PRESENT AND FUTURE SUPERCONDUCTING CYCLOTRONS*

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Introduction

This paper begins with a brief review of the status of present superconducting (SC) cyclotron projects, including the two which are currently operating and the six which are under construction. The next section summarizes the main features shared by five of these machines, while the third section presents recent developments and new concepts introduced in the other three "second generation" SC cyclotrons. Projects in early stages of development are discussed in the fourth section.

Review of SC Cyclotrons Operating or Under Construction

Description and status reports of eight projects are given below in chronological order of completion or expected year of completion as listed in Table I.

Table I

Cyclotron	Maximum k-value*	Beams	Complete
1.NSCL,MSU	500	heavy ions	1982
2.AECL,Chalk River	520	heavy ions	1985
3.Harper Hosp/MSU	100	50 MeV d	1987
4.NSCL,MSU	800(1200)	heavy ions	1987
5.Texas A&M	500	heavy ions	1987
6.Milan/Catania	800	heavy ions	1988
7.Munich	85	heavy ions	(1989)
8.Orsay/Groningen	600	$\vec{p}$, $^3He^{++}$, heavy ions	(1991)

*$E/A=k(q/A)^2$

MSU K500

The MSU "K500", completed in 1982, was the first operating accelerator based on a superconducting magnet. The 100 ton, 18 MJ magnet is a spin-off of the superconducting bubble chamber magnets developed at ANL by Purcell, et al,[1] and has proven rugged and reliable during these five years of operation. From the beginning this cyclotron has run beams over the full design dynamic range of the magnet, i.e. 3T-5T, without problems. (There is a normal-conducting short in one of the coils which displays itself as intermittent voltage spikes during magnet ramping, but does not affect operation in any way.) Design upgrades have been necessary, however, in various other subsystems, as discussed recently by Blosser, et al.[2] Although gradually improving, both the rf and electrostatic deflector systems still only operate at up to about 80% of their design voltage levels (100kV). A very recent improvement to the rf system was to add water cooling to the corona rings on the inner conductor near the vacuum feedthrough insulators via direct plumbing of polyethylene lines across the coax gap.[3]

Since early 1986 internal PIG ion sources have been replaced by an ECR-axial injection system, leading to greatly improved cyclotron performance with a much broader range of beams. The ECR,[4] ECR-K500 beam optics,[5] and the axial injection system[6] were described recently. The successful operation of the very small spiral inflector necessary for axial injections into the 5T magnetic field was an important landmark for this and future SC cyclotron projects. (See also Ref. 7 for more details).

Chalk River K520

This, the only other completed SC cyclotron in the world, was actually proposed before the MSU K500, but was delayed for several non-technical reasons. These two machines are conceptually very similar, but differ in some details as discussed below with the "first generation SC cyclotrons." The Chalk River magnet weighs 170 tons and has a maximum stored energy of 22 MJ. The details of the beam commissioning studies were published very recently.[8],[9] This cyclotron is injected from an MP tandem via the matching beam line[10] shown in Fig. 1. This complex is designed to accelerate ions from lithium (up to 50 MeV/A) to uranium (up to 10 MeV/A). During the commissioning period a 70.9 MeV $^{127}I^{7+}$ beam from the tandem was stripped to 23^+ by carbon foils inside a dee, accelerated to 10 MeV/A and extracted from the cyclotron. All subsystems worked satisfactorily, and since then a variety of beams have been used for nuclear physics experiments.

The foil-stripping injection scheme has worked well. For the 10 MeV/A ^{127}I beam injected at 71 MeV the foils lasted about 8 hours each and failed by thinning. For a 5.6 MeV/A ^{127}I beam injected at 42 MeV the average lifetime was 4 hours and they failed by thickening. Carbon foils 20 $\mu g/cm^2$ in thickness have been used. Foil changes are done in about 1 minute.

Field trimming for isochronization is done with adjustable iron rods,[11] not trim coils, and the system has worked well in practice. The extraction system uses a combination of an electrostatic deflector mounted inside a dee,[12] saturated-iron passive focussing bars, and active compensated superconducting dipole and quadrupole coils.[13] This system works well to the extent tested so far.

