APPLICATION OF SUPERCONDUCTIVITY IN CYCLOTRON CONSTRUCTION*

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Abstract.-This paper reviews major concepts and design features of the new class of cyclotrons which use superconducting coils to provide main magnet excitation. The discussion begins with a brief historical review tracing the evolution of these "superconducting" cyclotrons and the impact of this application of superconductivity in pushing back traditional cyclotron construction limits. This is followed by a review of the principal phenomena which come into play to set new limits on the operating regime, and the nature of these limits, some of which arise from orbit properties and some of which result from construction intricacies in the coil and in the rf system. Conclusions anticipate a future widely encompassing role in the application of superconductivity to cyclotrons.

I. INTRODUCTION.

The discovery of high field superconductors in the late 1950's raised an immediate issue for the cyclotron designer, namely would these materials be useful in increasing the performance and/or reducing the cost of future cyclotrons. A first negative answer to this question came quickly as a consequence of the primitive and unreliable state of the materials then available.1) Thus cyclotron development moved forward through the 1960's quite independently of the development of superconducting techniques, as we all well know. At the same time during these years, a basic technology for large scale superconducting coils was being vigorously developed2) in order to satisfy a need for large high field bubble chamber magnets.

Approximately eight years ago the cyclotron community was awakened to the promise of superconductivity by pioneering studies of a group at Chalk River under J.S. Fraser.3) Within a few months, a report4) from this group was in wide circulation, putting forward the assertion that application of bubble chamber coil techniques to cyclotrons was not only feasible but would lead to a cost reduction in the vicinity of 50 to 60%. In December 1973, a mini accelerator conference at McGill University listened with great interest to Fraser's report on the Chalk River work.5) Also three other groups, (Berkeley, Michigan State and Milan) had by this time contracted superconducting fever and were moving forward with serious preliminary design studies of possible cyclotron configurations. Figures 1 through 4 show some of the features of the structures which were being studied at this time; it is interesting to note that the difference in design styles was much greater then than now.

Rather quickly, in fact, a combination of the facts of nature and the close vigorous collaborative exchanges between the several groups led all of the superconducting design groups to a quite similar basic structure involving a solenoidal coil housed in a pill-box type yoke with major penetrations coming axially into the magnet for rf and for access, (in contrast with the radial access which had been the normal approach in previous cyclotrons). Figures 5 and 6 show these features schematically and photographically, the schematic drawing showing the basic structure of the Chalk River project to be described by Dr. Ormrod in a following paper and the photograph showing the nearly completed K500 cyclotron in East Lansing which will also be described in more detail in a following paper.

In spite of the fact that a superconducting cyclotron has yet to operate (although hopefully the first cyclotron in East Lansing will come into operation before the publication of these proceedings), a very convincing rationale has evolved from a series of major prototype and modeling studies at Chalk River,

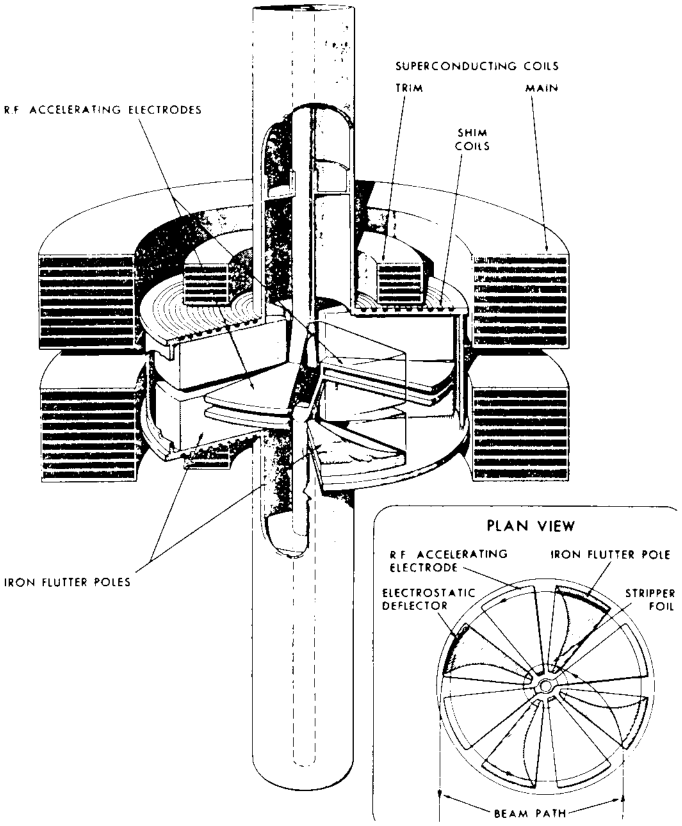

*Fig. 1: The early Chalk River cyclotron structure.*6)

Michigan State and Milan,10) supporting the basic viability of the concept. As a consequence, a large number of laboratories are now actively involved in design and/or construction of superconducting cyclotrons. Table I gives a list of projects known to me, including a brief itemization of major goals and parameters of the various projects. The objective of this paper is to review the major design features of this new class of cyclotrons, particularly emphasizing those design elements where superconducting cyclotrons differ significantly from room temperature cyclotrons.

II. NOVEL CHARACTERISTICS OF SUPERCONDUCTING CYCLOTRONS.

Introduction of superconducting main coils gives the cyclotron designer freedom to turn up the main coil ampere turns--not to infinity--but certainly up by a large factor--typically 10 fold relative to levels customary in room temperature cyclotrons (and still larger factors might be used in future designs, which are likely to push harder on the phenomena which come into play to limit the current as discussed in a later section of this paper). This rather small change in the overall constraints which limit cyclotron designs has a quite amazing impact on the basic cyclotron structure--such a large change that the effect is difficult to conceptualize. Clark presented a figure at Zurich,11) which I repeat here (figure 7) showing the change schematically. The small circle at the bottom is obviously compact relative to the large figure at the top but the real three-dimensional magnitude of the change is greatly underplayed by this figure. A much more adequate sense of the scale of change comes with the actual experience of standing beside a large room temperature cyclotron and then by a superconducting machine. The difference is really quite incredible--a visitor seeing the K500 magnet in East Lansing almost always has a comment along the lines, "It's really hard to believe that this is a 500 MeV magnet". It is, of course, and the basic principles of these superconducting cyclotrons are the same as those of any cyclotron, the major differences being really simply choices of parameters. Acknowledging the large fundamental overlap of room temperature and superconducting cyclotrons, there are at the same time many interesting differences and novel parameter interactions as following subsections consider.

