reduced range.

One of the nuclear physics superconducting cyclotrons, the MSU K500, is at present used on a part-time basis in an exploratory application project5) to assess the feasibility of measuring wear in mechanical systems by producing and implanting the 54 day isotope ^{7}Be as a tracer in parts such as engine cylinders, piston rings, etc. The radioactive tracer technique will hopefully provide a greatly speeded analysis of wear in such components and is particularly promising in the circumstance of ceramic or plastic engine components, where direct activation of the surface layer would not produce isotopes of adequate half-life for useful wear measurements. If the ^{7}Be based wear analysis program proves to be an important activity, dedicated cyclotrons for this purpose are likely with two possible configurations, 1) a cyclotron with a K value of approximately 500 MeV producing ^{7}Be by spallation of nitrogen or similar isotopes and implanting via the fragment recoil, or 2) using a cyclotron with K of about 50 MeV to implant commercially purchased ^{7}Be ionized to charge one in a source specially designed to handle radioactive materials.

Smaller superconducting cyclotrons of various energies may be effective in the isotope production application, although the requirement of high beam current is certainly more difficult to achieve in a compact structure, and depending on the energy, high magnetic fields may lead to excessive electric dissociation, cutting off the option of using negative ions in such fields. A novel, possibly broad cyclotron application is as a neutron source for airport, plastic-explosive-sensing, luggage inspection systems. A prototype luggage system based on neutron activation of nitrogen is presently in use in the San Francisco Airport in the US with other units to be installed in nine additional airports. The prototype units utilize Californium as the neutron source which is a convenient but relatively expensive way of producing neutrons. If this inspection technology comes into wide use, a miniaturized cyclotron will clearly be a leading technical option as a compact, reliable, and economical neutron source, with a superconducting cyclotron system as possibly the most attractive approach overall.

Following sections of this paper review features of major superconducting cyclotron application projects.

THE HARPER HOSPITAL CYCLOTRON

As noted above, a superconducting cyclotron with K of 100 MeV8) is nearing completion at NSCL and is scheduled to be moved to Harper Hospital in Detroit in a few months. This cyclotron accelerates deuterons to 50 MeV to produce neutrons in an internal Beryllium target. The complete cyclotron will move around the patient in the fashion of a cobalt or electron linear accelerator therapy unit so that, if the tumor volume in a patient is positioned at the system isocenter, the neutrons will always be directed at the tumor irrespective of the cyclotron rotation angle. The overall system is greatly simplified relative to neutron therapy systems in use today since the therapy system does not involve a beam extraction system in the cyclotron, a beam transport system, or a beam rotation system.

Rotation of the Harper Hospital cyclotron does lead to a number of unusual cyclotron design requirements. The rotation spans a full 360° with the cyclotron mounted on a cylindrical gantry and rotating about a supine patient as indicated schematically in Fig. 1 and in a photograph in Fig. 2. In the photograph the cyclotron is at 90° in a coordinate system in which 0° is the angle directly below the patient. The cyclotron rotation is limited to one full turn, i.e. a move from 0° to 359° must go by the path 0, 90, 180, etc. With this limitation, utility connections to the cyclotron hang from a circular drum and wind and unwind, except for the main rf feed which is in a rigid 10 cm O.D. coaxial line passing directly along the axis of rotation through a commercial rotating joint.

The cyclotron rotation places unusual requirements on the liquid helium system, namely to provide a path for boiloff gas which will not spill liquid in some inverted position. The design of the helium system for the Harper Cyclotron uses a patented array of encircling vent pipes to avoid the problem of liquid spillage, each vent pipe always being higher