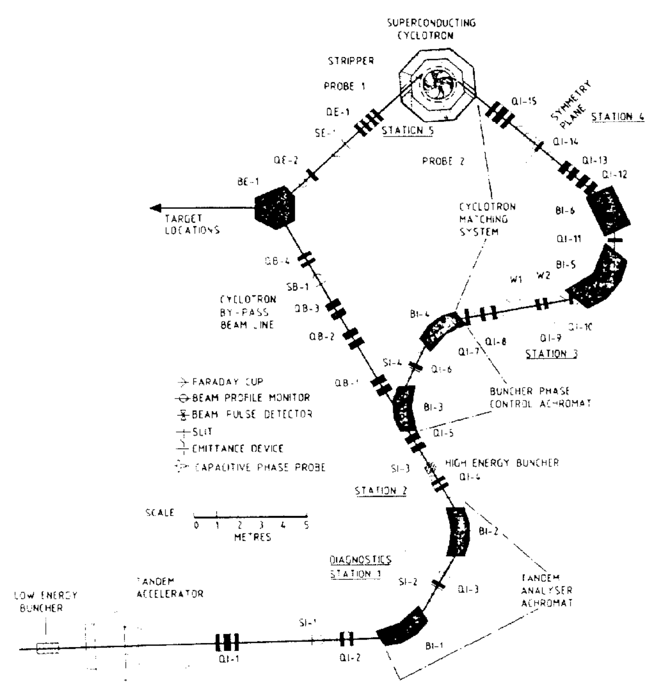

FIG. 1 -- Layout of the Chalk River Tandem Accelerator Superconducting Cyclotron (TASCC) showing the MP-tandem injector, the matching beamline, and the extracted-beam line.

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The cyclotron is currently shut down to repair some problems which developed in late 1986. The coil was warmed to repair a cryostat vacuum leak and the magnet is currently being recooled. Some modifications to the liquid helium cryopumps are being made to offset effects of rf heating. Also the radial probes are being replaced with a new design. Further beam development and nuclear physics experiments should resume in April, 1987 with full 24 hour/day operation.[14]

Harper Hospital/MSU K100

This small SC cyclotron (25 ton magnet) is being built and will be tested at MSU and will then be moved to the Harper-Grace Hospital in Detroit, MI. The cyclotron's 50 MeV internal deuteron beam will produce neutrons to be used for cancer therapy. In this case a significant advantage of the compact, lightweight SC magnet is that it will be mounted on a gantry to swing through a full 360° circle around the patient, a system highly preferred by the physicians.[15] This is a fixed energy cyclotron with no adjustments except the coil current and ion source. The coil cryostat was first filled with liquid helium on March 9, 1987. The magnet will be mapped, shimmed if necessary, and beam tests will be carried out in the next few months. Figure 2 shows the concept of the cyclotron-gantry-patient system currently under construction.

MSU K800 (K1200)

The MSU K800 (K1200) SC cyclotron is a 5T-m device based on a 265 ton, 60 MJ magnet. The magnet first operated in May, 1984 and the cyclotron beam tests are expected to begin later this year. The cryostat median plane penetrations were recently machined based on beam extraction calculations[2],[16] and the magnet is nearly ready for reassembly. The assembly of rf components is well underway. Beam extraction calculations with mapped magnetic fields are currently in progress to determine if any field shimming is required.

A section through the median plane is shown in Fig. 3. This shows the strongly-spiraled pole-tips and the several extraction channel elements (2 electrostatic deflectors plus passive iron focussing and dipole bars). Adjustable permanent magnet dipoles and quadrupoles are to be located in the exit beamline within a channel through the iron return path ring.[17] The wide dynamic range of beams in both m/q and E/A as well as the presence of several strong resonances near extraction place severe restrictions on field imperfections from either mechanical misalignments or uncompensated magnet structures such as yoke penetrations or extraction elements.

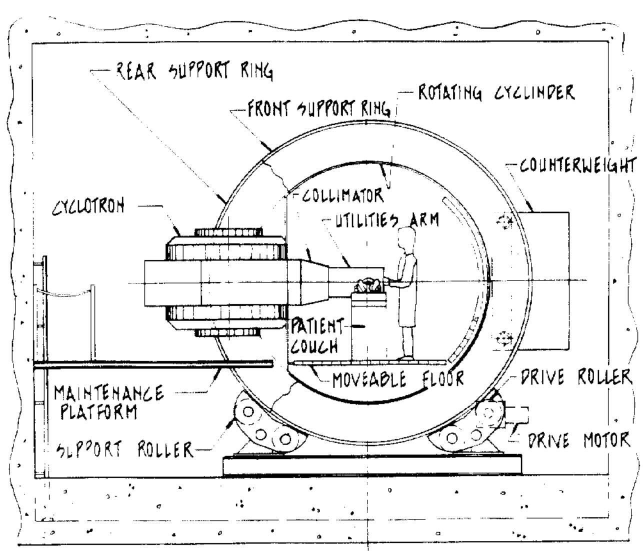

FIG. 2 -- Schematic view of the K100 neutron therapy cyclotron on a gantry to allow variations of the beam direction over a full 360°.