A. LIMITING PHENOMENA.-The increased ampere turns provided by the superconducting coils immediately help the designer in a direct way in that the behaviour of the iron is greatly simplified. Steel close to the median plane moves to a condition of full saturation and it becomes quite accurate to assume that all atomic magnetic moments are fully aligned. From elementary electromagnetic theory, a known distribution of magnetic moments can immediately be converted to either a distribution of magnetic charges or to a distribution of currents, and with either representation, it is straightforward to calculate the field. If the magnetic

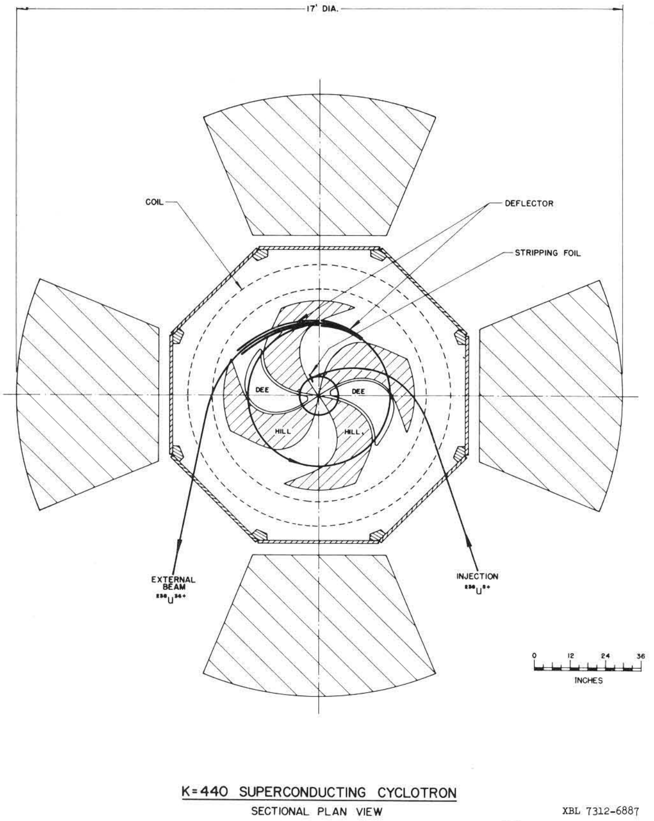

*Fig. 2: Plan view of an early Berkeley design.*7) *The Berkeley work grew out of a medical cyclotron study independent of the work at Chalk River.*

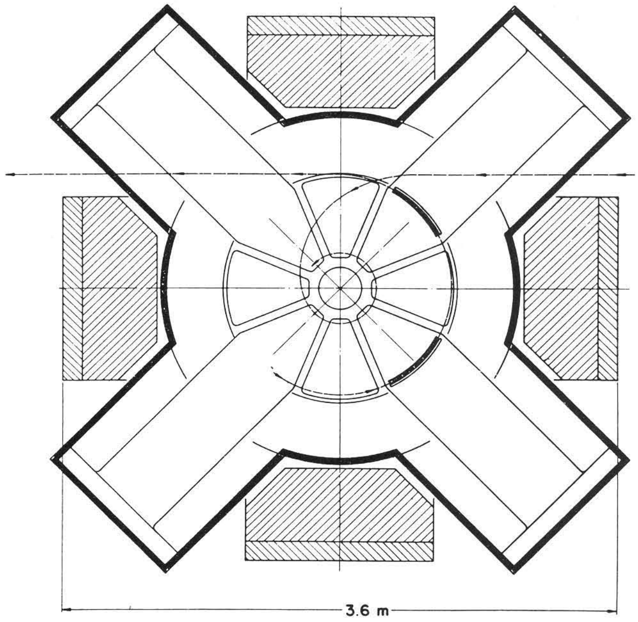

*Fig. 3: Plan view of an early MSU design.*8)

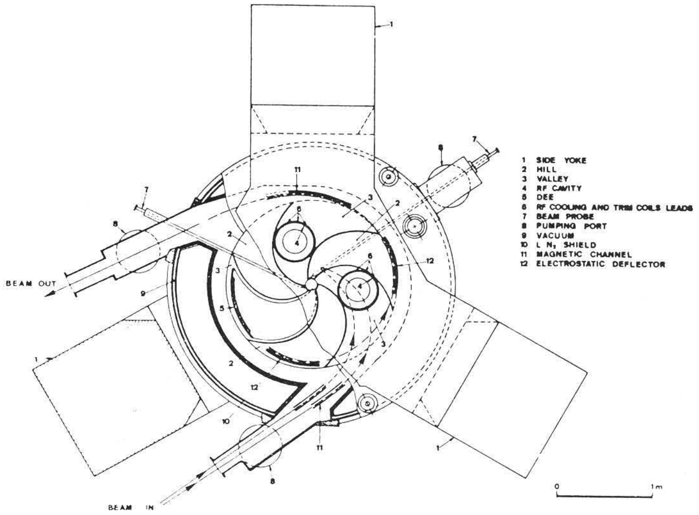

*Fig. 4: An early three sector Milan design.*9)

moment distribution is uniform, saturated blocks of iron such as are sketched in figure 8 are equivalent to uniform currents on the surfaces parallel to the field and the pleasing gift of nature is that this current is quite large, giving, for ordinary steel, a linear density of about 1.7 million amps/meter.

The first generation of superconducting cyclotrons has taken the easy path of using this powerful characteristic of magnetized steel as the source for the azimuthal field viaration or "flutter". In so doing, several significant changes in limiting phenomena are introduced relative to corresponding phenomena in low field cyclotrons. The crux of the difference is that once the steel is saturated, the aligned magnetic moments produce the 1.7 million amp/meter surface current and this current remains fixed irrespective of further increases in the main coil current. The flutter coefficients, f , (the ratio of the ith azimuthal fourier component of the field to the azimuthally averaged field, <B>) then take on a 1/<B> dependence. This is markedly different from the behaviour below saturation where the azimuthal components are proportional to main coil excitation and the flutter coefficients, are, to good approximation, independent of the main field. The orbit dynamics associated with this varying flutter lead to both a high limit and a low limit on the region of useable fields. These, and another set of limitations associated with the technical difficulty of increasing electric fields relative to traditional values, lead to a set of orbit related problems which limit the design of superconducting cyclotron magnets (replacing the traditional cost-of-electric-power limit of the room temperature cyclotron); major characteristics of these limiting phenomena are described in following subsections (1 thru 5).

1. High Field Limit.-When the flutter is produced by the aligned magnetic moments of iron sectors, the focusing becomes weaker as the field is increased, finally at some field value becoming too weak and therefore placing a "focusing limit" on the regime of usable fields.12) This usable regime of course depends on the charge to mass ratio of the particle, the more relativisitic the particle, the more focusing being required to overcome the isochronous field defocusing. Taking this into account the maximum energy per nucleon of a machine in this focusing limit regime comes out to be proprotional to Q/A (where Qe is the ion charge and Am_o is its mass) rather than to $(Q/A)^2$, a decrease in magnetic field being necessary to maintain focusing for particles with large Q/A, this decrease just canceling one of the Q/A factors in the usual energy equation. This phenomena is expressed quantitatively by introducing the quantity K_f, the focusing limit, where the maximum energy which can be focused is given by $E/A = K_f(Q/A)$.

The actual value of K_f depends on many factors as described in reference 12, including the hill and valley gaps, the relative width of hills and valleys, the spiral angle, etc. (Unlike separated sector machines, maximum axial focusing in a compact high field machine occurs when hills and valleys have equal width.) When all of the mentioned parameters are approximately optimized, the focusing limit of a compact high field cyclotron can be fairly accurately represented by simply computing the K value* corresponding to an average field of about 27 kilogauss, the variation in K_f from one machine to another thus dominantly being simply the variation in final orbit radius. (The 400 MeV K_f of the MSU K800 for example is very closely simply $K_{f800} = (\rho_{ex800} / \rho_{ex500})^2$) K_{f500}.)

Figure 9 schematically depicts the impact of the bending and focusing limits on the operating regime of the cyclotron. On the left of the figure (low values of Q/A) the operating regime is defined by the traditional bending limit whereas at the right (high values of Q/A) the useful operating regime is controlled by the focusing limit. These two limiting phenomena then seem to point to two distinct future lines of evolution, namely:

1) a line of development such as has already started at Munich,13) aimed at relieving the K limitation by going to active flutter coils in a separated sector type configuration, this line of development being particularly suited to highly relativistic light particles, and

2) a line of development which will push main coil ampere turns still higher, perhaps doubling the values now in use and therefore giving very high K values (2,000 to 4,000 MeV) in relatively compact magnets (≈1 m extraction radius) but with focusing limits about as now (K_f≈400 MeV). Cyclotrons of this latter type would be most attractive for very heavy ions opening the possibility of achieving interesting energies in a single stage accelerator, which should yield important advantages in both cost and intensity relative to the present generation of two stage systems.

