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OVERVIEW OF SUPERCONDUCTING CYCLOTRON PROJECTS

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Summary

Superconducting cyclotrons give promise of being exceptionally cost-effective heavy-ion accelerators, both as stand alone devices and as energy boosters. There are well advanced projects at Chalk River and Michigan State University as well as proposals for such cyclotrons from several other laboratories. Some of the properties of high-field saturated-iron cyclotrons are discussed and the current status and recent results from several of the projects are reported.

Introduction

Superconducting cyclotrons are admirably suited to the acceleration of heavy ions because the necessary large $B\rho$ product required to bend the heavy ions is achieved by increasing the average midplane induction (typically to $\sim$ 5 T) rather than the radius. This reduced size is the principal reason for the lower capital cost of such an accelerator compared to a normal coil cyclotron, and likewise reduces building and shielding costs. Operating costs are also reduced, a very important consideration in view of rapidly increasing energy prices. The smaller size is both a blessing and a curse, but the constraints introduced are far outweighed by the advantages cited above.

The advent of superconducting cyclotrons[1] followed the successful operation of high field superconducting bubble chamber magnets and a common feature of most of the cyclotrons described below is a cryostatically stabilized niobium-titanium coil cooled by immersion in a pool of boiling helium. The cryostat for this superconducting coil restricts radial access to the midplane and in all compact superconducting cyclotrons described below, except the ORIC conversion, the dees are interleaved with the flutter poles and the resonators extend axially through holes in the poles.

One of the earliest concerns in the design studies on superconducting cyclotrons was extraction, mainly because practical considerations do not allow the deflecting electric field to be scaled up with the increased magnetic field. However, computer studies have shown that by careful tailoring of the magnetic induction at the edge of the poles, the beams can be extracted with good phase-space properties[2,3].

A feature of all superconducting cyclotrons is the excellent agreement of the measured midplane inductions with the calculated values[4,5,6], especially at the higher excitations. This is because the steel near the midplane is completely saturated - well beyond the non-linear region of the magnetization curve - and its contribution to the midplane induction is almost independent of coil excitation. This permits the midplane induction to be calculated in two parts and then superposed. The contribution from the coils and that portion of the steel having axial symmetry is calculated using TRIM[7] or an equivalent program while the induction from the flutter poles and other steel components not having axial symmetry is calculated in the uniform magnetization approximation[8,9] using either equivalent current loops or charge sheets. Figure 1 compares the calculated midplane induction with the measured values at a radius of 482 mm over one quadrant of the Chalk River magnet. Over the entire accelerating region, at full excitation, the rms deviation of the measured induction from the calculated values is 0.26%[6].

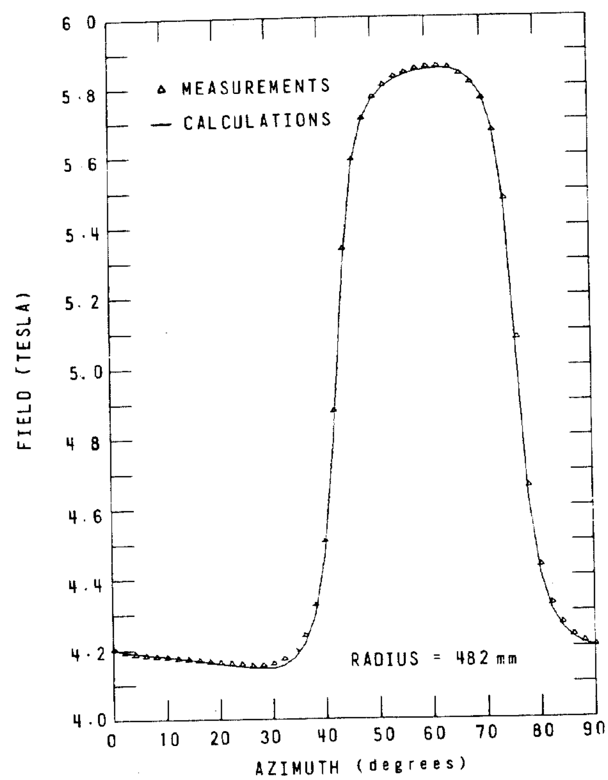

Fig. 1 Measured and calculated midplane inductions for the Chalk River magnet.