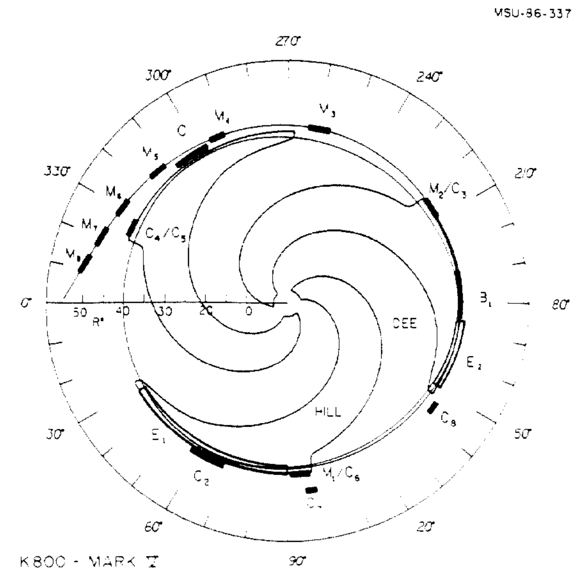

FIG. 3 - Section view of the median plane of the MSU K800 SC cyclotron. For Scale: the outside diameter of the cryostat, the largest circle shown 2.9 m.

This cyclotron will be operated initially from an ECR ion source with axial injection as currently used with the MSU K500 cyclotron. [2],[4],[5],[6] Depending on progress with the development of higher charge-state heavy ions from ECR ion sources the K500 and K800 cyclotrons may or may not be coupled in the future. Figure 4 shows several possibilities for E/A vs A compared with the original facility proposal of 1976. As the first step towards determining improved ECR operating parameters a superconducting magnet with broad magnetic field range and independently adjustable mirror and sextupole coils is being designed at MSU.[18]

Texas A&M K500

This SC cyclotron is a second version of the MSU K500 with some design changes to upgrade some of the subsystems.[19] The magnet achieved full field

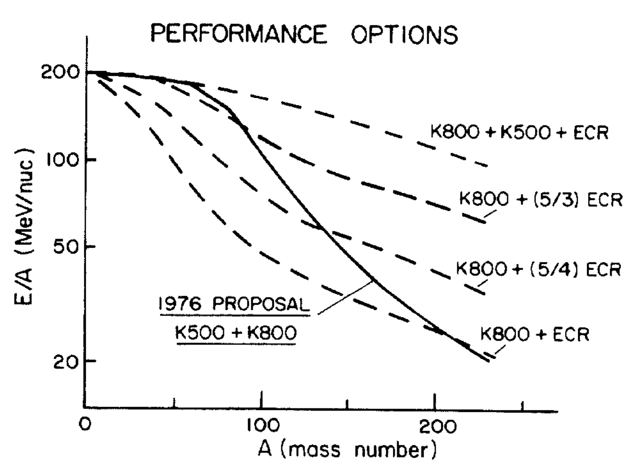

FIG. 4 -- Curves of E/A vs A for several scenarios of K800 cyclotron operation. (5/3)ECR means an ECR with charge state output 5/3 times the charge states achieved by ECR ion sources in 1986.

initially in July, 1985 and was mapped in detail in September and October 1985. The MSU K500 field has a large imperfection first harmonic (20 gauss) near the extraction radius which was predicted to be due to insufficiently compensated yoke penetrations.[20] Calculations and actual beams confirmed that the effects of this imperfection can usually be compensated for by proper adjustment of the harmonic coil at extraction radius.[21] The Texas A&M group reduced this error component by a factor of two by adding 436 lbs. of steel to the cyclotron in one of the median plane penetrations,[19] and moving the coil by 0.5 mm relative to the yoke to rebalance the decentering forces.