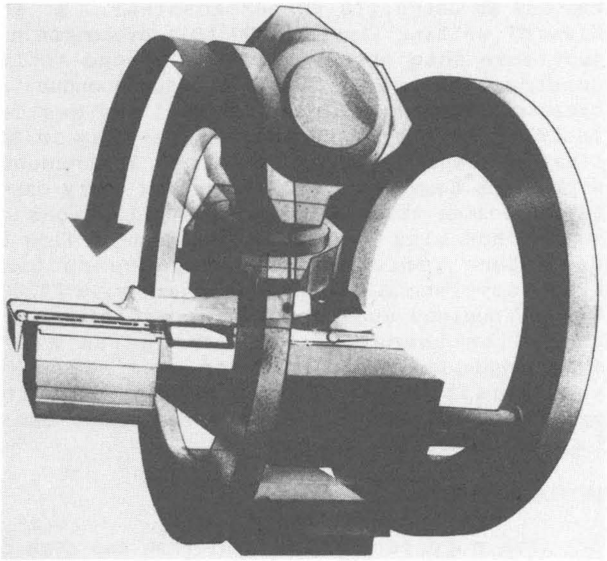

FIG. 1 -- Schematic drawing of the rotating ring mounting system for the K100 superconducting cyclotron. The cyclotron is shown in two positions (above and to the rear of the patient) with the counterweight opposite.

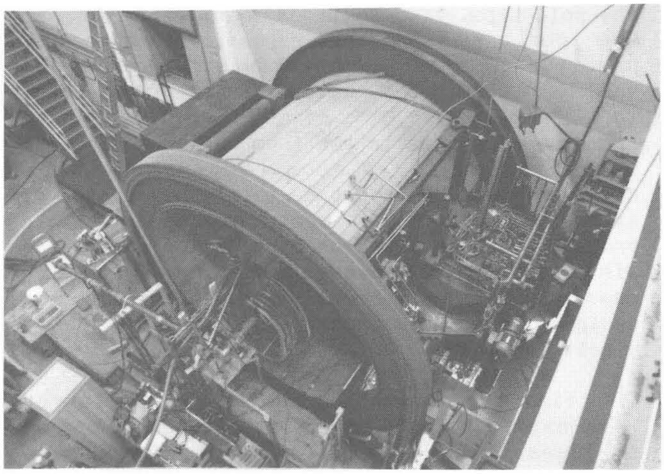

FIG. 2 -- Photograph of the K100 superconducting cyclotron and support ring system. The cyclotron is at the right opposite the counterweight.

than the liquid level in the coil in some part of its length, irrespective of the gantry rotation angle. Also, at least one vent pipe is always connected to the topmost part of the helium storage volume where boiloff gas collects.

Conventional liquid helium systems usually rely on gravitational stratification of warm helium gas as a component of the thermal insulation system. The horizontal axis of rotation means however that a line which is vertical at one rotation angle will be inverted at the 180° opposite angle; the Harper cyclotron therefore uses horizontal coil leads and warm gas exit lines as the best compromise position. Horizontal lines unfortunately may give higher convective heat transfer than would be the case for vertical lines, but this is difficult to positively identify. The heat leak in the coil is however higher than was expected neglecting such effects and a daily helium fill is necessary rather than the weekly fill anticipated in the original design.

The circular ring support system for the cyclotron performs nicely; deflections are within the design specification, namely that a line projected directly forward from the neutron production target shall pass through a 3 mm diameter sphere at all rotation angles.

A schematic view of the cyclotron proper is given in Fig. 3 and a median plane plan view in Fig. 4. The cyclotron is a three-sector, dee-in-valley design with six dee stems (a quarter wave shorted stem running up and down from each dee). Radio-frequency power is inductively coupled to one of the six stems and the sliding short in another stem is moveable to provide fine tuning of the resonant frequency.

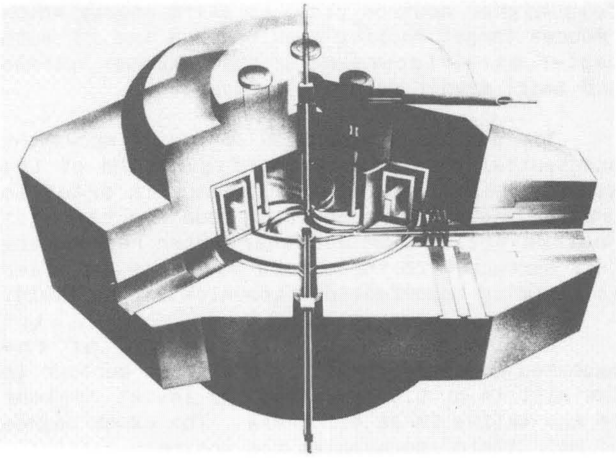

FIG. 3 -- Schematic view showing the internal structure of the K100 medical cyclotron with the magnet yoke and superconducting coil cutaway in the foward sector to show the three accelerating dees, the ion source, and the internal target.

