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LHC Project Report 58

SUPERCONDUCTING MAGNETS FOR ACCELERATORS: A REVIEW

M.N. Wilson

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LHC Division

ASC Pittsburgh '96

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 6/11/96

Superconducting Magnets for Accelerators: a Review

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Abstract - **Superconducting magnets have enabled the construction of some very large accelerators to explore the structure of matter at the highest energies. Small superconducting accelerators are used in medicine and industry. We review the special demands which accelerators make on superconductor technology, describe the magnets for large and small accelerators and mention some exciting prospects for the future.**

1. Introduction

It is now more than 30 years since the first proposals for a synchrotron accelerator with superconducting magnets [1]. In this pioneering work, Smith et al discussed not only the technical questions of ac losses etc., but also the economics of superconducting versus conventional magnets. Magnet costs, comprising mainly material and structure, increase with field approximately as B^2, but the number of magnets needed decreases with B; thus the total cost per unit particle energy increases linearly with B. Costs of tunnels and infrastructure increase linearly with size, so this cost per unit energy goes as $\sim B^{-1}$. Thus the total installation cost is the sum of two terms varying as B and B^{-1}. For costs at the time, Smith found a broad minimum at a field of 6T. It is interesting to note that, years later, a field of 6.5T was chosen for SSC.

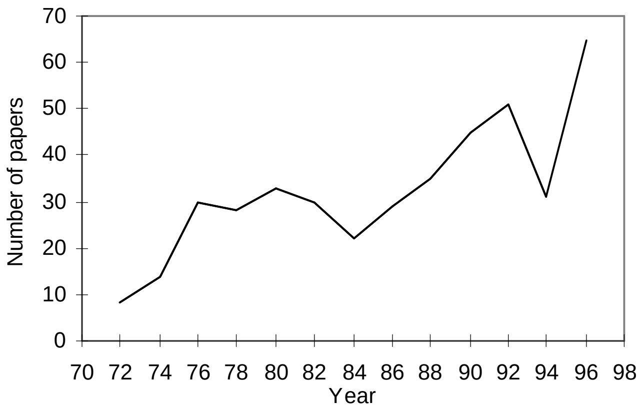

Fig. 1. Numbers of papers related to accelerators presented at A.S.C.

Ever since those early days, superconducting accelerators have remained a lively area, contributing strongly to the technology. Two large accelerators, Tevatron and HERA, are operating, RHIC is nearing completion and LHC is in progress. Fig 1 plots the number of accelerator related papers at this Conference.

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Manuscript received August 27 1996.

II. Conductors

A. Requirements

Accelerator magnets are special in several respects:

i) they must be ramped from low to high field.

ii) they must maintain an accurate field shape, under both steady state and ramping conditions.

iii) all magnets of a given type must be energized in series to ensure that they exactly carry the same current.

iv) although very large in one dimension, the magnets produce field over a small transverse aperture.

These requirements make demands on the conductor:

i) & ii) mean that the superconductor magnetization must be small and should not be significantly increased by coupling current effects during the ramp.

ii) means that the windings must be accurately located.

iii) implies that the operating current must be high and that the magnets must be self protecting.

iv) demands a high current density, preferably such that the winding thickness is less than the aperture.

In the following paragraphs we briefly examine some consequences of these requirements.

B. Composites and Cables

Early accelerator designs were for fixed target machines where collision rate is directly proportional to the number of accelerating cycles. Thus high ramp speeds were the order of the day and ac losses were the main problem. The first prototype synchrotron dipole reported at this conference [2] *'AC3'* was ramped with a rise time of ¼ second. Quite soon however, the emphasis changed to colliding beam machines, where more leisurely ramp rates were acceptable, but it was necessary to accumulate much higher currents at injection. Fine filaments and low magnetization were now needed for field shape, mainly at the injection (low) field. In both cases the preferred filament diameter is ~5-10μm - the smallest size which does not give proximity coupling through the copper matrix and which can be produced economically, with few breaks.