Several changes in the mechanical details of the rf system have been made based on SUPERFISH calculations.[19], [22] They have also designed and tested a new type of high voltage feedthrough for the electrostatic deflectors based on a standard cable encapsulated in a glass tube.[23]

In their original plan the Texas A&M K500 was to be an injector for their 224 cm conventional K147 cyclotron. However, the present achievements of ECR ion sources have made this proposal obsolete, so they are now designing and building an ECR ion source and the associated beamline and axial injection systems.[19] A beamline will also couple their polarized deuteron source to the SC cyclotron. The cyclotron is scheduled to begin operation with an internal PIG ion source in mid-1987 and change to ECR injection by mid-1988.

Milan K800

The SC cyclotron being constructed in Milan uses a 176 ton magnet with a stored energy of 40 MJ and is a "true" K800 cyclotron (the focussing limit is not less than the bending limit for q/m=0.5 ions as in other SC cyclotrons). It is designed to accelerate q/m=0.5 ions to 100 MeV/A and U^{38+} ions to 20 MeV/A. It is also designed to operate with axial injection from an ECR ion source (Fig. 5 and Ref. [24],[25]) as well as with radial injection via stripping of an ion beam from the 15 MV tandem in Catania. The tests with an ECR ion source will be done in Milan before the cyclotron is moved to Catania.[26]

The Milan project has had major setbacks due to 1) reworking of cryostat welds which did not satisfy

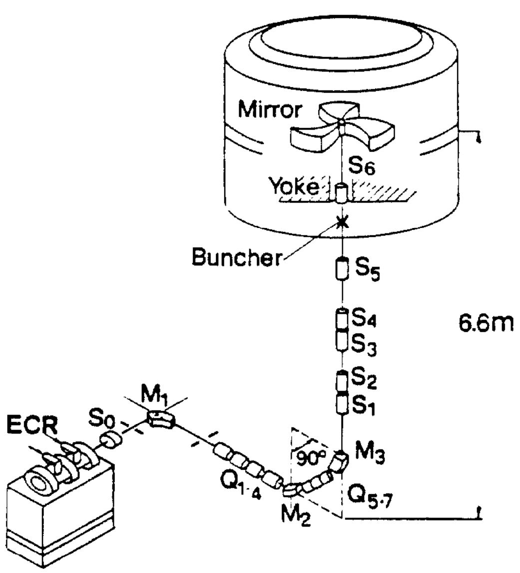

FIG.5 -- Perspective view of the Milan ECR source and axial injection system into the K800 SC cyclotron.

Italian codes initially, 2) problems caused by a low-Q ceramic insulator in the rf resonator, and 3) building construction delays preventing timely installation of the magnet and cryogenics plant. With these problems overcome the magnet is now installed in the new building and first cool-down is scheduled to begin in April, 1987. The ECR, axial injection system, and rf components will all be assembled by the end of 1987. Final cyclotron assembly (vacuum system, etc.) will be done in the spring of 1988 and internal beam tests should begin in the fall of 1988.[27]

Munich "Tritron" K85

A very innovative SC cyclotron project is underway in Munich,[28] where they are constructing a "tritron" which involves both a superconducting magnet and superconducting rf. The name "tritron" is used because its coiled-up magnet structure resembles a type of sea snail, the triton. It is a totally superconducting version of a separated-orbit cyclotron.[29],[30] The present project is to produce a quite compact after-burner for the Munich MP-tandem, capable of accelerating protons to 43 MeV and ions with q/A=0.5 to 21 MeV/A.

The magnet has twelve sectors and six rf cavities. The magnets are low-field (<1.5T) and axial focussing is accomplished via 9° edge angles at the entrance and exit of each sector. Because of the very small return paths in the channel magnets the system is very light weight, with the size being dominated by the vacuum vessel. All the 236 magnet channels are wired in series with one of the 24 turns on each magnet being shunted by a superconducting switch. By manipulating these switches the fields in individual magnets can be fine-tuned by 2%. It is required to have an energy gain per turn of about 1.4 MV at injection radius and 3 MV per turn at extraction radius to achieve the 4 cm turn-to-turn orbit spacing. The six lead-plated superconducting rf cavities (170 MHz) operating on the 20th harmonic of the orbital frequency provide this acceleration.

Orsay/Groningen "AGOR" K600

This is a collaborative venture between a Dutch group (Groningen) and a French group (Orsay) which officially began with funding in December, 1985. The project AGOR (Accelerator Groningen ORsay) involves the construction and testing of the cyclotron at Orsay and then moving it for final installation at KVI Groningen.[31] The magnet (Fig. 6) is specially designed with the goal of accelerating protons (polarized), $^3He^{++}$, and heavy ions.