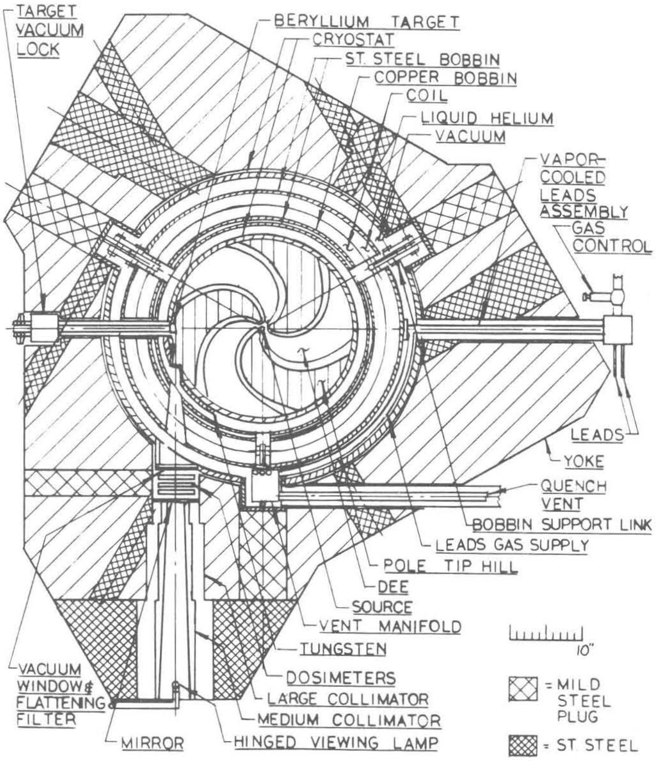

FIG. 4 -- Plan view of the K100 medical cyclotron showing important components. Vapor cooled leads and helium vent lines go off to the right so as to be always horizontal.

Deuterons were selected as the neutron producing projectile primarily for the reason of offering a convenient acceleration frequency, namely 105 Mhz, which allows the system to be driven directly from a 25 kw commercial radio station transmitter. The choice of deuterons relative to protons of course means that for a given neutron energy the K value of the magnet must be double, but for a superconducting magnet this is a relatively minor issue and was considered less important than the convenient frequency range. Other less important but significant advantages of deuterons are 1) a ten fold higher neutron yield at given energy which reduces target cooling requirements and 2) much easier axial focussing so that extreme spirals and small magnet gaps can be avoided.

The cyclotron plan view in Fig. 4 shows the substantially triangular configuration of the main yoke. This shape arises in order to provide a convenient mounting face for the main neutron collimator and thereafter reproducing this surface with three fold symmetry in order to minimize imperfection harmonics in the field.

Figure 5 shows a contour map of the measured magnetic field. The highest contour in the hill is at 5.5 tesla and the lowest contour in the valley is at 4.1 tesla. The exact degree of main field isochronism has not been carefully measured (the cyclotron has no moveable probes and only one intermediate radius beam stop). Beam however immediately accelerated to the neutron target in the first full radius beam test, (with the magnet current lowered by 1 part in 6,000 relative to the value predicted from field maps). The design does not include any provisions for making field shape adjustments, i.e. there are no trim coils and the main coil is a single series winding. The full energy beam makes about 250 turns on third harmonic which indicates that the field is isochronous to at least ±1 part in 3,000.