For practical coil winding, stability, protection etc., the filaments are embedded in a matrix of copper and, to minimize eddy current coupling during ramping, the composite wire is twisted. The time constant of the coupling currents is:

$$\tau = \frac{\mu_0}{2\rho_{et}}\left(\frac{L}{2\pi}\right)^2 \qquad (1)$$

where ρ_{et} is the effective transverse resistivity and L is the twist pitch. The currents produce a magnetization:

$$M_c = 2\dot{B}\tau = \frac{\mu_0}{\rho_{et}}\dot{B}\left(\frac{L}{2\pi}\right)^2 \qquad (2)$$

For the 1s rise times of fixed target machines it was necessary to increase ρ_{et} by putting resistive barriers around the filaments but, for the 1000s rise times of colliding beam accelerators, the resistivity of copper is quite adequate.

In 6T a 6μm filament of NbTi carries ~50mA and a composite wire of 5000-10000 filaments carries ~500A. Accelerator conductors must operate at 5-10kA and so need 20-30 wires in parallel. To avoid coupling and promote good current sharing, the wires must be cabled in a transposed configuration. Fig 2 shows early cables in Litz or braid configurations, but quite soon the flat twisted Rutherford cable was universally accepted, mainly because it may be compacted to ~90% density without damage, thereby ensuring good dimensional stability.

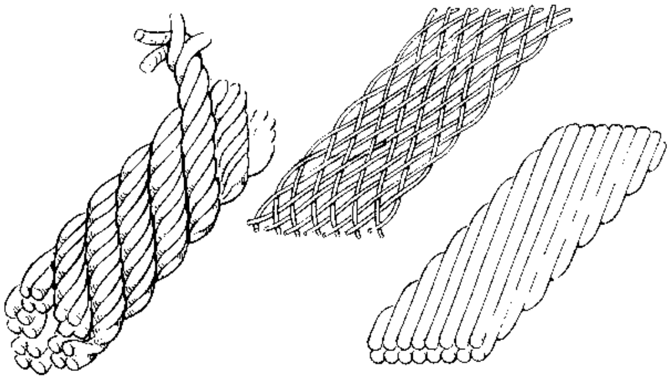
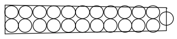
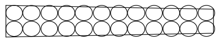
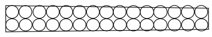
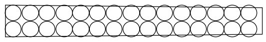
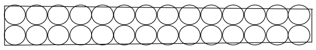


Fig. 2. Different styles of cable: Litz, braid and Rutherford.

Changing fields induce coupling currents to flow between the wires of a transposed cable, just like those flowing between filaments in a composite wire. In the worst case, when the changing field is perpendicular to the broad face of the cable, magnetization is given by a formula similar to (2), but multiplied by α^2, where α is the aspect ratio of the cable - typically 5-7. The minimum practical twist pitch for cables is typically have 10-15x that of their constituent wires, so αL is increased by a factor 50-100. For a given ρ_{et} and $\dot{\boldsymbol{B}}$ the coupling magnetization of a cable will thus be up to 10^4 greater than the wire. Even with the 1000s rise times of colliding beam machines, this coupling is too strong for a ρ_{et} corresponding to pure copper. Some kind of barrier is therefore needed between strands. Early magnets made with cables having with fully (varnish) insulated strands performed extremely badly, presumably due to current sharing problems. The general feeling is now that the interstrand resistance should be 'enough but not too much' - but this feeling is not well quantified. The natural oxide on copper gives an adequate barrier, but unfortunately tends to dissolve into the copper when the finished magnet is heated to cure the insulation. Thicker oxide layers produced by the *Ebonol* process or equivalent give a higher resistance. Coating the wire with *Staybrite* silver tin solder gives a more reproducible resistance which is less sensitive to heating; presumably it also comes from an oxide layer. The Tevatron *zebra* cable used alternate strands coated in *Ebonol* and *Staybrite*. Alternatively, with some small loss of filling factor but much more controllability, one may put a resistive barrier, such a stainless steel foil, into the cable. This gives an anisotropic resistance, ie high between crossover strands to minimize magnetization, but low between adjacent strands for good current sharing and stability [3]. Table 1 lists some parameters of cables used in large accelerators.

