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Accelerator Magnet Designs Using Superconducting Magnetic Shields

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Abstract

Typical superconducting dipoles and quadrupoles for accelerator use have a coil surrounded by an iron shield. The shield limits the fringe field of the magnet while having minimal effect on the field shape and providing a small enhancement of the field strength. The potential availability of new materials, including high temperature superconducting materials, prompts us to consider creation of shields which utilize superconductor. Boundary conditions for these materials, material properties, mechanical force considerations, cryostat considerations and some possible geometrical configurations will be described. Some possibilities for initial tests will be considered.

1 Magnetic Boundaries:

General considerations for design of a magnet must begin with consideration of electromagnetic boundary conditions. Boundary conditions for infinitely permeable iron demand that the magnetic field component parallel to the surface is zero while the component perpendicular to the surface is continuous. In two dimensions, some simple but instructive situations can be explored by the method of images in which one discovers ways to create a magnetic field outside of the magnetic materials which matches the boundary conditions by replacing the iron with a suitable array of currents. The simple case of a plane iron surface and a single current carrying wire which is parallel to it can be solved by a parallel wire at the position which would be occupied by the (optical) image of the wire if the iron surface were replaced by a mirror (the image wire is on the other side of the plane surface and at the same distance as the original wire.) Similar considerations allow the solution of the case of a wire inside a cylindrical iron boundary.

A conjugate solution exists when the iron boundary is replaced by a superconducting boundary (perfect diamagnetism). In the perfect shielding case, the boundary conditions are conjugate to the iron case. The perpendicular component of magnetic field must be zero but the parallel component is shielded by the surface current. The image current solution for a wire parallel to a plane of superconductor is again a wire in the position of the optical image, but this time of opposite direction. This wire, rather than being attracted to its image, it repelled from the image.

We illustrate these in Fig 1 in which we illustrate the magnetic field of a pair of wires separated by a distance 2d. In the upper figure we show the field when the currents are in the same direction and in the lower figure, when the currents are equal but opposite. These illustrate the fields for a variety of circular hole configurations in which the centers are on the line connecting the wires. The circular hole will have radius a, the (real) wire will be at radius r and the image wire will be at radius R where $R - r = 2d$ and $Rr = a^2$.

2 Multipoles with Cylindrical Shields:

The magnetic field produced by a multipole coil within a cylindrical iron shield is subject to analysis by image methods. The fields and resulting forces are analyzed by Halback [1]. The resulting formulas will apply to the case with a diamagnetic shield by an appropriate change of sign. For dipoles, we find that the field is given by

$$B = B_o(1 \pm (\frac{a}{R})^2) \tag{1}$$

where the plus sign applies for a perfect ferromagnetic shield.

When a superconducting coil is surrounded by an iron shell there is a well known de-centering force between the coil and the shell. This is of considerable significance in design of cryostat systems since the allowance for an imperfect alignment requires the cryostat to withstand the forces generated. If the iron shield is to be held at a different temperature than the coil, the ability to reduce the conduction between the two parts will be limited by the requirement to support de-centering forces. Since the image current is in the reverse direction for the diamagnetic shield, an off-center

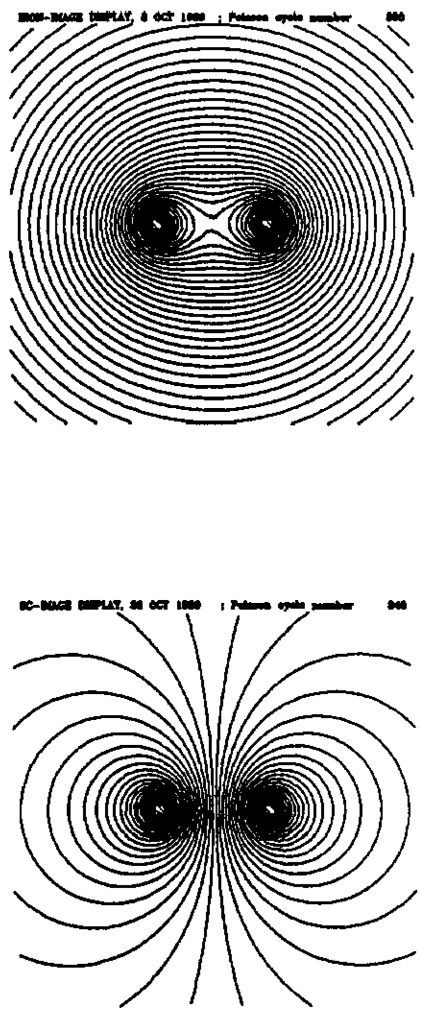


Figure 1: The image of current-carrying wire in a cylindrical hole in Iron (above) and the conjugate image of a hole in superconductor (below).

coil will experience a restoring force rather than a de-centering one. The magnitude of these forces was calculated by Halbach [1] to be

$$f = \frac{1}{2}\pi\mu(N+1)H^2\rho\,\delta z \tag{2}$$

for the case in which iron saturation effects are ignored. This force is large in proportion to the enhancement sought from the iron shield.