The initial magnet geometry was based on cylindrically symmetric relaxation calculations with azimuthal variations added assuming aligned, fully saturated, magnetic moments in the pole tips. Two small changes were made in the iron after the first magnetic measurements, namely a 13 mm thick sheet was added on the valley floor in the radius interval from 3.5 cm to 14.3 cm and a 0.5 mm of material was removed from the pole tips in the 1 cm region nearest to the outer edge. A room temperature K100 cyclotron would almost certainly have involved extensive model magnet measurements and would probably also have included pole face correcting windings to avoid machining corrections on massive pieces of steel -- the superconducting design allows these laborious procedures to be nicely bypassed.

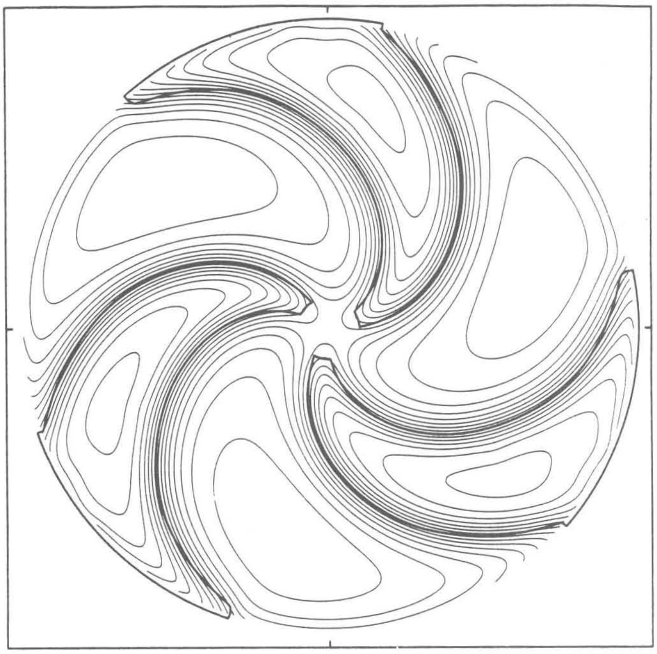

FIG. 5 -- The measured magnetic field of the K100 superconducting cyclotron with hill edges superimposed as a heavier line. Highest and lowest contours are 5.5 and 4.1 tesla.

Figure 6 is a photograph of the cyclotron with cap raised and an operator touching one of the dees. The upper set of dee stems are decoupled from the dees as the upper cap is raised, mounting connections for these stems on each of the three dees being clear in the photo. Near the center each of the magnet hills has a copper extension to shape the electric field

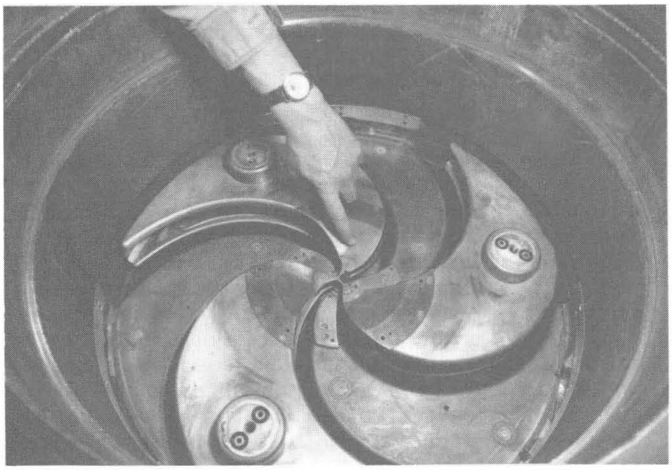

FIG. 6 -- Photograph of the K100 medical cyclotron with the upper pole cap raised to display the dees and lower pole tips.

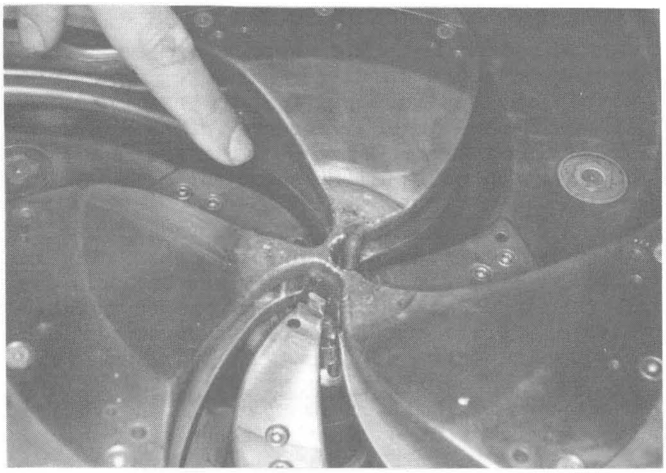

FIG. 7 -- Close up view of the central region of the superconducting medical cyclotron with the ion source chimney (a straight vertical cylinder) showing at the center of the figure.