Small valleys in the pole tips are used in this design to prevent the radial focussing frequency for the 200 MeV protons from increasing to the forbidden ν_r=3/2 resonance. In a standard 3-sector machine the rapid increase of B_{av} with radius necessary to keep the field isochronous for such relativistic particles would also drive the value of ν_r to this resonance. The valleys or grooves reduce the flutter which results in a less rapid increase of ν. Since the flutter reduction also reduces ν_z, the $\nu_r+2\nu_z=3$ resonance which creates the low field limit in SC cyclotrons drops to less than 2T. It is at about 3T in the MSU machines. Hence, it is predicted that this magnet design can allow the acceleration of protons over the energy range from 130 MeV to 200 MeV.

Another unusual aspect of this cyclotron is a split cryostat which permits better access to the median plane for diagnostic probes and extraction elements. The 1400 ton force between the upper and lower coils is carried by six "cold" supports across the median plane. The unusual coil geometry seen in Fig. 6 is also related to the desire to accelerate both protons and heavy ions. The small coil near the

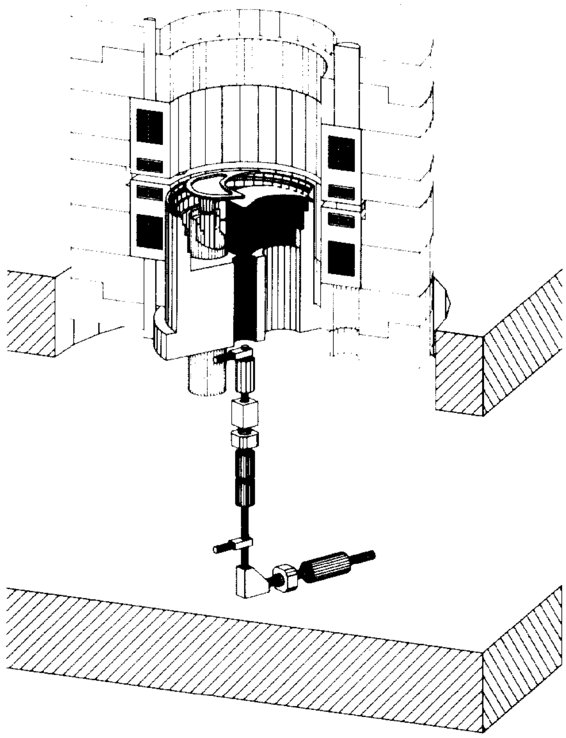

FIG. 6 -- Cutaway view of the AGOR SC cyclotron magnet which has 350 tons of steel and will operate over a dynamic range of 1.75T to 4.07T. It is a 3 sector machine with additional smaller valleys in the center of each hill to permit acceleration of up to 200 MeV protons. The unusual splitting of the 2 pairs of main coils are seen here. The axial-injection system is also shown.

median plane produces the rapidly increasing B_{av} vs r necessary for the relativistic protons, while the sum of two coils produces a flat field for low energy heavy ions.

Procurement of major components is beginning this year and it is expected to take 5-6 years to complete the project.

Common Features of Present-Day SC Cyclotrons

Of the cyclotrons listed in Table I and discussed above #1,2,4,5, and 6 are very similar devices and, hence, possess the common characteristics of the first generation SC cyclotrons. The magnets all have fields up to about 5T and stored energies in the 20-60 MJ range. They have iron return yokes from 100 to 265 tons and coils structures with cold masses in the 10 ton range. These SC coils are all NbTi, cryostable, liquid helium pool-boiling types; either layer wound or wound in pancakes. Each magnet has two pairs of main coils, one near the median plane to create B_{av} increasing with radius, and one pair away from the median plane. For non-relativistic ions the 2 pairs are excited nominally equal to produce B_{av} ~ constant with radius. In the Milan K800 and MSU K800 the outer pair can be run with opposite polarity to the inner pair to enhance the increase of B_{av} with r for the most relativistic ions, e.g. up to 200 MeV/A for q/A=0.5 in the MSU case. The operating currents are generally 700-2000 a, and the cryostat heat loads are 10-40 watts at 4.5 K. All but the Milan machine use liquid helium cryopumping in the beam chambers. For these machines the vacuum in the beam chamber needs to be in the 10^{-6} to 10^{-7} torr range to have negligible beam loses of high mass heavy ions.