3 Some Superconducting Materials

In Table 3 we list some of the materials which might be considered for magnetic shielding applications. We note that successful magnets have been constructed with $NbTi$ but that the cost of this material is fairly high so its use would be restricted to applications in which this design provides some essential new feature. Pure Niobium has the advantages associated with Type I superconductors: no flux penetration at all. This has been utilized in shielding tubes in the past but is limited to relatively low fields even at helium temperatures. Nb_3Sn has been difficult to use in magnets but as a shield, its mechanical limitations may be more easily overcome. In addition, it may be possible to use it at a temperature near 10 degrees which could be suitable for the thermal shield layer in a low temperature cryostat. The possibilities for utilizing the new high temperature superconductors is more speculative but more exciting. It seems clear, for materials currently under development, that their magnetic shielding properties at nitrogen temperatures are not interesting. However, it is quite possible that interesting shielding properties could be obtained at temperatures of 20 to 30 degrees where intermediate temperature thermal shields are very favorably designed into existing large magnets [2]. As developments continue for high temperature superconductors, other alternatives may be developed.

The current required to shield a given magnetic field can be calculated by assuming that a current density J_c is carried within a thickness w near the surface of a superconductor at which the magnetic field parallel to the surface is B. Utilizing the usual Ampere's Law integral we find

$$w = \frac{B}{\mu_0 J_c} \tag{3}$$

For $NbTi$ and Nb_3Sn we will take a value of $2000A/mm^2(2x10^9A/m^2)$ while for the high temperature materials we will assume $100A/mm^2(10^8A/m^2)$.

Table 1: Some Superconducting Materials

Material	Temperature	Useful Field
Niobium	$4K$	0.2 T
$NbTi$	$4K$	5 T
Nb_3Sn	$10K$	5 T
High Temp SC	$20-70K$	0.2 T

Thus a shield using Nb_3Sn for 3 T would require 1.2 mm of material while it would require 1.6 mm of High Temperature material for shielding 0.2 T. Since the current carrying capacity of superconductor improves when it is shielded, the outer portion of the shield layer may be more effective, making this estimate conservative.

4 Magnet Configurations and Fields

Since accelerator magnets have uniform cross sections along the beam orbit, they are well represented with two dimensional calculations. For a multipole magnet of symmetry 2N (N=1 is a dipole) we know that as we move outward away from the coil the field is completely dominated by the lowest order harmonic component. In designing a shield, we will be satisfied with such single term expansions (The problem is to select a useful effective radius.) The peak field at radius R is given by the formula

$$B = B_o(\frac{a}{R})^{N+1} \tag{4}$$

where B_o is not very different than the field at the effective radius a. In Table 4 we illustrate a few interesting cases.

With these numbers in mind, we suggest three applications in which a superconducting shield may offer important advantages over an iron shield.

1. For very high field accelerator dipoles, the enhancement due to an iron shield will be a relatively smaller effect than for magnets which provide 4-6 Tesla fields (see section on dipoles). It is likely that this application will require special cryostat considerations. Being flexible in avoiding

Table 2: Some Fields and Radii in the Effective Radius Approximation

B coil	a	R(2 T)	R(0.2 T)
Dipoles			
6 T	4 cm	7 cm	22 cm
8 T	4 cm	8 cm	25 cm
13 T	4 cm	10 cm	32 cm
Quads			
6 T	4 cm	5.7 cm	12.4 cm
8 T	4 cm	6.3 cm	13.7 cm
13 T	4 cm	7.5 cm	16.1 cm

the weight of a cold iron design and possible iron saturation problems may make this attractive.

2. For quadrupoles in a p-p colliding beam collision region, as the transverse separation between orbits decreases we must choose between quadrupoles which are nearby but independent and a shared quadrupole (large aperture). The iron required for shielding a quadrupole pair which produces 2 T at the iron surface is likely to have a thickness of several cm whereas we have suggested above that a few mm of Nb_3Sn might provide the same shielding. Thus, one may have quadrupoles with equal strength and aperture but smaller orbit to orbit separation using superconducting shields. For quadrupoles, one cannot achieve a substantial field enhancement with iron (or decrement with superconductor) because the field naturally falls with radius more quickly than for dipoles.