near the center. Figure 7 shows this structure in more detail and the cylindrical ion source chimney can be seen sticking up through the central electrode which joins the three dees. Spark marks on the central electrodes show clearly in Fig. 7 and give an impression of greater depth than is actually the case (touching these surfaces gives no feeling of surface roughness).

Operating tests with the Harper cyclotron began in April 1989 with beam accelerated to full energy for the first time on April 18. The testing in April involved an unshielded operator location; a radiation interlock set at 200 mr/hr interrupted the tests too quickly to allow meaningful assessment of the beam current relative to the design 10 microamp level. As this paper is written the computer control system for the cyclotron is being connected and debugged which will allow operation of the cyclotron from a remote site -- accurate intensity measurements can then be made. An interim effort to measure current by introducing a beam stop at one-third radius was thwarted by rf pickup, the dee aperture at this point being one half of its width so that field penetration is large. In an earlier test of the ion source with a DC extraction electrode, currents of 300 microamps were obtained. It then seems likely that the design 10 microamp beam will be smoothly achieved but this remains to be established.

The intermediate radius beam stop at approximately 30 MeV has a flat face perpendicular to the beam so that the distribution of radioactivity on this probe shows the beam height and the radius gain per turn. Fig. 8 is an autoradiograph of this probe and indicates that the beam height is about 10 mm and the radius gain is about 2 mm, values which are in good agreement with design expectations.

OXFORD INSTRUMENTS ISOTOPE CYCLOTRON

The British firm Oxford Instruments is involved in constructing a 12 MeV, 100 microamp proton cyclotron[3] tailored for production of short-lived medical isotopes, particularly isotopes of interest for Positron Emission Tomography. Figure 9 is a perspective view showing major features of this cyclotron. The design is quite interesting in that many features developed in the design of magnetic resonance imaging systems are adapted to the cyclotron, including an outer iron yoke at liquid helium temperature which reduces iron weight without excessively adding to helium cooling requirements. At the time of this conference,[7] components of the Oxford cyclotron have been fully fabricated and magnetic fields have been mapped and found to conform to specifications. The ion source and rf systems have been separately tested and the cyclotron is in the process of final assembly in preparation for overall system tests.

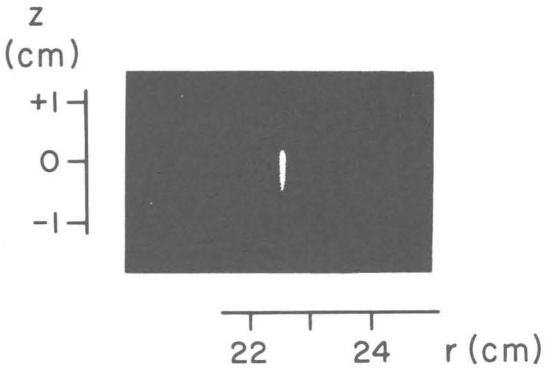

FIG. 8 -- Autoradiograph of the intermediate radius target after initial beam runs in the superconducting medical cyclotron.