Unlike conventional cyclotrons, approximately 70% of the midplane induction derives from the air core component of the coil when it is at maximum excitation. This imposes very tight tolerances[10] on the coil's position relative to the poles because the saturated steel contributes a magnetization component to the midplane induction that is amost independent of the field contribution from the coil and the two centroids must coincide. A radial coil displacement relative to the pole center of 0.1 mm introduces a significant first harmonic component in the midplane magnetic induction. Minimizing first harmonic components is especially important because of the low radial betatron frequency over much of the operating range and the use of precessional extraction. An axial displacement of the coil midplane from that of the poles introduces a radial component to the midplane induction that will deflect the beam axially. We have demonstrated at Chalk River that the required tolerances can be achieved and the reproducibility of the measured midplane induction is excellent.

For all but the heaviest ions, the maximum energy from a superconducting cyclotron is limited not by its bending strength, but by vertical focusing[11]. Because the flutter poles are saturated over the entire operating range, the hill-valley induction difference,

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ΔB, is independent of excitation level. The flutter, $F \sim \Delta B^2/\langle B\rangle^2$; hence, as the midplane induction is decreased, the flutter and therefore the vertical focusing is increased. This leads to the characteristic specific energy curve from superconducting cyclotrons that increases as the atomic number (and the mass to charge ratio) of the accelerated ion decreases. Figure 2 illustrates such curves for the accelerators discussed below.

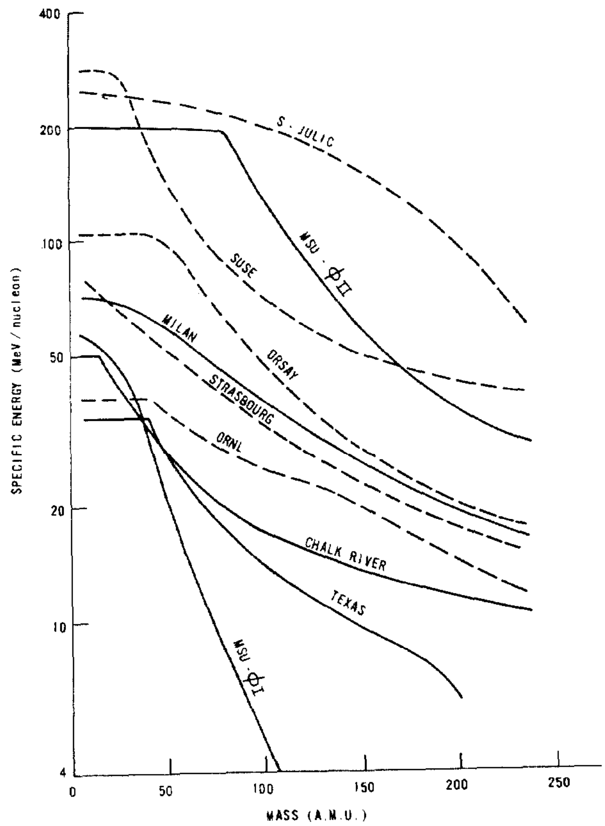

Fig. 2 Maximum specific energy versus mass of accelerated ion for funded (solid lines) and proposed (dashed lines) superconducting cyclotrons. See text for details.

Chalk River

The Chalk River K=520 (where E_{final} = K (ion charge)^2/ion mass) superconducting cyclotron[6] shown in Fig. 3 has four sectors and uses a 13 MV tandem Van de Graaff as injector. The ion beam enters the cyclotron on the midplane and near the center is intercepted by a carbon stripper foil located in the middle of a dee. The injection trajectory and foil radius are chosen to have the desired charge state (roughly 3-times the incoming charge state) emerge from the foil on a properly centered accelerating orbit. The dees operate at 100 kV and with eight accelerating gaps give a large energy gain per turn. A single electrostatic deflector directs the beam into a magnetic channel composed of iron bars and superconducting windings that provide both adjustable bias and adjustable focusing to guide the beam out of the cyclotron.