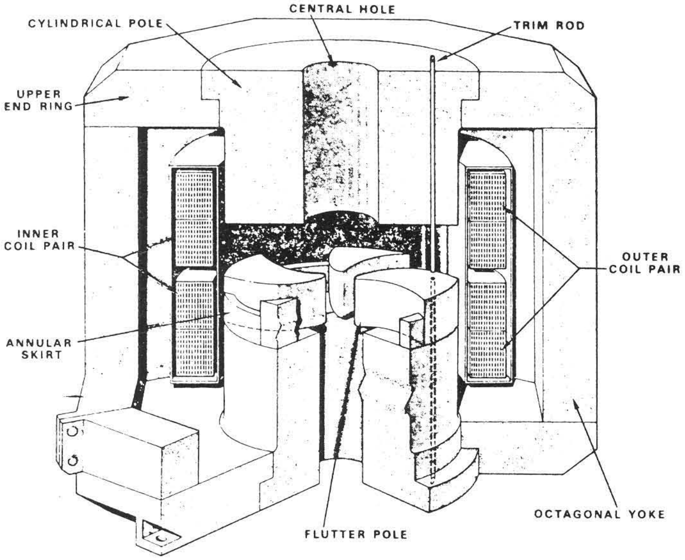

*Fig. 5: Schematic view of the Chalk River K510 magnet as actually constructed.*10)

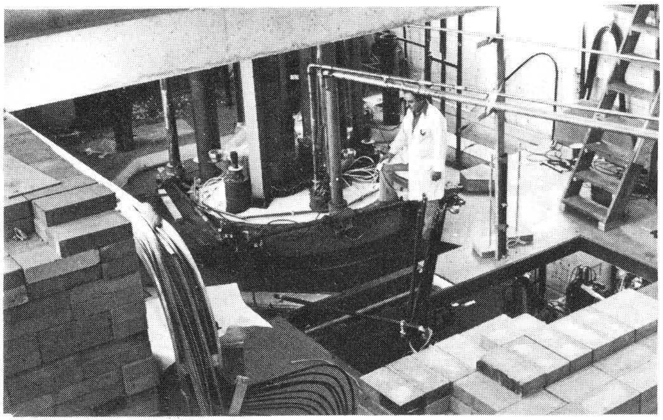

Fig. 6: Photo of the MSU K500 in late August 1981.

* "K" without a subscript denoting the traditional bending limit K, namely $K = (eB\rho)^2/2m_o$.

Table I. Survey of Superconducting Cyclotron Projects

Lab/ Location	Cyc Name	Maximum Energy (MeV/A)			Magnet			Source or Injector	Comments
		Q/A			Field (kilogauss)		Stored Energy M Joules		
		=1	=½	=1/10	Hill$_{max}$	$<B>_{max}$ @r_{ex}			
CONSTRUCTION PROJECTS:									
Chalk River/ Canada	Chalk River SCC (K=520)	X	50	10 @.14	60.5	50.5 @ 65cm	21.5	13 MV Tandem	1st beam 1983
MSU/E. Lansing, MI, USA	K500	X	80	5.1	58.5	48.5 @67.3cm	16.9	Internal PIG or axial external	Final assembly in process, 1st beam fall 1981.
MSU/E. Lansing, MI, USA	K800	X	200	14	62.3	53.1 @103cm	60.6	K500, or axial or internal PIG	Major components ordered. Beam fall 1984.
Milan Univ/ Milan, Italy	C.S.	120 @.67	100	8	58.8	49.3 @86.7cm	40.2	16 MV Tandem- Internal PIG- Axial External	Major components ordered. Magnet operating Jan. 82 Beam Mar. 85.
Texas A&M/College Station, TX, USA	K500	X	80	5.1	58.5	48.5 @67.3	16.9	Internal PIG or axial external	Ordering components beam late 1984.
DESIGN STUDIES:									
AFI/Stockholm Sweden	K500	X	80	5	59	50 @66 cm	17	Internal PIG or axial external	Proposal
Beschl.Lab.LMU-TUM/Munich, Ger.	SuSe	450	300	24 @0.16	48.0	22.7 @240cm	112	13 MV Tandem	1:1 model of main coil on order, tested fall 1981
Chalk River/ Canada	K60	X	15	X	69	62 @18cm	small	Internal	Medical cyclotron conceptual Design
CRN/Strasbourg France		X	85	12.4	53.9	44.7 @83cm	43	16 MV tandem	Project
I.P.N./Orsay France	K600	200	105	6	50	40.5 @87cm		Axial external Duo, Ebis and Tandem 15 MV	Proposal first beam in 89
Jyväskylä,/Finland	K500	X	80	5	59	50 @66cm	17	Internal PIG or axial	Proposed for construction 1985
ORNL/Oak Ridge, TN, USA	ORIC SC Conversion	75	40	3.0	39.3	32.7 @76 cm	53	25 MV Tandem or internal	Proposal
Triumf/ Vancouver, Can.	CANUCK I	3000	X	X	50	12 @10.1 m	X	500 MeV H^- cyc	Feasibility study underway
Triumf/ Vancouver, Can.	CANUCK II	8500	X	X	50	15 @20.6 m	X	CANUCK I	Feasibility study underway

2. Low Field Limit.-As the magnetic field is decreased in a compact type superconducting cyclotron, the focusing frequency increases due to the higher flutter and the operating point in the ν_r, ν_z plane moves to larger value of ν_z and ultimately into some region of focusing resonance difficulties. Specific details of such resonance limitations are, of course, strongly dependent on other design choices such as 1) sector number, 2) spiral angle, 3) whether there is reserve strength and adjustment capability in the extraction system to allow extraction inside of near-the-edge resonances, etc. A geometrical issue is also important for three sector designs, namely, whether the variation in orbit scalloping due to the varying flutter ($\Delta r/r \approx f/N^2$) leads to a misfit between deflector shape and orbit shape. The details of this low field limit must be independently worked out for each particular cyclotron; essential features of the phenomena are shown in figure 10 for the MSU K800, the figure showing ν_r vs. ν_z for a Q/A = 0.2 ion at two different field levels, the lower of which is nearly at the point of low field difficulty due to the $\nu_r + 2\nu_z = 3$ resonance.

The MSU K500 behaves similarly i.e. its lower limit for useful operating field is also in the vicinity of 30 kilogauss. The Chalk River and Milan designs in contrast push the lower limit down to about 20 kilogauss, the wider usable field range in the Chalk River machine resulting from the four sector magnet, while the wider range in Milan is obtained by using a broadly variable, bendable deflector to extract the beam inside the limiting resonances.

The low field limit is fortunately not an actual performance restriction for any except the very lightest ions, since for most ions, as soon as the field is reduced by an amount corresponding to a charge change of one, further energy reductions can thereafter be obtained by shifting to a charge state which is one step lower and at the same time stepping the field back to its full value. Using this technique relatively high values of the low field limit such as the 30 kilogauss of the MSU designs never-the-less allow continuously variable energy for all but the very lightest ions (H, He, Li).

Separated sector designs will be less effected by this low field limit since the average field and azimuthal harmonics scale in the same way therefore giving approximately constant flutter and hence greatly reducing difficulties due to the operating point moving onto a resonance.