3. If a colliding detector is to be based upon a dipole field, one will need a compensating dipole within the straight section to cancel the dipole bending of the detector. Typical large aperture experiments will wish to exploit all of the available angular regions to look for particles. We illustrate this with Fig 2. The angular region ϕ blocked by the com-

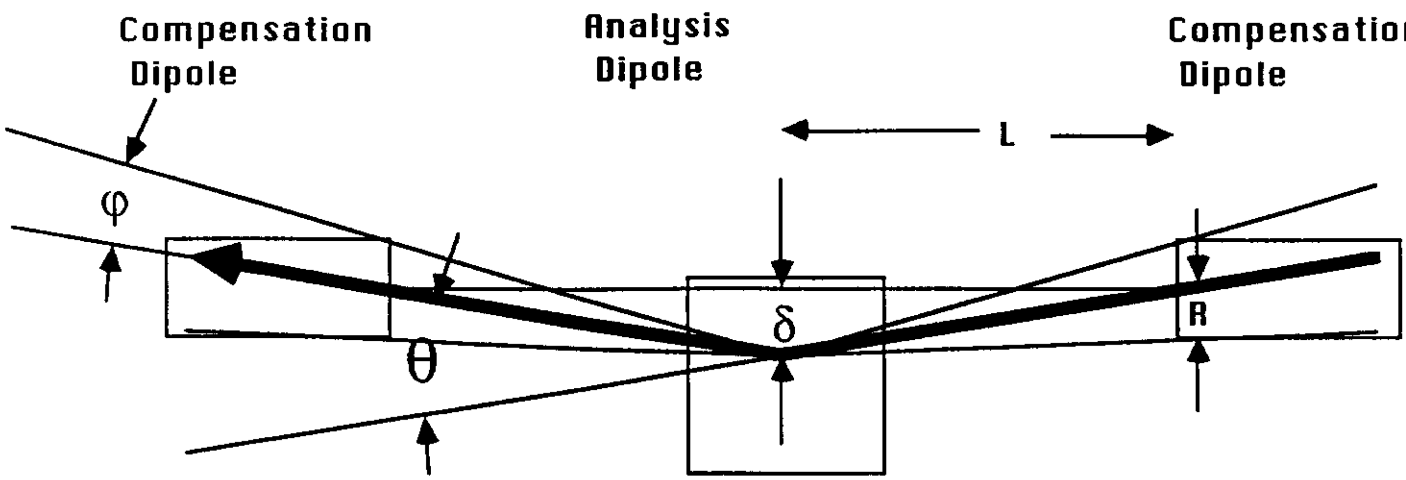
pensating dipoles is determined by their overall radius R and distance from the interaction point L giving $\phi = R/L$. Assuming that the analysis dipole must operate at fields from zero to its maximum, the beam pipe must be clear for a radial distance δ determined by the distance L and the bend strength $\int Bdl$ of the analysis magnet. Maintaining a small δ allows the experiment to examine particle decays very close to the interaction point. Reducing the overall radius R of the compensating dipoles will allow one to reduce the required beam pipe size in the detector. The cost of providing a superconducting shield at $4K$ may be a very desireable trade-off in this situation.

5 Effects of Shields on the Maximum Field in Superconducting Dipole Magnets

As discussed above, at a given current, a superconducting magnet design will realize an enhanced field at a fixed current by adding an iron shield. At the maximum current for which the iron is unsaturated, it will add about a Tesla to the central field of a dipole. A perfect superconducting shield of the same radius will result in a similar decrement to the field. However, ignoring the costs of power supply changes (small), the proper comparison of such designs is at the point for each design for which the coil reaches its current carrying limits. A suitable way to explore this is shown in Fig 3 in which we show the body field (solid diagonals) and maximum field at the coil (dashed diagonals) for three magnet options. Each has a coil with inner radius of 3.5 cm. When required, the shield has an inner radius of 9.624 cm. The three cases include an iron shield (assumed unsaturated), no shield, and a superconducting shield. The superconducting cable properties at either $1.8K$ or $4.35K$ are shown by the characteristic lines which cross the magnet load lines. These are calculated with a program based on the model of Green[3]. The coil and shield designs are from a high field dipole design[4]. Some numerical results corresponding to Fig 3 are shown in Table 3.

These results are obtained from an analytic calculation of the fields, assuming unsaturated iron (thus the straight load lines). The magnetic field enhancement from the iron *at constant current* is the large factor expected (in fact, very large, since the shield radius is small enough that even at the $4.35K$ operation, the iron shield will be saturated. The extrapolated enhancement for $1.8K$ operation is very optimistic). However, the calculated

Collider Detector with Dipole Analysis Magnet



θ	Bend Angle
φ	Minimum Detector Angle
δ	Beam Offset (with analysis dipole off)
L	Detector Open Length
R	Compensation Dipole Vacuum Can Radius

$$\delta = \theta \, L = (\theta / \varphi) \, R$$

Figure 2: Compensation Dipoles for a Collider Detecter with Dipole Analysis Magnet illustrating the advantages of small overall magnet radius achieved with a Superconducting Shield