A unique feature of this cyclotron is the use of trim rods rather than trim coils to isochronize the magnetic field. Coarse isochronization is achieved by adjusting the excitation in the inner and outer coil pairs. Thirteen trim rods per hill, eight with 40 mm diameter and five with 60 mm diameter, provide the fine adjustment. The rods are used as top-bottom pairs and locally decrease the field when retracted.

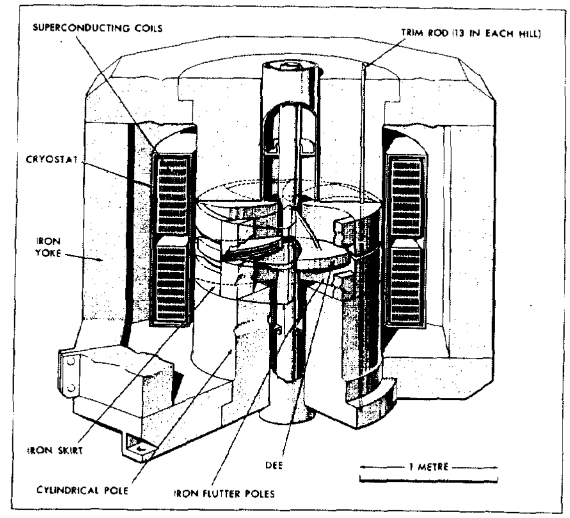

Fig. 3 Cutaway view of the Chalk River superconducting cyclotron.

Concurrent with magnet development, the full-scale radiofrequency accelerating system has been tested in a separate vacuum vessel that simulates the magnet geometry. The choice of four sectors permits a simple rf system with opposite dees mounted on the center conductors of the coaxial tuners located in the axial holes in the top and bottom poles. Use of in-phase and out-of-phase modes and harmonics 2, 4 and 6 allows coverage of the full energy range with a tuning range of 31-62 MHz. Operation over the full frequency range has been demonstrated at 70 kV and at the full design level of 100 kV at selected frequencies. The rf control system is designed to have the main tuners adjusted under power. Conventional finger contacts on the sliding shorts failed because of limits in their mechanical range and a new design of rf finger is being developed; we still anticipate tuning under power rather than retreating to clamped shorts and auxiliary tuners.

The midplane vacuum is to be pumped by two cryopanels nested between the hills above the dees. The first cryopanel has been tested in the rf vacuum system where the helium boiloff rate increased from 0.6 ℓ/h with no rf applied to 0.75 ℓ/h with 70 kV on the dees. A Mark II cryopanel is being built that takes advantage of a measured dee asymmetry and will have modified rf baffling and twice the pumping speed.

Tests on the cable and support structure for the electrostatic deflector have shown that they operate well at the design voltage of 100 kV and can withstand vacuum sparks at 110 kV. Fabrication of the magnetic channel elements has not yet begun.

The magnet was first operated in 1978 and extensive field mapping was carried out in 1979. During these tests, the cryostat helium boiloff rate was 18 ℓ/h and the cryogenic system performed satisfactorily. The ability to center the coil adequately was demonstrated and the reproducibility of the measured first harmonic component showed that the required tolerance was maintained. Figure 4 shows the first harmonic component as a function of radius for an average midplane induction of 1.2 T and 5 T. At 1.2 T, the first harmonic at all radii is due almost entirely to flutter pole manufacturing and assembly tolerances. The small change on increasing the induction to 5 T shows that the yoke wall asymmetries are properly compensated and that coil imperfections give a negligible contribution. Because the first harmonic is almost independent of field level it can be significantly reduced by modest shimming of the flutter poles.