3. Turn Spacing Limitation.-Limitations due to too small a turn spacing are one of several problems which follow from the absence of techniques making it possible to significantly increase the strength of electric fields.

Particles must clear the injection device whether it be internal source, the edge of a stripping foil frame, or some form of injection channel and for all these cases, the basic scaling rule for the clearance varies like the final radius divided by the number of turns, i.e. as $\Delta r = r_{max} \Delta V/(KQ/A)$ where $Q\Delta V$ is the energy gain per turn. An increased magnetic field must therefore be compensated by either higher energy gain per turn (increased dee voltage, more dees, use of more favorable harmonic numbers, etc.) or by tighter engineering of the mechanical structure of the object to be cleared. Reacting to this difficulty, designers of superconducting cyclotrons have all moved to acceleration systems with high energy gain per turn, typically having a dee in every valley to give six or eight acceleration gaps and using somewhat higher voltages than had been previously customary--100 kV dee to ground at Chalk River, Milan and the MSU K500 and 200 kV as the design goal for the MSU K800.

4. Extraction Limitations.-In the extraction process, an electrostatic deflector is traditionally used to enlarge the orbit radius so that the orbit breaks free from the field or has a clearance adequate to enter a following magnetic extraction device. To achieve the same orbit geometry, the ratio of electric force to magnetic force must be maintained. Noting that this ratio can be written as $F_E/F_B = 2eE\rho/(KQ/A)$ and since ρ, the bending radius, must be the same to have the same geometry) we see that for given Q/A, the electric field must rise like the K value to hold the same geometry but, also, lower Q/A linearly offsets the effect of higher K. Some gains, relative to this limit, can be made by pushing harder on design details than has been normal in present cyclotrons, i.e. using several electrostatic deflectors, using longer deflectors, combining several deflectors with magnetic devices, etc.

Another important gain can be achieved by sharpening the field edge, the job of the extraction system really being to increase the apparent rigidity of the beam to a value beyond the maximum rigidity which the magnet can contain, i.e. beyond the $B\rho$ associated with the $\nu_r = 0$ point. The present generation of superconducting machines have already utilized this last aid in a very substantial way as can be seen by comparing the $B\rho$ max point of the first Chalk River design (figure 1) with that of the final design (figure 5).

Even when all design tricks are used, extraction remains a design limiting problem. Thus, for example, in a K500 machine, the extraction problem makes it quite difficult to go beyond a 25 kilogauss average field for protons or beyond a 35 kilogauss field for deuterons. The extraction limit thus behaves in basically the same way as the focusing limit, forcing the use of lower fields for lighter, high Q/A particles, and channeling

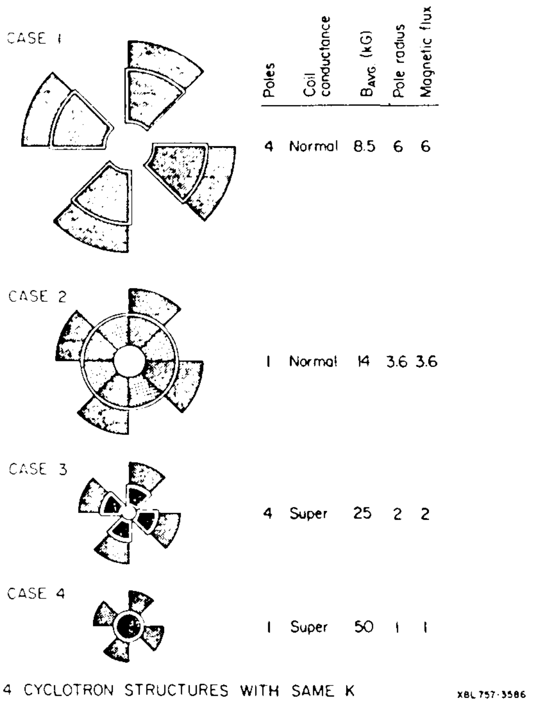

Fig. 7: Comparison of separated sector (case 1) and compact (case 2) room temperature cyclotrons with corresponding superconducting designs (cases 3 and 4) from ref. 11.

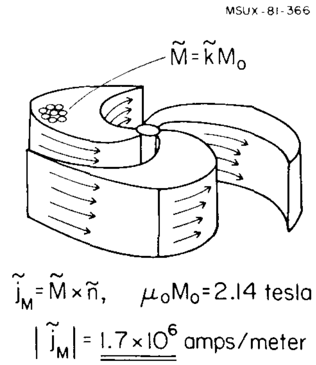

Fig. 8: Schematic showing equivalent surface currents in uniformly magnetized, fully saturated iron.

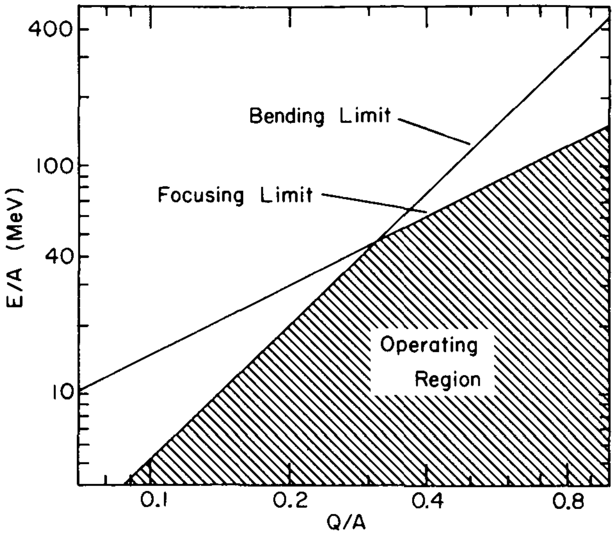

Fig. 9: Graph of bending and focusing limits for a K=440, K_f=160 MeV cyclotron.

the application of very high <B> values to ions with large A.

5. Source-to-puller transit time limit.-For cyclotrons which use an internal ion source, higher magnetic fields lead to a transit time problem in the first gap. The time available to cross this gap gets smaller, the higher the frequency (and for given harmonic number the frequency increases like <B>), whereas the distance to be traveled remains basically fixed due to the inability to increase electric fields beyond the values normally used. The scaling characteristics for this factor is given by the Reiser[14)] criterion $\chi = (\ell/E)B^2(Q/A)(e/m_o)$ and as the magnetic field increases, χ decreases quadratically corresponding to less favorable transit time factors. In part this can be offset by shifting the rf frequency to lower harmonic numbers but unity is the lowest harmonic number which can be used, and so this transit time problem has pushed designers toward rf systems with very broad tuning range in order to operate mostly on the lowest possible harmonic. Depending on the specific application of a particular cyclotron, the Q/A values can vary over an extremely wide range (from 1.0 for the proton to 0.025 for a 6+ Uranium is a factor of 40). Designers are then forced to use several harmonics, any thought of covering such a broad range on a single harmonic being quickly buried by the intricacies of the rf design problem. (In addition the proton because of its unique frequency requirement is usually omitted from the set of particles to be accelerated.) Summarizing, the phenomena discussed in these five subsections are the major orbit related limitations on the useful operating regime of a superconducting cyclotron. Additional limitations are set by engineering features of the major components, as described in the next sections.

B. SUPERCONDUCTING COIL DESIGN.-The introduction of low temperatures involves the superconducting cyclotron designer in many novel new technical details not relevant in room temperature designs.