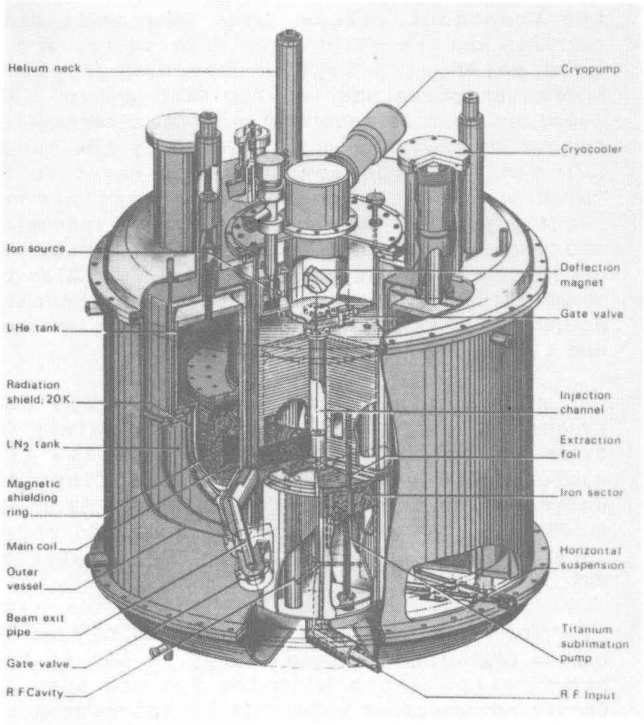

FIG. 9 -- A schematic drawing showing the structure of the 12 MeV superconducting cyclotron under construction at Oxford Instruments, Ltd. (Courtesy of Oxford Instruments).

K=250 SYNCHROCYCLOTRON FOR PROTON THERAPY

The use of protons for cancer therapy is presently in process at a number of laboratories in various countries and a new proton therapy accelerator for the Loma Linda Hospital in California is nearing completion at the Fermi National Accelerator Laboratory.[8] Accepted design requirements for a proton therapy system are energy of up to 250 MeV (corresponding to 37 cm penetration in tissue) and currents of 2 to 20 nanoamps depending on whether scanning or scattering is to be used to spread the beam over the treatment volume. The very small beam currents and the relatively high energy are a good match with typical synchrocyclotron characteristics and led the NSCL group[9] to consider such an accelerator as an alternate to the synchrotron approach selected by the Fermi Lab medical accelerator team. Relative to isochronous cyclotrons, synchrocyclotrons readily produce beams of the desired intensity and are less demanding in most aspects of construction. The magnetic field can also be somewhat higher since no flutter component is needed and this makes the overall magnet smaller and lighter.

MSU studies indicate that a 250 MeV synchrocyclotron will weigh approximately 65 tons which is light enough to allow the cyclotron to be gantry mounted if that is desired. An arrangement of this type is shown in Fig. 10, the particular configuration shown here having been suggested by U. Schryber of PSI.[10]

The beam transport layout shown in Fig. 10 allows degrading the beam energy to adjust the penetration depth with the feature that an energy homogenizing wedge can be introduced at the intermediate focus to restore much of the phase space dilution which occurs at the degrader.[11] An alternate system, which can be used if desired, positions the cyclotron in a separate fixed location and feeds beams through a conventional beam transport system to rotating magnet systems in any desired number of treatment rooms. This one-cyclotron/several-room approach involves more difficult operation in switching the beam from room to room and in accounting for the crossed bending planes in the system and their interaction with the inherently asymmetric emittance of the accelerator's extracted beam. Such a system is however clearly workable and somewhat less costly relative to a multi-room system based on one cyclotron per treatment room. The latter system has an important advantage in providing a fully redundant therapy capability which can continue to perform in one treatment room even in the circumstance of an unscheduled breakdown of one of the accelerators. The accelerator/treatment room configuration which is optimum in a given situation then depends on the weighting factors assigned to these advantages and disadvantages by a particular institution. If a one accelerator per treatment room configuration is selected, the synchrocyclotron becomes a particularly compelling choice as a consequence of its compactness.