TABLE 1: CABLES FOR ACCELERATORS

		filament dia μm	cable width mm	twist pitch mm	wire surface
Tevatron		6	7.8	66	zebra
HERA		14-16	10	95	AgSn
RHIC		6	9.7	73	copper
SSC		6	12.3	79	copper
LHC		7	15	115	not decided

C. Current Partition

It was first seen in HERA magnets [4] that dipole and higher harmonic field terms show a modulation along the beam direction with a wavelength which is exactly equal to the cable twist pitch. It is now thought that this modulation comes from an unbalance in current distribution between strands in the cable. Although the strands are perfectly transposed with respect to uniform or constant gradient fields, the symmetry between strands breaks down at the current contacts and at the ends of the magnet, where different strands may see different flux linkages. For this reason Verweij [5] has called them *Boundary Induced Coupling Currents* BICCs. They are induced on ramping to high fields, and remain on ramping down to zero, thereby leaving residual currents which are positive in some strands and negative in others. Eventually the BICCs decay to a steady state value (or zero at zero net cable current), but the time constant is now related to the distance between boundaries rather than the twist pitch and can thus be hours or even days.

Modulation of the field with a wavelength of ~ 100mm is no problem in a large accelerator, where the particles oscillate with wavelengths of ~100metres. Two related effects can cause problems however: quench behavior when ramping and 'snap back'. When quench current was measured for SSC booster magnets as a function of ramp rate [6], it was found that magnets could be divided into two broad categories. As shown in Fig. 3, type A magnets (in which the cable has a low crossover resistance) behave as might be expected in a magnet in which the temperature rise resulting from ac loss reduces critical current. Type B behavior (magnets with a high crossover resistance) was quite unexpected however and is thought to be the result of BICCs causing some strands in the cable to reach critical current quicker than the rest. In the example shown, the BICCs seem to saturate at a ramp rate of ~100 A/s.

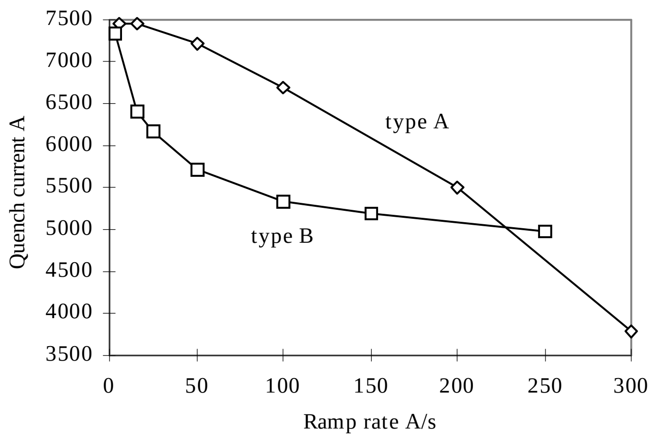


Fig. 3. Type A and B behavior for fast ramping of SSC booster magnets [6]

Snap back is a problem at injection. During the necessary wait at constant field during injection, after a previous ramp to high field, the field error terms decay with long time constants. On starting the ramp to high fields, these error terms snap back to their starting values, causing a sudden glitch in field shape which could lose the beam. Time constants for the decay are 100s of seconds, which is too long for eddy current coupling and too short for flux flow. It is now thought that the effect is caused by BICCs. At first sight, this idea is surprising because fields due the BICCs oscillate ± and the errors have a unidirectional component. As explained in [7] however, it is possible that magnetization currents within the filaments provide a sort of rectification. To a first order, changes in local field or current can only reduce the magnetization or leave it constant. Thus a ± oscillation leaves a net reduction in magnetization.

D. Stability

In the early days, it was hoped that the fine subdivision needed for low magnetization would eliminate flux jumping and hence training. The first hope was indeed fulfilled, but not the second. Training still occurs in accelerator magnets and is probably caused by motion within the winding. Much has been done to reduce the problem by careful mechanical engineering, but some training remains. It may therefore be useful to look at the problem from a different viewpoint - the response of a cable to a given energy input - generally called stability. An early indication that this might be important was given by the Tevatron dipoles, which recorded much better training behavior than their Europe counterparts, although all magnets were made with Rutherford cable and the mechanical support structure of the European magnets was at least as good as the Tevatron magnets. The difference seems to be that the European magnets were impregnated with epoxy resin whereas Tevatron magnets were porous to liquid helium. Although the steady state heat transfer to liquid helium is far too small for classical Stekly stabilization at the high current densities involved, it seems that transient heat transfer, which is much higher, can provide a significant effect if the liquid is in direct contact with the metal. Results supporting this idea for single wires were presented at an early ASC [8] and results on cables are presented at this conference [9].