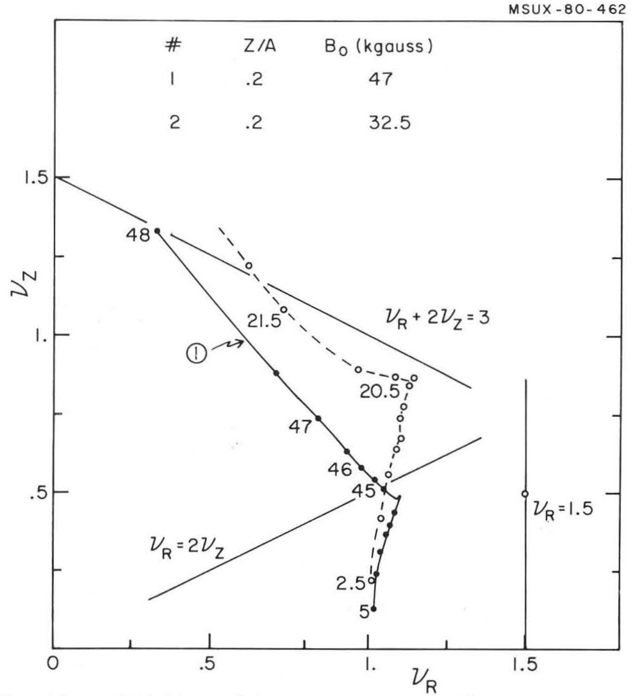

Fig. 10: Evolution of the ν_r, ν_z operating point at two different field levels in the MSU K800 field.

First of all the magnetic field design process for high field magnets is quite different, the pill-box type magnets which are used in compact type superconducting machines, fortunately allowing a significant simplification of the magnet design process. An array of detailed coil design decisions must also be made including: 1) choosing the basic size and shape of the coil, (this being an important issue because the amount of space required for the restraining hardware tends to push the coil to larger r and z values and therefore works against the extraction related desire for a sharp field edge), 2) designing for the new feature of using the main coil as a field shaping element (the coil being wound with at least two independently excited sections, so that the ratio of currents in the separate sections can be varied to obtain a gross adjustment of the average field shape, thereby greatly reducing the power required in the room temperature trimming windings), 3) an array of judicious compromises between an intricately related set of cryostability, cryosafety and mechanical stress issues, all of which interact strongly with the basic choice of field strength and current density, and 4) designing to minimize thermal losses, (since the power required for operation of a superconducting coil goes mostly to the refrigeration system, and coil heat loss and cryogenic efficiency are then dominant operating cost parameters and cool down time and inductance are important start up parameters). Following subsections discuss major features of these several issues.

1) Magnetic Field Design. A major design simplification can be introudced for high-field, pill-box type cyclotron magnets, namely to utilize a fully aligned magnetic moment approximation to separate the design problem into an azimuthal component and an r,z component.

The computation of the azimuthal dependence of the field is carried out assuming that all of the azimuthally varying magnet structures are fully saturated so that these structures can be replaced by surface currents as illustrated in figure 8. For the magnet structures in typical use in cyclotrons, these azimuthally varying components of the magnet are mainly in the close-to-the-median-plane, high-field region and it is then not surprising that the assumption of full alignment leads to calculated fields which agree quite accurately with measured values; using such calculations differences between calculated and measured values for the principle azimuthal fourier components of the field tend to be in the few percent range at average field levels around 25 kilogauss and the agreement improves as the average field is increased. This level of accuracy is more than adequate, corresponding to a small level of uncertainty in the axial focusing frequency, ν_z, the

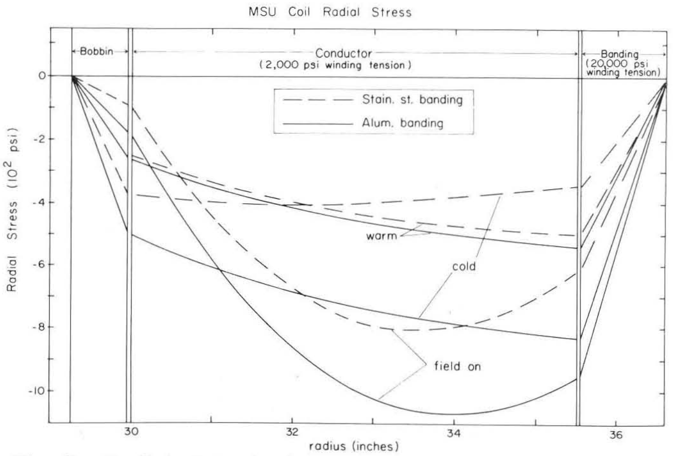

Fig. 11: Radial stress in the MSU K500 coil. Negative stress values indicate inward radial pressure.

quantity most influenced by the field azimuthal variation.

The r,z behaviour of the magnet is handled by a relaxation calculation after first reducing the magnet to a two dimensional problem by doing a θ average over the magnet structure to obtain an average density of ferromagnetic material as a function of r and z. Using this average density as a multiplying factor for the B vs. H relationship at each r and z position, one then proceeds with a normal 2 dimensional relaxation calculation of the field. Limitations of the various codes force numerical compromises on the level of detail to which the azimuthal average of the ferromagnetic distribution can be represented and also in the details of the basic geometry, but in spite of this, for typical magnets, a surprising accuracy can be achieved, calculated and measured average fields typically agreeing to an accuracy of a few parts per thousand. At this level, the differences between observed and expected field behaviour can be handled by the trim coil network or, if the designer is inclined to "gilding the lilly", small corrections to the iron shape can be introduced after a first cycle of field measurements, this typically bringing the agreement between the actual and desired <B> profile to the few parts in ten thousand level.

With calculations of this accuracy, one of the largest tasks in the previously typical procedure of cyclotron design can be eliminated, namely the design and construction of model magnets (Prof. Resmini has remarked that, "the most important result of the Milan model magnet program consisted of showing that models were no longer needed").

Whether this important design gain will also apply as superconducting cyclotrons evolve in the separated sector direction is an important open question. Design calculations for such magnets now rely on three dimensional relaxation programs and the limitations on the accuracy of such calculations due to the numerical limitations forced by the compromise between presently available computers vs the vast number of grid points needed to accurately describe such a magnet may well lead to significant inaccuracies. The operation of the Munich magnet will give the first source of real data on this issue; hopefully these data will confirm the viability of also bypassing the modeling process for the separated sector type magnet.

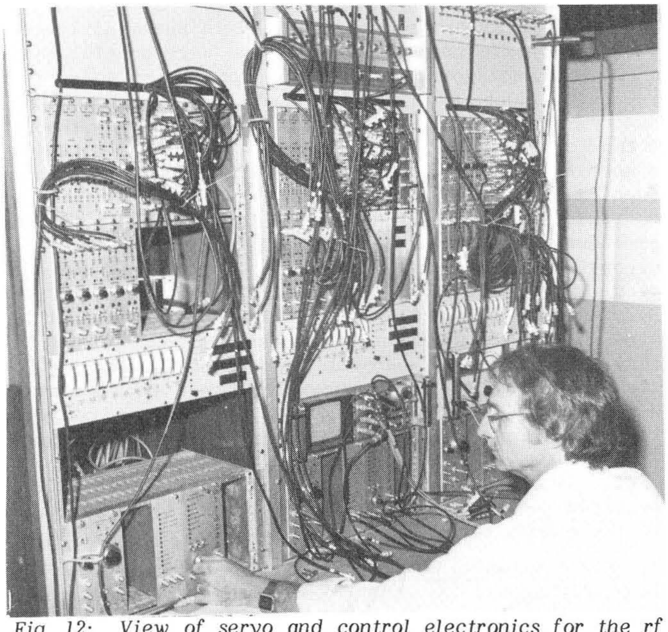

Fig. 12: View of servo and control electronics for the rf system of the MSU K500.