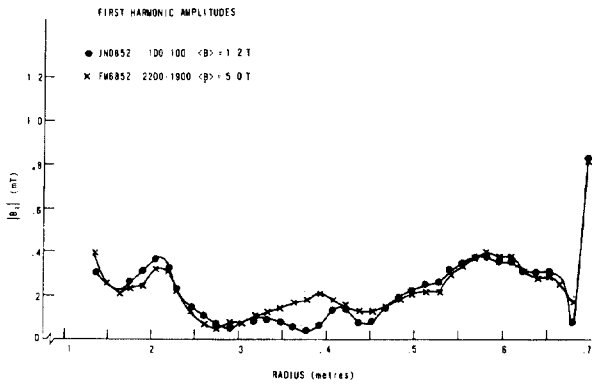

Fig. 4 First harmonic amplitudes as a function of radius for an average midplane induction of 1.2 and 5 tesla.

The reproducibility of the midplane induction at constant temperature is very good but varies by ~ 0.5 mT/°C[12]. This variation is caused by the temperature coefficient of the saturation magnetization of steel and should not present a problem in the temperature controlled accelerator hall. At constant temperature, the measured field stability is better than the required $1{:}10^5$.

The magnetic corrections provided by the trim rods agree with calculations and operation of a prototype motor drive has been demonstrated on a single 60 mm rod.

Orbit studies using the measured fields showed that for carbon at 50 MeV/u and uranium at 10 MeV/u extreme settings of the trim rods were necessary, and extensive calculations have been made to optimize the flutter pole shape to reduce the required trim rod settings. Shims up to 2 mm thick have been added to the flutter pole faces at inner and outer radii and approximately 1 mm has been removed from intermediate radii.

The magnet and cryostat were dismantled in late 1979 to effect several major tasks, the first one unplanned:

A ground fault had occurred between the superconducting coil and the stainless steel vessel containing it that compromised operation of the coil monitoring and threatened damage to the coil. The source of this fault was an accumulation of slightly ferromagnetic debris that entered the can when repairs to the stainless steel container were made. A special tool was developed to clean the bottom surface of the upper can between the ninety-six 3 mm high spacer-insulators and 100 mg of extraneous material was removed. The coil to can resistance now exceeds 3000 MΩ at 300 V dc.

The initial field measurements were made with only three trim rods installed in each flutter pole. The other 80 trim rod holes have now been bored in the flutter poles and the full complement of 104 trim rods with their adjustment mechanisms have been installed. Only one quadrant will be operated under motor driven computer control in the present round of tests to ensure all components function properly in the 100 mT fringing field.

Five large apertures have now been cut in the inner wall of the cryostat to accept the rf cavity wall sections and the extraction channel entrance. This will permit the rf structure to be installed in the magnet after the remapping of the magnetic field that is now in progress.

A year ago, the Canadian Government approved the funding to convert the magnet into a working accelerator. The beam transport components were then ordered and construction of the extension to the tandem building committed. The current schedule calls for first beam in late 1983.

Michigan State University

The MSU heavy-ion accelerator facility[13] is divided into two phases. Phase I is the soon to be completed K=500 superconducting cyclotron with internal ion source that will be used as a stand-alone facility but also as injector for a K=800 superconducting cyclotron that comprises phase II of the project. Both are three sector cyclotrons.

Figure 5 shows a sectional view of the K=500 cyclotron. The superconducting coil is split into inner and outer pairs for coarse adjustment of the field's radial gradient. The field is isochronized with thirteen sets of room temperature trim coils wound around the midplane third of each flutter pole. A central ion source can be inserted along the axis of either the upper or lower pole. The three dees are supported by their top and bottom resonators that extend through the dee stem holes in the poles; these stems are 5 m long and have support insulators at the yoke boundary. These insulators also form a vacuum interface and the clamped sliding tuners operate in air. Each dee is independently powered and will be in phase or ± 120° relative to the next dee, permitting operation with harmonics 1 to 5 and 7. The frequency range is 9-32 MHz and the dees operate at 100 kV. Two electrostatic deflectors located in hills deflect the beam into a passive magnetic channel comprised of six sets of iron focusing bars. These elements and the two electrostatic deflectors can be moved over a small radial range to accommodate the small differences in extraction trajectory of different ion beams.