III. Large Accelerator Magnets

This section briefly compares the design styles of magnets for the five large accelerators. We consider only dipoles and it should be emphasized that this is by no means the whole story. For example, the LHC will have 1232 main dipoles, and yet the total count of dipoles quadrupoles, sextupoles, decapoles and correctors is 8396. Nevertheless, dipoles are the most important, not only because they fill most of the ring perimeter, but also because they are technically the most challenging Usually the general design style of the dipole sets the style for all the others. Fig. 5 shows a montage of dipole cross sections for each accelerator and Table II presents a few key parameters.

TABLE II: Parameters of Large Accelerator Dipoles

		Tevatron	HERA	SSC	RHIC	LHC
Max field	T	4.4	4.68	6.79	3.46	8.36
Max current	kA	4.4.	5.03	6.5	5.09	11.5
Injection field	T	0.66	0.23	0.68	0.4	0.58
aperture	mm	76	75	50	80	56
length	m	6.1	8.8	15.2	9.4	14.2
operating temperature	K	4.6	4.5	4.35	4.6	1.9
number off		774	422	3972	396	1232

A. Tevatron

The first superconducting accelerator to be built, Tevatron has still the most compact magnets. The iron is at room temperature, which allows a very compact cryostat, but makes the field quality sensitive to location of the (cold) coils within the (warm) iron. Many features of the Tevatron set the style for those to follow, notably the use of precision punching techniques, already proven in producing iron laminations for conventional magnets. Punching was used to produce not only the laminations for the warm iron yokes, but also the force supporting collars: a series of half rings punched from 1.5 mm thick stainless plate, shaped to fit around the outer surface of the coil. Collars of alternating pattern, fitted around the coil, are pressed to a precise dimension using a hydraulic press and then welded together. In this way, it is possible to benefit from the economies of mass production, while retaining the precision of the punching process.

B. HERA

Aluminum alloy collars are used for the HERA magnets, giving a better match to the transverse contraction of the coils. The iron is placed immediately around the collars at low temperature, so that the coils are accurately centered in the iron. Being closer in, the iron contributes more to aperture field but, by the same token, saturation contributes more to the errors. The cold mass is more rigid and so needs fewer supports from room temperature, but the cryostat is bigger and heavier. Electrical connections are easier because the current return buss can be outside the iron, still at low temperature, but not affecting aperture field quality. This arrangement makes protection easier, by enabling a cold diode to be connected across the magnet terminals.

C. SSC.

Similar in many aspects to HERA, the ill fated SSC used cold iron and stainless steel collars, with the iron participating strongly support of the electromagnetic forces. A wider cable, which was graded between inner and outer layers, allowed higher fields to be achieved.

D. RHIC

Perhaps the simplest and most economical design so far, RHIC uses a single layer coil [10]. Despite this simplification, the field quality is at least as good as HERA and better than Tevatron (both 2 layer designs). The iron yoke is used as the force supporting collar, being separated from the coil by a precision molded phenolic spacer. An important first for RHIC was the decision to reduce costs by not cold testing all magnets. After testing the first 33 production dipoles, cold testing was reduced to a 10% sample. Important factors in reaching this decision were thereliable quench performance and good correlation between warm and cold field shapes, as measured in the first 33 magnets. Fig. 4 illustrates this correlation by plotting warm/cold measurements of the quadrupole harmonic term.

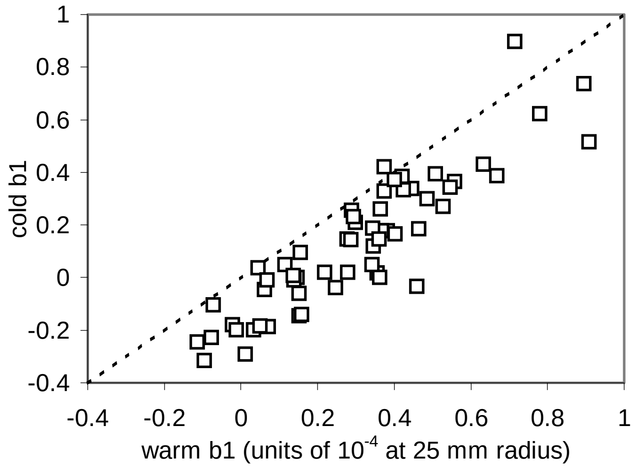


Fig. 4. Correlation between measured quadrupole term in RHIC dipoles at room temperature or cold at full field. The offset is caused by assymetrical location of the cold mass in the steel outer vacuum vessel of the cryostat [10].