2. Coil Size and Shape vs. Cryostability.-Field shaping requirements in both the acceleration region and the extraction region are best satisfied by coils which are compact and close to the magnet edge, with an aspect ratio which is well described as a split, medium-length solenoid. The optimum choice of axial height vs. diameter gives a field contour which increases with radius in approximately the fashion of the desired isochronous field. Unfortunately compact coils correspond to high current densities and this works against a desired design characterisitic known as, "cryostability", this term referring to the presence of a cooling capability in each section of the coil adequate to override resistive losses which would be present if that coil section were fully normal. (A transition to a fully normal state can easily occur locally when a wire moves, the flash of frictional heat being more than adequate to raise the temperature of a strand of conductor above the critical temperature.) A local normal region is however of no consequence in a cryostable magnet, since the cooling capacity of the bath will proceed to reduce the temperature of the normal section in spite of its resistive loses and finally this section will reach a temperature where superconductivity is restored. In contrast a normal region in a non-stable magnet immediately moves into a thermal runaway leading to the phenomenon known as a "quench" in which the temperature and resistance of the coil rise rapidly and the high coil resistance leads to dissipation of the magnetic energy in the coil. For small magnets, quenches are a harmless event, magnetic energies in the hundred kilojoule range being too small to cause damage. Magnets used for cyclotrons have much more stored energy, however, generally in the range of 10 to 100 megajoules. This amount of energy can typically heat the whole magnet by 100 to 200 degrees (or it heats a local section by a correspondingly increased amount if the resistive dissapation is not uniformly distributed). The cyclotron designer then ends up wanting to use high current densities because they give a better field shape and are less costly, but at the same time he wishes to

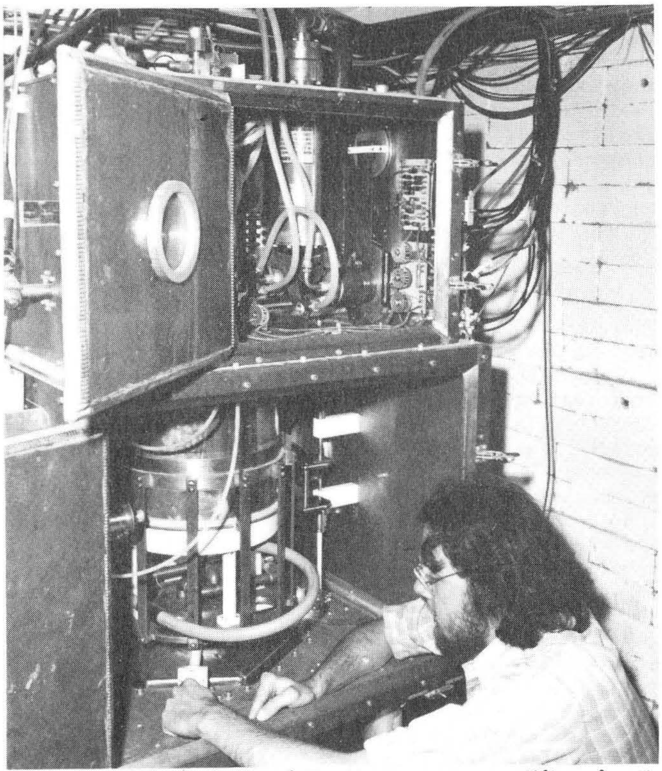

Fig. 13: A view of one of the three power amplifiers for the MSU K500.

design a magnet which will survive in possible cryogenic accident situations.

Designers of superconducting cyclotron coils have generally reacted to this dilemma by 1) electing a current density more or less on an empirically established frontier in a current density vs. stored energy plane and 2) guarding against possible damage in a cryogenic accident by using a multiple defense design.

The first element of the multiple cryogenic defense is to try to suppress sources of frictional heat in the coil by building clamping forces into the coil in the fabrication process adequate to prevent conductor motion. Typical designs utilize winding tension, thermal shrinkage and, for pancake type coils, an array of clamping fixtures or bolts which hold pancakes together. Figure 12 shows the calculated features of the conductor restraining system used in the MSU K500 coil. The objective of this design is to provide an inward radial pressure in the coil sufficient to prevent wire motion; this radial pressure comes from winding tension in the conductor, and from a layer of aluminum banding wound with a much higher tension. In the cooling process both conductor and aluminum shrink more than the stainless steel bore tube, therefore further increasing the pressure as indicated by the curves marked "cold" in the figure. As the field is turned on, the magnetic force gives an outward pull on the conductor which reduces the radial pressure, but the minimum pressure (≈170 psi) at the bore tube surface still gives frictional forces substantially exceeding the magnetic force trying to move the conductor in the axial direction. If these calculations were exact, and if the magnet were with certainty fabricated with design values of the tension and with materials corresponding to design characteristics, no conductor motion would occur. Unfortunately the calculations are not exact--it's very difficult to go beyond an infinite solenoid approximation--and it is also very difficult to accurately know the tension throughout the thousand odd hours of winding or to reliably know the material characteristics in the hundreds of thousands of feet of conductor and banding.

Accepting that conductor motion could occur in spite of the design effort to prevent motion, the next defense of the designer is to introduce cryostability, that is to use a combination of current density and cooling such that the cooling can override the heat flash and ensuing resistive losses produced by possible conductor motion. The thermodynamic details of the cooling process are extremely complicated so coil designers normally use extrapolations from known empirical data based on scaling rules for the major phenomena. The K500 magnet at MSU is an example of a specific design, this magnet operating at a current density of 4000 amps/cm^2 averaged over the coil or 5700 amps/cm^2 in the conductor proper, the total winding area being 70% conductor and 30% cooling system and insulation.

Even when a coil design is based on closely relevant empirical data there is never-the-less in the end always considerable uncertainty regarding the cryostability cutoff point in any given coil due to the complexity of the basic phenomena and to uncertainties regarding the properties of the materials. (The 4K resistivity of copper is very sensitive to small amounts of cold work - the exent to which the resisitivity is increased in the winding process is usually a large source of uncertainty.) The designer must furthermore allow for the possibility of operator errors in the cooling system (operating the coil with a low helium level) which can always move a coil into a region of cryoinstability (the quenching of the 15 foot 400 megajoule Fermilab bubble chamber magnet in its 10th year of operation was a dramatic example of such an event).

Accepting that operator errors can always lead to a coil quench, the designer next introduces the "dump" system as a further cryosafety defense, the essential components of this system being a rugged external resistor and a switching and triggering system which places the resistor in series with the coil when signals of a quench occur. Time constants are arranged so that the stored energy of the magnet will be largely absorbed by the dump resistor so that coil heating is correspondingly reduced. Compromises must however be introduced in this process since internal coil damage can also result if a short to ground should develop and large resistance values in the dump, such as most effectively remove the coil energy, at the same time expose the coil to a high voltage and the possibility of electrical breakdown at weak points in the coil electrical insulation system. Again using the MSU K500 as an example, the dump resistor for the large coil section is sized to produce 200 volts at peak operating current (and the resistor on the smaller coil is sized to give the same time constant as used on the large coil). These values tend to be on the low resistance end of the spectrum of typical designs, but nevertheless in an inadvertant quench induced in the K500 coil (by operating with low helium level) approximately 75% of the energy was absorbed in the dump resistor and there was no damage to the coil. The dump resistor design is, of course intimately related to the choice of inductance, i.e. the higher the inductance the more voltage is required to quickly reduce the current to a safe level before the rising conductor resistance at the quench center can reach a level inducing a disruptive temperature extreme--other factors effecting the choice of inductance are discussed in a following subsection.