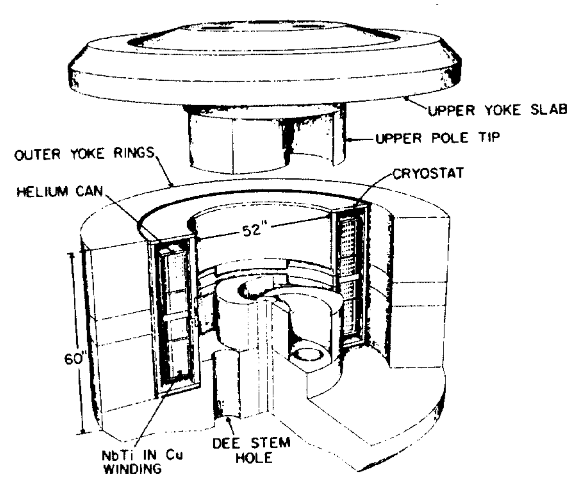

Fig. 5 Cutaway view of the MSU K=500 superconducting cyclotron.

The magnetic field with the flutter poles was mapped in 1978 and then the magnet was used as a test bed for ion source development. These experiments showed that a conventional Penning source operated in a satisfactory manner in the much higher magnetic field of a superconducting cyclotron. The magnet was dismantled throughout most of 1980 for several major modifications: axial holes were drilled in the poles for the rf drives and the trim coil leads, and the trim coils were mounted on the flutter poles. The cryostat was dismantled, the radiation shield rebuilt, a small helium can leak was sealed and the radial midplane penetrations incorporated for the radial probe and each of the eight extraction elements. On reassembly, the helium boiloff rate increased to 32 ℓ/h compared to 16 ℓ/h in the tests preceding the introduction of these tight clearance penetrations through the cryostat midplane. This rate is within the capacity of the present liquefier. Final mapping of the midplane magnetic field is now complete including the trim coil characteristics.

The midplane vacuum will be pumped by 3 large cryopanels, one located inside each dee. A prototype cryopanel has been tested in an auxiliary vacuum vessel where a pumping speed of 4000 ℓ/s was demonstrated which did not deteriorate during 20 days operation with 1 cc/min of nitrogen flowing - a typical source gas load.

The three 100 kW power amplifiers are located around the cyclotron to permit the tuning stubs to extend down into the cyclotron pit. The first of these amplifiers has been operating for some time and was used in experiments on the prototype dee resonator; the other two amplifiers are nearing completion. Fabrication of the radiofrequency accelerating structure is also nearing completion.

The cyclotron is already positioned in the extension built to house it and beam lines are being installed to transport extracted beams to the existing experimental halls. First beam is expected later this year.

Phase II of the Michigan State program is to boost the energy of the beams from the K=500 using a K=800 superconducting cyclotron. It is very much a "big brother" of the smaller cyclotron but it has some important differences besides its larger size. The superconducting main coil is again split into an inner and outer pair, but to isochronize the field for the higher specific energy ions, the outer coil current will be reversed. Analysis of the forces has shown that this mode of operation is practical. Injection is along the midplane with a carbon stripper foil intercepting the beam near the center and increasing the ion charge. A novel solution was found to keep the stripper foil out of the valley region - the spiral of the flutter poles was reversed for the first 300 mm radius, as shown in Fig. 6. Axial focusing is adequate in the region where the spiral reverses. The trim coils are wound around the flutter poles in a manner similar to the K=500 cyclotron, but the large radius requires 22 coils per sector. The three dees are independently powered at the same frequency as the K=500 and all amplifiers will be run from a common master oscillator, however, the K=800 dees are required to operate at a peak voltage of 200 kV. The beam is extracted with two electrostatic deflectors, and nine sets of focusing bars.