E. LHC.

Because it is intended to reach the highest possible energy in an existing tunnel, magnets for LHC must achieve high fields. After an initial assessment of Nb_3Sn, it was decided that NbTi cooled to 1.9K provides a more economical and reliable solution. Cooling NbTi from 4.2K to 1.9K offers an extra 3T at the same current density. To minimize costs and space required in the tunnel, the magnets use an elegant 'two in one' design [11].

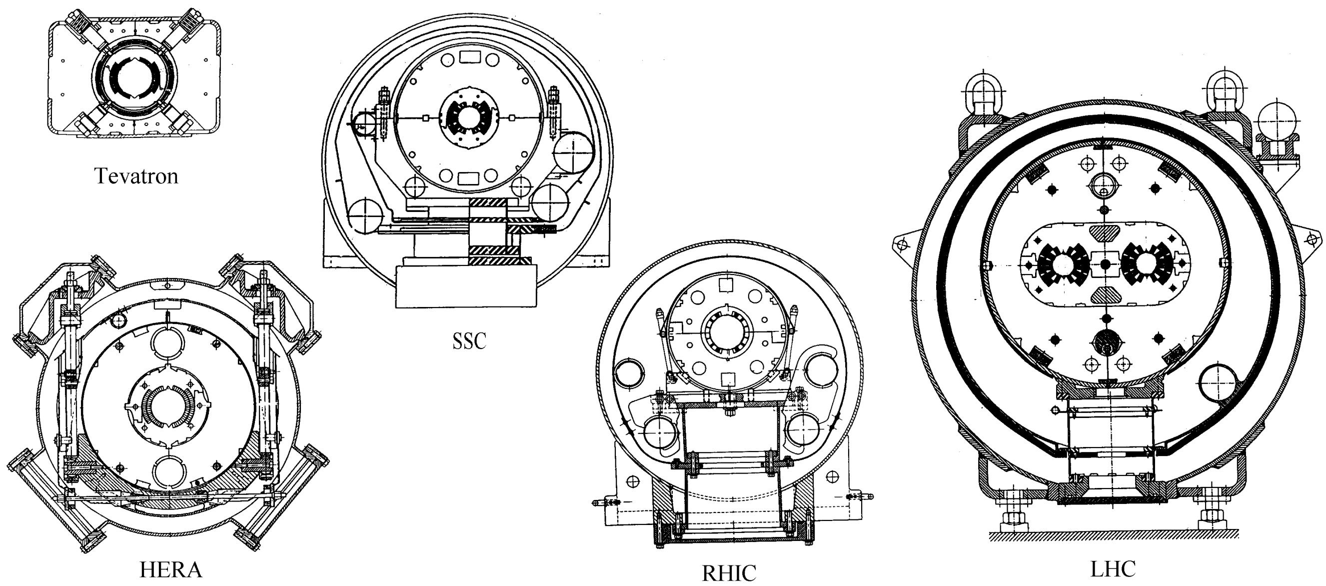


Fig. 5 Montage of dipole cross sections for superconducting high energy accelerators, in each case the beam pipe has been omitted to show the magnetic aperture.

IV. Small Accelerators

A. Microchip Lithography

X-ray lithography, a technique of using soft X-rays to imprint the image of a mask onto a silicon wafer, offers the prospect of putting even more complexity onto a single microchip. Electron storage rings are the only source capable of providing sufficient X-ray intensity for economic production throughputs. Superconducting rings are much more compact than conventional and are therefore preferred in the ultra clean environment of a wafer fabrication facility. Six superconducting rings are currently operating world wide.

In Japan, four superconducting rings are in operation for X-ray lithography. The Aurora ring of Sumitomo Heavy Industries, now at Ritsumeikan University is unique in using a single split solenoid for the bending field, which has the advantage of simplicity and compactness, but means that the rf cavity, injection, diagnostics etc., must be located within the magnet aperture. Other rings use a separated function layout with the accelerator hardware in straight sections between either 2 or 4 bending magnets. Because the bending radius of ~0.5m is so small, these magnets must be curved into a banana shape - a difficult fabrication task. NIJI 3 at Sumitomo Electric Industries uses four dipoles of 90° each with the classical $Cos\theta$ winding section, and no iron. The ring at Mitsubishi Electric Corp and Super ALIS at NTT have racetrack configurations with two 180° dipoles using coils made from rectangular section blocks, both with warm iron yokes.