Even with a proper dump system, the possibility of component malfunction in the trigger system or of a mechanical hangup in the massive mechanical components of the dump switch generally cause desingers to introduce a fourth cryosafety defense, namely to try to construct coils in a fashion such that any normal region will spread rapidly through the coil so that a quench will approach the situation of distributing the energy uniformly through the coil (a very simple total energy calculation quickly shows that the temperature excursions are harmless when the energy is uniformly distributed). A number of computer codes are available which approximately treat the very complicated time dependent thermodynamic and electromagnetic problems in the vicinity of the initial quench point. Tight thermal coupling is helpful in enlarging the volume of the region in which the magnetic energy is being disipated. Electromagnetic coupling can also be very helpful since mutual inductance can shift the current to some other component such as the aluminum banding and a large component of the energy thus also shifts. Similarly, in a two coil system, currents tend to transfer to the non-quenching coil thus again spreading the energy in a harmless way.

Summarizing, in spite of the array of complicated phenomena and the potentially serious hazards, cryosafety experience with large dc coils of the type used in superconducing cyclotrons has been generally very favorable. Coils have performed as expected and have displayed an inherent ruggedness and ability to survive in the face of substantial amounts of miscellaneous abuse. Nevertheless, as cyclotron designers push toward coils of more complicated shape or toward higher field levels, the complexity and intricacy of the many cryosafety phenomena which come into play certainly mean that a great deal of careful work will be required to develop reliable and economical coil designs in these much more difficult regimes.

3. Field Trimming Considerations.-As the energy/nucleon is pushed upward into the relativistic regime the change in field shape required for variable - energy multiparticle operation reaches large values - the shape

change for the K800 cyclotron at MSU covers a range of about 10 kilogauss for example. The power required to produce such a field change with room temperature trim coils would be prohibitive and it is therefore essential to accomplish most of the needed corrections using the zero power windings of the main coil. (The Chalk River trim rod approach is a zero power trimming system, but the range of corrections is nevertheless limited and the Chalk River group then also uses the main coil as a trimming element.) Designers thus far have used a two component main coil, the shaping capability of such a two section coil reducing the total power in the trimming windings to a level below 100 kilowatts which is then a relatively insignificant contribution to the total operating cost of a typical machine.

Resmini has described an elegant procedure for optimizing the overall trimming problem including the choice of how to divide the main coil.15) In general, the section of the coil close to the median plane the socalled inner coil, is used to provide a field component which increases with radius approximately corresponding to the isochronous contour for the most relativistic particle and the section further away from the median plane, the outer coil, is used to produce a field which peaks at the cyclotron center, thereby flattening the total field as needed for extreme nonrelativistic particles. If the structural design of the coil is such as to allow the outer coil to be operated with a reverse current relative to the inner coil, this coil can also work to depress the center of the field for extreme relativistic particles and in this circumstance, a further reduction in total trim coil power results. Also in this case the optimum size for the outer coil becomes smaller, corresponding to about 1/3 of the total coil size when reverse currents are allowed v.s. 2/3 as the optimum arrangement if reverse currents are not allowed. The K500 coil at MSU is an example of a coil design where only positive currents are allowed, while the K800 coil, which is in the process of fabrication, is designed to permit reverse current in the outer winding.

The principle difficulty which must be overcome in a reverse current system is to arrange the mechanical design such that the alternating axial force on the outer winding (toward the median plane for the normal current direction and away from the median plane for the reverse current direction) does not lead to fatigue phenomenon in the coil restraining system such that the winding could begin to move back and forth - if such a situation, were to develop, both thermal and electrical difficulties would undoubtedly quickly follow.

4. Refrigeration System and Magnet Inductance.-A helium refrigerator operating in the 4K range typically produces liquid at the low temperature point of the refrigeration cycle and yet is quite different from a helium liquifier in that in the refrigeration situation, the 4 - 5K gas boiled off from the evaporating liquid is returned to the refrigerator and heat exchanged against incoming gas thereby becoming a major source of cooling. A liquifier in constrast, increases the inventory of liquid in a system, or provides liquid to be removed from the system, the boil off gas from the removed liquid coming back at room temperature (if it is returned at all) and this gas therefore being of no use as a source of cooling. A commonly used refrigerator, the CTI 1400 is thus rated at 72 Watts of refrigeration at 4.5K or 26 liters/hr of liquid production at the same temperature whereas the heat required to boil 26 liters/hr of liquid helium is only 19 Watts. There is then an approximate 4 fold increase in capacity when this machine is operated in the refrigeration mode as compared with operation in the liquifier mode.

The refrigerator for a large superconducting coil must typically operate in a combination liquifier-refrigerator mode, part of the boil-off gas being returned to the refrigerator at a temperature of around 5K and another component of the boil-off gas feeding to the electrical leads to reduce the dominant system heat leak associated with this substantial metal path connecting the low temperature and room temperature worlds. Since leads are the principle heat leak, cryogenic designers have invested much effort in the design of optimized leads, leading to a scaling rule, namely that an optimized lead consumes approximately 1.4 liter/hr of liquid helium for each 1000 amps of current carrying capacity. Thus if the cyclotron designer moves in the direction of fewer turns of larger conductor he lowers the magnet inductance which is desirable from the stand point of cryosafety and ease of magnet variability but he then incurs an added liquification load for the electrical leads. Since the refrigerator-liquifier is a major cost item (a 25 liter/hr system costing $100,000 to $200,000), the designer must compromise between the benefits of low inductance vs. the benefits of lower heat leak. As an example of the spectrum of design choices, the MSU K500 is designed as a 700 ampere 70 Henry magnet whereas the Chalk River K500 is a 2300 ampere 11 Henry magnet.

5. Coil Construction Problems.-Most of the large superconducting coils presently in operation use a "bath" type cooling system, that is, the coil is designed with a labyrinth of internal passages which are intended to contain liquid helium in intimate thermal contact with the conductor. (The close contact between helium and conductor in combination with the large heat capacity of liquid helium gives a cooling source adequate to satisfy the cryostability requirement.) The cooling aspect of this design detail favors bare conductor whereas electrical considerations demand insulation, and these two opposite requirements are then typically met by using a partially insulated, partially bare internal structure. Typical designs generally involve large areas of bare conductor; and such a structure is then obviously quite vulnerable to possible electrical shorts or grounds due to miscellaenous small metal fragments. Both Chalk River and MSU have experienced difficulties with this problem and sizable effort has been expended in both laboratories in the process of diagnosing and/or correcting the difficulty. The problems are not calamitous but certainly quite onerous--the experience of both groups underlines the prudence of exercising extreme caution to guard against introducing metal fragments in the winding process.

An alternate coil structure has been utilized by Morpugo at CERN16) and is the basis of the Munich coil design, namely to go to an internally cooled conductor, the coil structure then being much the same as a typical room temperature coil except that internal water cooling is replaced by internal 4K cooling. With this type of coil structure the vulnerability to metal fragments is greatly reduced (the issue becomes the same as the chip problem for room temperature coils). There are, however, disadvantages in that the large conductor cross section gives higher lead losses and there is also added uncertainty associated with the relatively small operating experience thus far accumulated with coils and cooling systems of this type.