The design of this cyclotron has advanced to the stage where major components have been ordered. The superconductor, magnet steel, liquefier and 1.2 MW dc power supply for the rf are scheduled to be delivered this year. Construction is now in progress on the building extension to house the expanded facility. Operation of the coupled cyclotrons is scheduled for 1984.

University of Milan

A K=800 three sector superconducting cyclotron is being built at Milan[14] intended as a booster for the 16 MV tandem Van de Graaff at Catania. It will first be tested in Milan with either a central ion source or

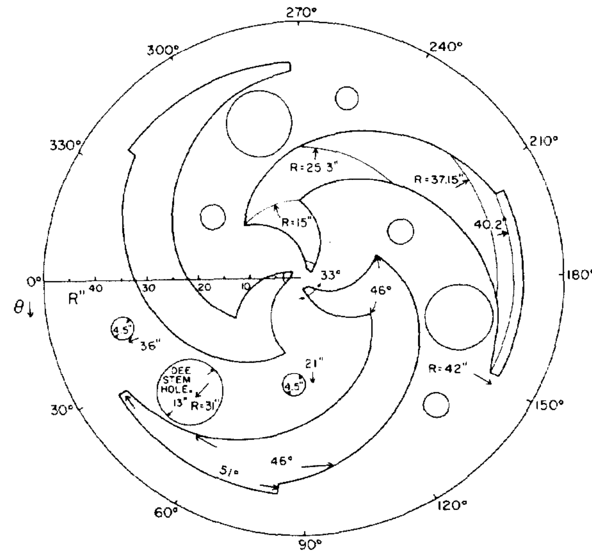

Fig. 6 Plan view of the MSU K=800 superconducting cyclotron flutter poles.

an external high charge state heavy-ion source and axial injection. The specific energy curve shown in Fig. 2 is for the tandem injector arrangement. The pole radius is 900 mm and the average midplane induction is 4.8 T at full excitation. The frequency range is 15-48 MHz and harmonic numbers 1, 2 and 3 will be used.

A 1/6 scale model of the magnet was built and the midplane field mapped in 1977. Following successful operation of this model there was a hiatus of over two years because of lack of funding. Funding for the project was approved this year and procurement of major items such as the superconductor, magnet steel and liquefier is now in progress. First beam from the cyclotron is scheduled for 1985.

Texas A and M University

Texas A and M proposes[15] to build a copy of the Michigan State K=500 cyclotron; the only significant change being considered is the possible lowering of the radiofrequency. As a stand alone facility it will deliver beams to some of the existing target locations currently serviced by their K=147 cyclotron as well as to a new experimental hall.

The superconducting cyclotron will also be used to inject into the K=147 cyclotron to give the specific energy curve shown in Fig. 2. The project has been funded and building construction is scheduled to start late this year. First beam from the superconducting cyclotron is expected in 1985 or 1986.

Superconducting Cyclotron Proposals

A group at Orsay[16] is in the early stage of a design study on a K=600 three-sector superconducting cyclotron with either radial injection from a 15 MV tandem or axial injection from an electron beam ion source (EBIS). The cyclotron will have an extraction radius of 0.75 m and the average midpane induction range spans 2 to 4.7 T.

A project study is in progress at Centre de Recherches Nucléaires in Strasbourg[17] to build a K=500 three-sector superconducting cyclotron using a central ion source or an external high charge state ion source (CRYEBIS or ECR) or a 15 MV tandem as injector. The average midplane induction at full excitation is 4.1 T and the extraction radius is 0.83 m.

At Jülich, there is a proposal[18] for an ECR ion source injecting into a K=500, four-sector superconducting cyclotron followed by a second superconducting cyclotron with K in excess of 1000. The proposal is in a preliminary stage and no details of the cyclotrons are available. However, the ECR ion source is being built and will be used to inject into the conventional K=180 cyclotron now operating there.