Fig 5 shows Helios 2 currently being commissioned at Oxford Instruments. Helios 1 has been running routinely at the IBM East Fishkill facility for 5 years, with an up time in excess of 99%. The magnets for both rings use no iron and are made from a miniature Rutherford cable, producing 4.5T at a current of 1000A. A bonus of cryogenic magnets is that the cold bore of the magnet can serve as a cryopump, thereby improving the quality of vacuum, which is in important factor in determining the electron beam lifetime.

Fig 5 Helios 2 being prepared for testing at Oxford Instruments

B Radioisotopes

The use of short lived isotopes in Positron Emission Tomography PET has created a demand for small cyclotrons to produce isotope locally in the hospital. Here again, superconductivity can help by providing a magnet which is lighter and needs less power. The Oxford Instruments 12 MeV cyclotron OSCAR uses a split solenoid magnet with warm iron pole pieces to produce the required cyclotron field shape. Cold iron is used to shield the field, with a novel arrangement of superconducting bucking coils outside the iron, forcing the iron into saturation and thus reducing the weight of iron needed. Oscar is also being used as a transportable neutron source for radiography.

V. The future

A. Muon Colliders

Recently there has been an upsurge of interest in the idea of high energy muon colliders. Like electrons, muons have the advantage over protons that their full collision energy is available in the interaction. Unlike electrons, they do not lose significant energy via synchrotron radiation and may therefore be accelerated in a circular machine. However, muons must be created specially by the decay of pions after which they only live for a short time. For these and many other reasons, construction of a muon collider poses strong scientific and technological challenges. Superconducting magnets will be called on at every stage of the acceleration and storage cycle. With many options still to be assessed, it is too early to talk about a definite design, but Fig 7 shows a schematic of one possible arrangement [11]. At a final muon energy of 2 TeV, the collider perimeter would be ~ 8km.

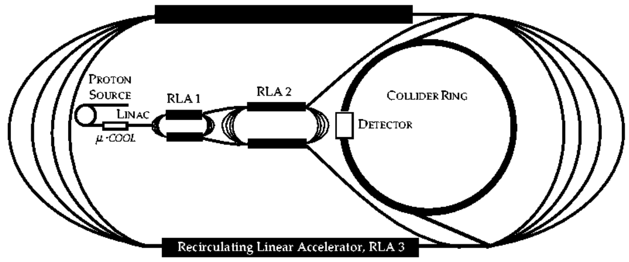


Fig. 7 Schematic arrangement of the Muon Collider

Starting at the left hand side of Fig.7, protons from a fast cycling synchrotron (conventional magnets) impinge on a target to produce pions, which then decay to positive and negative muons $\mu\pm$. Because the pions are emitted over a wide angular spread, they are focused by a 20T solenoid. Given the problem of heating by stray particles, it is proposed to use a hybrid solenoid with water cooled Bitter coil insert (120mm bore dia) and NbTi outsert. Still under the focusing action of a string of solenoids, the muons pass first to a phase rotation linac, where their energy spread is reduced by accelerating the slow muons and decelerating the fast ones, and then to a cooling channel, where their angular and spatial spread is reduced.

Having achieved beams of $\mu+$ and $\mu-$ with good optical properties, they must be accelerated before they decay. Fortunately the muon lifetime is extended by relativistic effects, from 2μs at rest to 44ms at 2TeV, but a rapid acceleration is nevertheless needed if most of the muons are to reach full energy. Two alternative ideas are proposed for the acceleration: recirculating linacs or rapid cycling synchrotrons. The recirculating linac uses a racetrack configuration of bending magnets to direct the beam repeatedly through the same linac. Different bending fields are needed for each orbit to keep pace with the rising beam energy. One possible superconducting dipole design has 16 apertures in the same (cold) block of iron, with the field increasing from 0.4T in the first aperture to 7T in the last. The rapid cycling synchrotron could involve dc superconducting dipoles, interspersed with pulsed (±) normal magnets. A novel alternative would be to replace the pulsed magnets with rotating permanent magnet dipoles.

When they reach final energy the μ^+ and μ^- are stacked in a collider ring. To ensure the maximum number of collisions before decay, this ring should have the shortest possible perimeter, ie. the largest possible bending field. Following LHC, 8.5T seems quite feasible, but unfortunately there is a complication that the muon decay products cause heating in the winding. Thus the windings must either be shielded by ~65mm of tungsten, giving a large magnet aperture of 160mm, or alternatively, the windings must be designed with no windings on the mid plane. Clearly there is great scope for innovation here.