In each case the axial focussing is provided by thick saturated-iron pole tips giving a flutter of about ±0.8T and with a fairly tight spiral (~30 mrad/cm). Generally, these machines can focus 50-200 MeV/A light heavy ions and can bend 10-100 MeV/A mass 200 ions (depending on the charge state injected). Special operating limitations for SC cyclotrons are associated with the ν_R=N/2 resonances which limit light ion energies to ~220 MeV/A in N=3 sector machines, and the $\nu_R+2\nu_z$=N resonance which sets a low field limit of ~3T in the N=3 sector machines. Field trimming is accomplished via room temperature trim coils wound around the pole tips and using up to ~100 kW of power, except in the case of Chalk River which uses adjustable iron trim rods.

Magnetic fields for SC cyclotrons have been calculated with two-dimensional programs such as TRIM and POISSON with a stacking-factor option for B_{av}. The variations from azimuthal symmetry are then calculated using a uniform magnetization current sheet or charge sheet approximation. Measured field deviations from such calculations have been in the few percent range so that very little field shimming has been required to achieve the required cyclotron field shapes. Some methods are being developed to refine these calculations.[32],[31]

The rf systems for these machines all consist of room temperature quarter-wave resonators above and below the median plane. Resonator geometry calculations are being improved with programs such as SUPERFISH.[33],[34],[35],[22] Except for Chalk River, these are three sector machines with three dees which can operate on first, second, or third harmonic. In first and second harmonic the 3 dees run with 120° relative phases, i.e. they are 3 phase rf systems. With proper central region design[6],[25] the dee-to-dee capacitive coupling can be reduced low enough to make the 3 phase operation routine. The Chalk River machine has no central region so the rf resonators connect to the dees in the center of the machine. It has 4 sectors and 4 dees, 2 opposing dees connected to the upper resonator and the other 2 to the lower. They run in either second or fourth harmonic with the dees in push-push or push-pull mode.

These machines are designed to be injected radially via stripping of some injector beam such as a tandem or axially from external ion sources such as ECR's. Both systems have worked well: stripping injection at Chalk River[8],[10] and axial injection at MSU[2],[6]. The axial injection-ECR combination will probably eliminate the use of internal PIG ion sources.

Beams are extracted via a combination of electrostatic deflectors, passive saturated-iron focussing bars and dipole bars, and active compensated superconducting magnetic channels. At MSU the deflector design voltages of 100 kV (140 kV/cm) have not been achieved in the cyclotron. Developments are in progress to try to improve the performance. [23],[36],[37]

Recent Developments and Concepts in SC Cyclotron Designs

The cyclotrons #3,7, and 8 in Table I each have features not found in either of the currently operating machines. The Harper/MSU cyclotron has only one pair of coils and has no trim adjustments. Hence it relies very heavily on careful construction, mapping, and possibly shimming. Since this machine rotates through 360° the cryostat plumbing had to be developed so that the liquid helium was always vented, but does not spill out (the so-called "magic bottle").

The unique features of the Munich Tritron are obvious: separated orbit magnets, superconducting rf, and operation on a very high harmonic number, ~20.

The Orsay design also has some unique features: the special carving of the pole tips to accelerate high energy protons as well as heavy ions and the unusual cryostat and coil structure.

SC Cyclotrons in Design, Study, or Conceptual Stage

In addition to the eight SC cyclotrons built or under construction there are about that many more in the conceptual or planning stages. The smallest of all these projects is a 12 MeV H^- cyclotron being designed by Oxford Instruments[38] to produce positron emitting isotopes such as ^{11}C, ^{13}N, and ^{15}O. This will be a very small machine with a very efficient cryostat and weighing only about 3 tons. With a beryllium target it could be a "portable" neutron generator for radiography or activation analysis.

An isotope producing machine is also being considered at MSU, a 20 MeV p machine to produce ^{13}N for the Crop and Soil Science Department.

A feasibility study for a 250 MeV p synchrocyclotron is also in progress at MSU.[2],[39] This machine would be designed with an external beam gantry system for proton cancer therapy. It is possible that the SC synchrocyclotron may be significantly cheaper and smaller than the SC synchrotrons being considered by other groups for this application.