At the Research Institute of Physics, Stockholm, there is a proposal[19] for a K=500, three sector superconducting cyclotron, similar to that at MSU but injecting axially from an external high charge state heavy-ion source.

ORIC at Oak Ridge is a three-sector K=100 cyclotron with room temperature coils that is normally operated with an internal ion source. Recently it has accelerated ions injected from the new 25 MV tandem (still being commissioned) demonstrating excellent operation of the new injection line and midplane stripper mechanism.

A proposal has been submitted to replace the main magnet coils with superconducting windings that would increase the average midplane induction to 3.3 T thus increasing the cyclotron constant to K=300[20]. Two separate cryostats will be used, one on each side of the midplane, with the attractive force supported by the vertical walls of the yoke (ORIC's midplane is vertical) rather than the midplane bridge common to other compact superconducting cyclotrons. This arrangement allows the existing rf accelerating structure to be retained.

This conversion is an excellent example of the possible savings in operating costs using superconducting main coils. Currently, the main coils dissipate 1.5 MW whereas the liquefier for the superconducting coils will require ∿ 100 kW.

A project study[21] is in progress at TRIUMF (British Columbia) to use their meson factory cyclotron as injector for a two stage isochronous ring cyclotron to accelerate a 100 μA proton beam for the production of kaons. The first ring cyclotron with 15 sectors would accelerate a 450 MeV beam from TRIUMF to 3 GeV. A second ring cyclotron of 30 sectors and 20.6 m extraction radius would accelerate this beam to 8.5 GeV. All the sector magnets would be excited by superconducting coils to a hill field of 5 T. Computer studies are in progress on ion optics, magnet configurations and extraction schemes.

SUSE[22] is a project study in Munich for a separated-sector cyclotron with superconducting coils injected from a 13 MV tandem Van de Graaff. Figure 7 shows a midplane plan and elevation view of one of the four sectors. The superconducting coils are wound around the iron pole tips that are also at liquid helium temperature. The field is trimmed by a set of nested superconducting windings on the pole faces. At the highest excitation at the extraction radius of 2.4 m, the pole induction is 4.5 T. Two accelerating cavities in opposing sector gaps operate from 29-39 MHz and harmonic numbers 3 to 9 are proposed. The accelerating voltage in each cavity increases with radius to 1 MV at extraction and the phase compression resulting from this gradient reduces the energy spread in the extracted beam to $1:10^4$. Superconducting septum magnets are proposed to steer the externally stripped beam from the tandem into the cyclotron and electrostatic and magnetic deflectors for extraction. A quarter scale cavity and a single full scale superconducting main coil winding are being fabricated for initial tests.

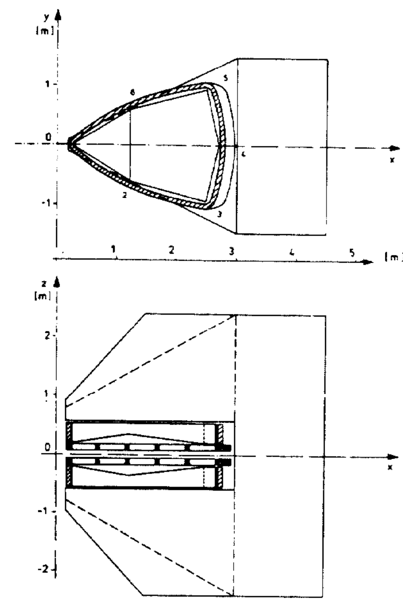

Fig. 7 Plan and elevation view of one of the four sectors of SUSE.

Summary

From the number of projects under construction and proposed, superconducting cyclotrons are obviously a popular approach to accelerating heavy ions beyond the coulomb barrier. The use of superconducting windings, the large forces associated with the high magnetic fields and the restricted access to the midplane have provided interesting problems for cyclotron designers. We all look forward to the initial operation later this year of the MSU=500 facility that will provide the first heavy-ion beams from a superconducting cyclotron.

Acknowledgements

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