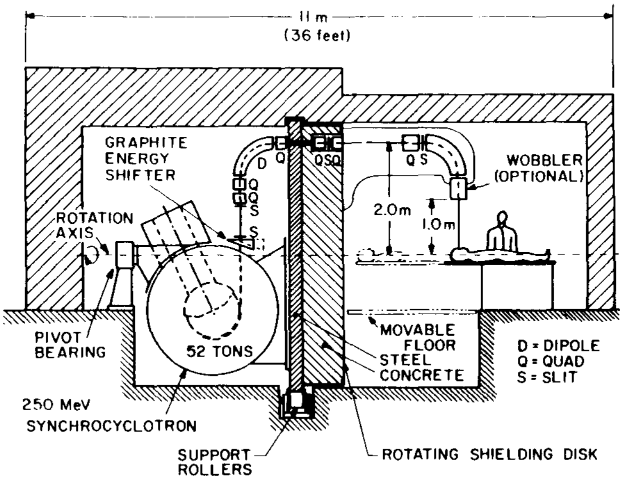

FIG. 10 -- Possible arrangement of a 250 MeV superconducting synchrocyclotron for a one accelerator per treatment room configuration.

HEAVY ION THERAPY CYCLOTRONS

The EULIMA group has been working for several years on the design of a large superconducting cyclotron to accelerate fully stripped (Q = Z) ions to 400 Mev/nucleon.[4] The cyclotron concept developed in this study is based on a separated sector iron magnet with all of the sectors driven by a single pair of large cylindrical superconducting coils as indicated schematically in Fig. 11. Design of a magnet of this type is more difficult than designing a magnet for a conventional superconducting cyclotron in that the quasi-cylindrical approximation which is the key design technique for such magnets seems clearly not applicable in the highly non-cylindrical separated sector arrangement. Truly three dimensional calculations are then needed and the EULIMA group is investing much effort in such calculations. The granularity of these calculations is much coarser than would be desired and either a large model or a trial full scale magnet may have to be used to achieve the stringent field shape tolerances needed for such a cyclotron.

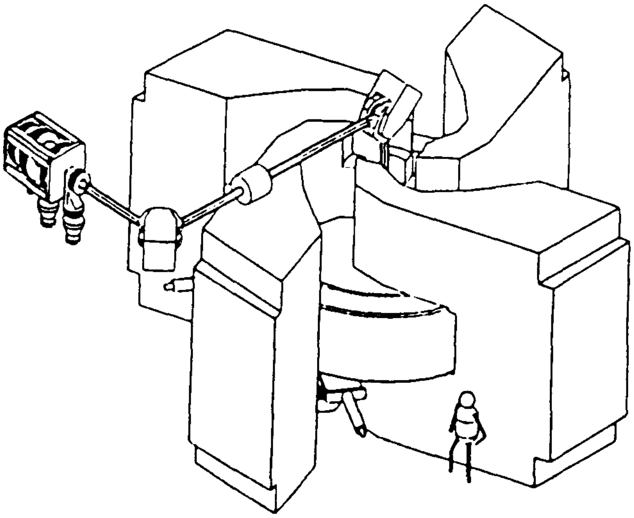

FIG. 11 -- Sketch of the basic magnet structure being explored by the EULIMA project.

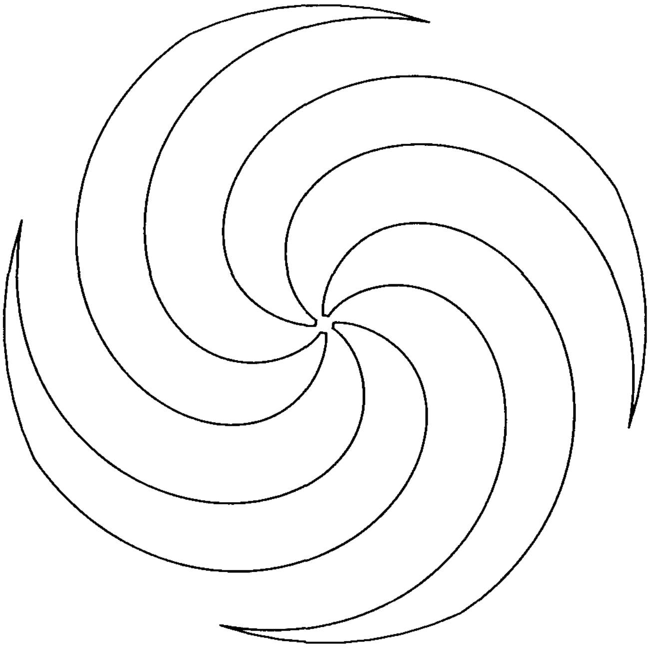

FIG. 12 -- Pole tip shape for a 400 MeV/nucleon (Q/A=1/2) superconducting cyclotron based on a scaled up MSU K1200 magnet. The outer pole tip radius is 1.37 meters.