Another highly non-trivial construction difficulty in a large superconducting coil system is the problem of helium leaks from the coil vessel into the insulating vacuum, since such leaks can easily overload the capabilities of the cooling system. Further, the mass flow through a given orifice increases by approximately two orders of magnitude in the transition from room temperature to 4K, so that leaks which are below the detection threshold of normal mass spectrometer systems at room temperature can nevertheless be an important problem in the cold vessel. Since gasketing techniques are either extremely difficult or ineffective at low temperature, the sealing method of choice in almost all situations is welding and successful welds require both a good design (careful planning of the stresses which will act on the weld) and a skilled and careful welder. Designs which allow step by step testing of welds as they are made (preferably with a thermal shock from several exposures to liquid nitrogen) are strongly preferred since it is usually much easier to repair a defective weld if the part is still at the stage of being a small assembly and the process also gives valuable short term quality control feedback, helping the welder to learn techniques which most effectively produce leak tight welds.

Many other small details are important to the successful construction of a large superconducting coil... Putting a thermal insulation system together from multiple layers of aluminized mylar and spacer, with care at corners and penetrations and careful thought to avoid a layer of mylar crossing over other layers in a way which creates a thermal short circuit...The design of a coil support system to resist the forces associated with the unstable equilibrium position of the coil with respect to the surrounding yoke while at the same time minimizing the coil heat leak.... Planning carefully for shrinkage so that the 1 in 300 length change of most components will not lead to excessive stresses......

Summarizing, the design, construction, and operation of a large superconducting coil is far from simple, but it is at the same time something which can be learned by groups with little or no previous low temperature experience and there is a most enjoyable stimulation and liveliness associated with the novelty and fun of this new regime. Many more cyclotroners will undoubtedly be sharing this as a personal experience in the coming years, the overall attractiveness of superconducting coils being clearly convincingly established.

C. ACCELERATION SYSTEM.-The selection of frequency range is the critical first choice in the design of the radio frequency accelerating system for a superconducting cyclotron. Generally the system will be more compact the higher the frequency, and the use of high magnetic fields, or course moves toward high frequency, (the orbital frequency in MHz being 15.36 times the magnetic field in Tesla times the particle Q/A). If the cyclotron uses a central ion source, the source-to-puller transit time is a problem as was discussed in a previous section, and this issue pushes the design to low harmonic numbers. The selection of low harmonic numbers, and the broad Q/A range which the cyclotron is normally intended to handle, lead to unusually wide tuning requirements for the rf system, the 9-32 MHz span of the K500 system at MSU being an extreme example. The need for multiple dees and high dee voltage was also discussed in a previous section (these factors substituting for the inability to increase electric fields in a fashion corresponding to the magnetic field). Finally, the overall compactness of the superconducting cyclotrons often leads designers to mount important components in the dees, whether it be the all important puller electrode for an internal source machine, or a stripping foil or a deflector as at Chalk River; all of these items have sensitive mechanical positioning requirements which are best met by a highly rigid electrode structure.

The combination of requirements described above constitute an extremely difficult rf design problem, involving a wide frequency range, a multi-electrode system with tight phase stability requirements, (and for the case of the MSU and Milan designs, the need for the novel requirement of 120° phasing), unusually high voltages (100-200 kilovolts dee to ground), and often the use of insulators to preserve mechanical stability and put tuning elements at atmospheric pressure or, alternatively, the design of tuning elements and position stabilizing systems to work in vacuum. In attempting to solve this design problem the small size of the superconducting cyclotron adds significantly to overall rf system difficulties, the limited space for tuning elements being particularly troublesome as it pushes the design toward higher current densities in elements such as contact fingers on sliding shorts (the design of such a system being particularly difficult when the system must operate in vacuum). Undaunted by this awesome array of difficulties and unaided by special gifts of nature (such as the discovery of hard superconductors bestowed upon the magnet designers) rf designers have stepped dutifully forward and undertaken the development of systems having the desired near-miraculous properties. A full demonstration of the success of these efforts is, at the time of writing of this paper, not quite yet in hand. A prototype resonator has been successfully operated at MSU over the desired frequency and voltage range and the complete resonator has operated at Chalk River, but with voltages some what lower than desired as a consequence of difficulties with the contacts on the sliding shorts. High power testing of the complete resonator system is about to begin at MSU and figures 12&13 give some indication of the physical characteristics and complexity of the system. Hopefully in a matter of weeks, the viability of this system will be established.

A curious fact of our mutual profession is that cyclotron construction projects seem most often to be directed by magnet builders. Those of us who are magnet builders of course regard this as simply the proper order of things. In our laboratory recently a memorandum was circulated taking issue with this view. I quote,

"WHAT IS A CYCLOTRON?"

"There are...some people here at the (MSU) Cyclotron Laboratory who still don't know what a cyclotron is...I thought it would be beneficial to enlighten them. A cyclotron consists, in the main, of a radio frequency system which powers accelerating dees with very high alternating voltages in such a manner as to impart energy to a beam of ionized particles...These rf energized bunches...are guided out of the dees by apparati called "the extraction system",...(and) to produce the ionized particles there is something called an "ion source" imbedded rather inconveniently in the middle of the dees and causing great problems to the rf system...The rf system pulls the ions out of the ion source, rejects undesirable ions, accelerates them, (and) ejects them into the extraction system...Also, the dees are surrounded by iron in such a way as to make access to them very difficult (but) this iron...produce(s) the guide field...necessary for the rf system to continuously accelerate the particles, so we have to put up with it. I hope this short treatise...help(s) you understand what a cyclotron is."

"J. Riedel,
Ozarks, Arkansas"

It can perhaps be argued that this statement is somewhat exaggerate for the case of the conventional cyclotron but without contest the heart of the superconducting cyclotron, the focus of difficulty, the place where inventive cleverness is most essential, is its rf system. The accomplishments of the rf group in pressing these frontiers are a critical and essential element in achieving the desired goal - these accomplishments are herewith gratefully acknowledged by this author (who is of course of the magnet builder genus).

III. CONCLUSIONS.

Superconductivity applied in the main magnet coils of cyclotrons has had a revolutionary impact on the general structure and cost of the complete cyclotron system. Linear size of the accelerator is reduced to one third of the previous size, and quantities of materials are reduced by ten to twenty fold. In the process the cyclotron becomes markedly more intricate (and many would say more interesting) and it clearly becomes much less costly, one half to one third of the cost of a comparable room temperature cyclotron. Given today's stringent funding situation in virtually every country, it seems clear that cyclotrons of tomorrow will utilize this new approach almost without exception and today's novelty will be tomorrow's commonplace. And of course we stand today on a threshold - the prototypes of magnets and accelerating systems have been built and tested and the first complete accelerator is expected to operate in a few months - and with that will come the opening of a bold new chapter in the history of the cyclotron. And the next of these conferences will certainly have a special intense interest and excitement as we listen to reports on the startup and early operating experience with these novel devices, the superconducting cyclotrons, and the trusty old atom-smasher of the 1930's, will leap once again, like the cat, into a new life of exciting service carrying the frontiers of science forward!

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" DISCUSSION "

J.A. MARTIN : Would you comment on how high the magnetic fields might be in the next generation of the superconducting cyclotrons ?

H. BLOSSER : I feel 8 Tesla is likely next step. This can be done with Nb Ti thereby avoiding the difficult problems of Nb_3 Sn which must be refracted at a high temperature after winding and it can also be handled with "normal" cooling 4.5 K. Beyond 8 Tesla either Nb_3 Sn or 2.1 K cooling will be needed and both of those will require significant further technical development.