B. Pipetron.

Moving in somewhat different direction, and recognizing that the feasibility of new accelerators is at least as dependent on financial as it is on technical considerations, proponents of the pipetron [12] seeks to minimize costs by technical innovation. The goal is a factor 10 reduction in the magnet cost per TeV and starts from idea of 'an accelerator in a sewer pipe', first raised by RR Wilson in 1982. If tunnel costs can be got down to a low level by horizontal drilling techniques, then the cost optimum will shift to larger perimeters and lower field magnets. Superferric magnets have the potential to be rather cheap because they are simple, they use less superconductor and the field quality is determined by iron (not coil) shape. By suitable design of the iron, one may keep the peak field on the superconductor to less than half the aperture field, say 1T for a 2T aperture field. High temperature superconductors already have sufficient current capacity at this field to permit 78K operation. Fig 8 shows the 'double C' magnet design in which apertures for the two contra rotating particle beams are driven by a single transmission line conductor, running at liquid nitrogen temperature and carrying 60kA.

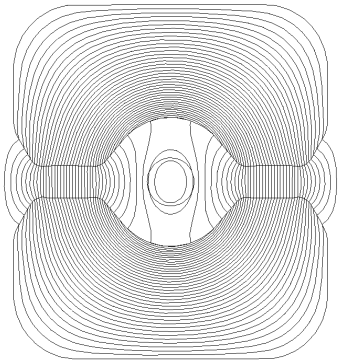


Fig 8. Double C magnet for the Pipetron .

VI CONCLUDING REMARKS.

Continuing development over 30 years has brought the technology of superconducting accelerator magnets to a high level of perfection. Demands for even higher performance will be made in new machines now under consideration, but perhaps the most important technical challenge is going to be cost reduction by innovation

ACKNOWLEDGEMENTS

I am grateful to CERN for a stimulating 2 year Associateship and to colleagues at CERN for advice on this paper, also to A.Greene, G.W.Foster, J.C.Gallardo, T. Hosokawa M. Kruip, E. Malamud, T. Nakanishi, R.Palmer, P.Schmuser, H.Takada, J.Tompkins, M.C. Townsend and P.Wanderer, for help in supplying information.

REFERENCES

[1] P. F. Smith and J. D. Lewin, "Superconducting proton synchrotrons," *Nucl Inst & Meth* Vol 52 pp298 (1967).

[2] M.N.Wilson et al "AC3 - a prototype superconducting synchrotron magnet," proc 1972 Applied Superconductivity Conference pp277.

[3] J.D.Adam et al "Rutherford cables with anisotropic transverse resistance," paper LT-8 at this conference.

[4] H.Bruck et al "Observation of a periodic pattern in the persistent current fields of the superconducting HERA magnets," proc Particle Accelerator Conference San Francisco, IEEE 91CH 3038-7, pp2149

[5] A.P. Verweij, M.P.Oomen,, H.H..J. Ten Kate, "Boundary-induced coupling currents in a 1 m Rutherford-type cable due to a locally applied field change," paper LDA-5.at this conference.

[6] J.Tompkins, C.Haddock, G.Snitchler. "Ramp rate issues in HEB magnets," Chap. 31 in SSC Report SSCL-SR-1235 (1994).

[7] L. Bottura, L. Walckiers, R. Wolf, "Field Errors Decay and 'Snap-Back' in LHC Model Dipoles," paper LKB-10. at this conference.

[8] D.E.Baynham, V.W.Edwards, M.N.Wilson, "Transient stability of high current density s/c wires," IEEE Trans MAG-17 No1, pp733

[9] A.K.Ghosh, W.B.Sampson,, M.N.Wilson, "Minimum quench energies of Rutherford cables and single wires," paper LT-7 at this conference.

[10] P.Wanderer et al, "Construction and testing of arc dipoles for RHIC," paper at the 1995 Particle Accelerator Conference, Dallas.

[11] N.Siegel, "Status of the large hadron collider," paper LC-3 at this conference

[12] R.Palmer et al, "μ+μ- Collider feasibility study," Brookhaven National Laboratory Report BNL-52503

[13] G.W. Foster E. Malamud "Low cost hadron colliders at Fermilab" Fermilab Report TM-1976 (1996)