A brief study at MSU has explored the feasibility of extending the basic quasi-cylindrical structure used in the existing K1200 cyclotron to a K1600 device, and simultaneously to raise the focussing limit from 400 to 800 MeV. The calculations have been carried to the point of establishing the basic feasibility of such a cyclotron. The magnet must have four sectors and a very tight spiral as shown in Fig. 12. A major advantage of this design is the clear validity of the quasi-cylindrical approximation so that the magnet could be designed using the techniques developed for conventional superconducting cyclotrons.

OTHER SUPERCONDUCTING CYCLOTRON APPLICATIONS

As noted in the introduction, the MSU K500 cyclotron has been used to explore the feasibility of producing and implanting the isotope ^{7}Be via heavy ion fragmentation reactions. Preliminary results from this work are described in a separate paper at this Conference.(2) This work establishes that production and implantation of ^{7}Be can be accomplished, although the economic viability of the process is at this time not clearly established. A dominant cost determining factor is the amount of cyclotron time which is required per useful irradiation, i.e. what beam intensity can reliably be accelerated and extracted from a production cyclotron? With an external beam of 1 particle-microamp the fragmentation process is viable and with 10 microamps would almost certainly be widely used.

Currents at this level have mostly not been attempted in the existing superconducting heavy ion cyclotrons (possibly because the nuclear physics programs are almost always limited by data processing considerations rather than by cyclotron beam current). With the nuclear physics program at MSU shifting from the K500 to the K1200 cyclotron, time on the K500 is expected to be available for explorations of high current limits and such studies should move forward in coming months.

An alternate approach to the implantation of ^{7}Be is to procure the isotope from commercial sources and feed this material to a ion source designed to appropriately contain the radioactivity. A development effort along these lines is being pursued at KFK in Karlsruhe.(3) With this approach, the dominate economic parameter is the ionization efficiency in the source, which determines the efficiency of usage of the expensive radioactive feed material. If adequate ionization efficiency can be achieved, a cyclotron with a K value of 50 could accelerate singly charged ^{7}Be to an energy of 1 MeV/nucleon which would give an interesting implantation depth. A cyclotron for this purpose could be either superconducting or room temperature, and injection efficiency would be an important consideration in weighing this choice. (The superconducting option would presumably offer the usual advantages of greatly reduced weight and significantly lower cost.)

Design studies for superconducting cyclotrons with K values of 20, 50 and 70 MeV have been carried out at MSU in response to requests from various laboratories interested in particular isotope production applications. These studies establish that the superconducting cyclotron concept can be tailored to virtually any requirement in this general energy range and in each of these studies a compact, highly cost effective, accelerator design has resulted.

An interesting exercise raising the question as to whether there is a lower energy limit on the region where the superconducting cyclotron approach is useful has been brought up by the need for a compact, 5 MeV cyclotron to produce neutrons for airport luggage inspection systems. At 5 tesla the bending radius of a 5 MeV proton is 6 cm which seems obviously too small to be helpful and so a much lower magnetic field seems indicated -- exploration of advantages and disadvantages of various possibly appropriate cyclotron configurations is in process at MSU. (At present, the option of fixing the magnetic field to match an fm radio station transmittor on third harmonic is viewed as a probable most attractive approach, but the studies need to include direct comparison with room temperature cyclotrons, which are not complete at this time.) A possible large scale application of either room temperature or superconducting cyclotrons seems however not unlikely in response to this need for detection systems for plastic explosives.

CONCLUSIONS

Several important practical applications of superconducting cyclotrons have already arisen and additional applications are likely. Overall, it seems probable that the superconducting cyclotron will come into rather wide use as an important device supporting diverse aspects of the sophisticated technological society evolving in the world in the late 20th century.

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