A totally air-core SC cyclotron is being studied by Subotic in Belgrade.[40] The main coils of these air-core designs are quasi-spherical rather than solenoidal as in all the machines discussed above. The quasi-spherical geometry is more efficient in amp-turns than the solenoidal, and the external fields are not excessively strong and could be suppressed by external compensating windings (as is standard in magnetic extraction channels, for example) if necessary. The size currently being investigated for feasibility is a K115 proton cyclotron. Many details such as the rf system remain to be worked out.

A design study for a very large SC cyclotron for heavy ion therapy has been carried out by a European group. The project, called EULIMA, EUropean LIght Ion Medical Accelerator, calls for beams of carbon to neon ions at energies of several hundred MeV/A.[41] One design option involves four separated sector magnets mounted around a single circular SC coil with a 3m outside diameter. Their plan is to inject radially from a smaller cyclotron without stripping as shown in Fig. 7. An alternate, more expensive option, necessary to get to higher energies utilizes six sectors and a much more massive machine (~1000 tons). The project is currently awaiting funding.

In his summary talk at the Tokyo cyclotron conference Craddock[42] mentions several studies of Fixed Field Alternating Gradient (FFAG) cyclotrons. None of these projects were superconducting, but in a paper submitted to this conference a study of a SC FFAG cyclotron (sometimes called synchrotron) is presented.[43] They discuss extraction, stripping, and recirculation of heavy ions in the same ring.

Concluding Remarks

At this stage it is certainly safe to say that SC cyclotrons are a proven technology. They are much more intricate than corresponding conventional cyclotrons, but the details of how to handle these complexities are being ironed out. Reliability should increase with each successive machine. In principle, SC cyclotrons are less expensive both to build and operate than conventional cyclotrons and require much less building space. The trend in magnet masses to

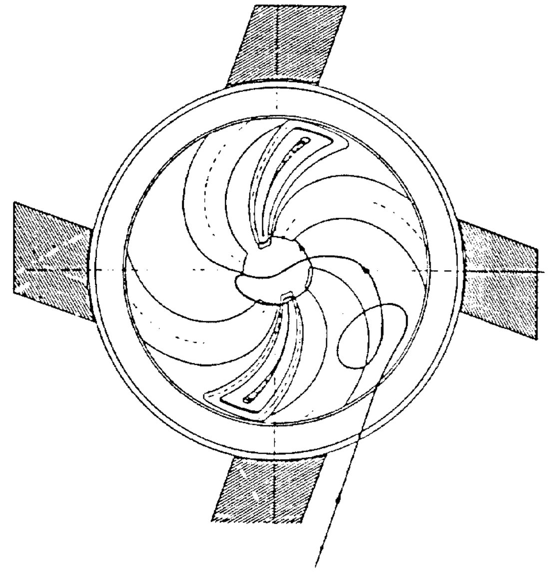

FIG. 7 -- Preliminary design of a separated sector 6 TM SC cyclotron for 400 MeV/A light heavy ions: the EULIMA project.

date is that SC magnets of a given bending power are about 17 times lighter than conventional magnets.

To date SC cyclotrons have not developed high intensity beams, partly due to their tight orbit spacing and partly due to inadequate deflector cooling. However, Chalk River should achieve single turn extraction very soon and some experiments with internal phase slits have been initiated at MSU.[44]

The magnets currently being used in SC cyclotrons (18-60 MJ) are small by present-day SC magnet technology since systems with stored energies of several hundred MJ have been successfully built.[45] Also even with NbTi conductor fields as high as 10T are possible at 2K. Hence, it is possible to begin looking at SC cyclotron designs with 8-10 T-M magnets or larger. (The EULIMA project is a step in this direction).

Also, once the present "tritron" concept is proven by the Munich group, a second generation, larger machine of this type would be on the horizons.

Finally, all heavy ion cyclotrons have benefited enormously by the developments of ECR ion sources during the past few years.[46],[47] Still, the biggest gain in beam energy for very heavy ions (mass ~200) for the least incremental cost is probably in the area of further high charge state ion source development. This could come from the high frequency and/or high field studies initiated by Geller's group in Grenoble,[46] from a revival of electron beam ion source efforts, or from some innovative new concept.

Acknowledgements

Progress in the technology of SC cyclotrons over the past few years is due to the hard work of many people, as is partially indicated by the reference list below. Unfortunately, due to space limitations many important references are not included. I would like to thank the many people from MSU and other SC cyclotron labs who have provided information for this paper, and Julie Parker for the skillful preparation of this manuscript.

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