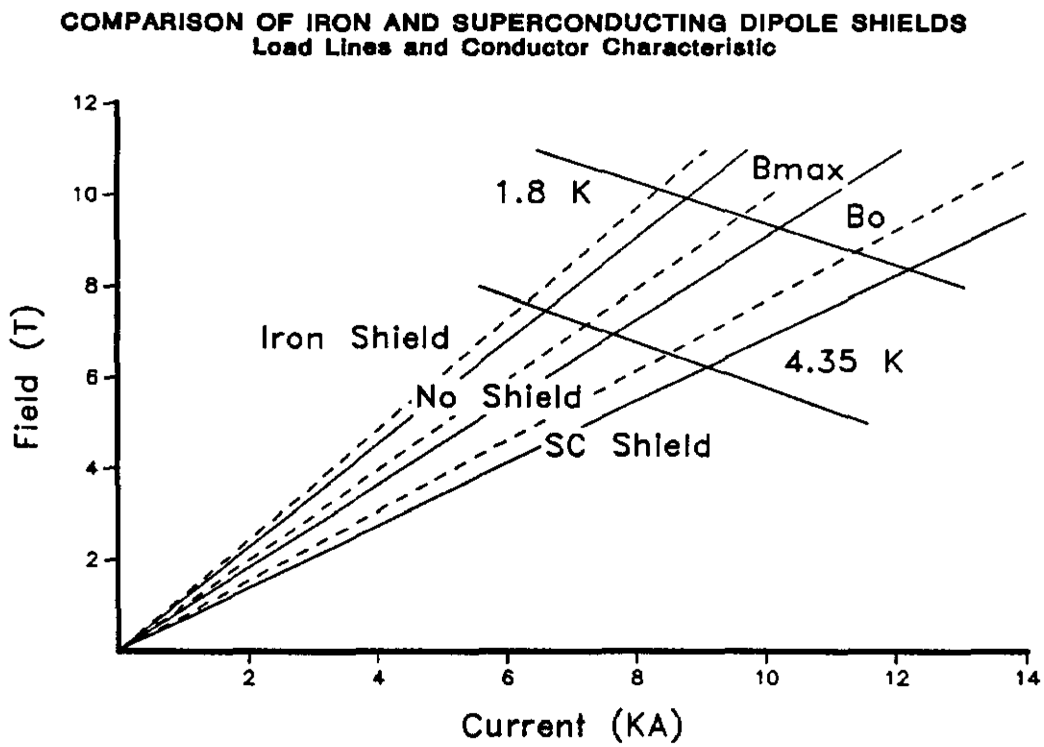


Figure 3: Operating Limits for Superconducting Coils. Magnet Body Field Load Lines (solid) and Load Lines for Coil High Field Points (dashed lines) and $NbTi$ Superconductor Characteristics at $4.35K$ and $1.8K$ are shown for three coil/shield combinations

Table 3: Comparison of Iron and Superconducting Shields for Dipoles

	Iron Shield	Lo Field Shield	SC Shield (Hi Field)
Shield Radius	9.6 cm	large	9.6 cm
Cable limit in Coil (4.35K)	6.30 KA	7.23 KA	8.50 KA
Resulting Field at Coil	7.64 T	7.18 T	6.54 T
Corresponding Body Field	7.13 T	6.58 T	5.84 T
Relative Field Strengths	1	0.926 T	0.826
Cable limit in Coil (1.8K)	8.36 KA	9.63 KA	11.39 KA
Resulting Field at Coil	10.14 T	9.56 T	8.76 T
Corresponding Body Field	9.46 T	8.76 T	7.82 T
Relative Field Strengths	1	0.922	0.818
Relative Strength (Constant I)	1	0.818	0.634

enhancement when taking into account the conductor properties, is only about 8% when compared to a shield at large radius and only 18% when compared to a high field shield (only required when seeking minimum radial aperture). A superconducting shield at a radius corresponding to the outside iron radius will have a load line with slope slightly shallower than the "no shield" case shown. A calculation which accounts for the saturated iron will show somewhat less enhancement at 4.35K and much less enhancement at 1.8K. We note that the superconducting shields will not result in any change in field shape (harmonic content) due to saturation, unlike saturated iron shields.

In Fig 4 we illustrate the sort of geometrical differences which a superconducting shield permits for design of an accelerator dipole. The dipole with iron shield which is illustrated is typical of the SSC generation of low heat leak, cold iron superconducting dipoles. Using a high field shield permits a very compact design. Superconducting shells which shield 1 or 2T could be used in a design with this geometry. Such a geometry would provide adequate space for the coil package to be cooled to 2K with the shell held between 4K and 10K if that was desired for a very low temperature design.

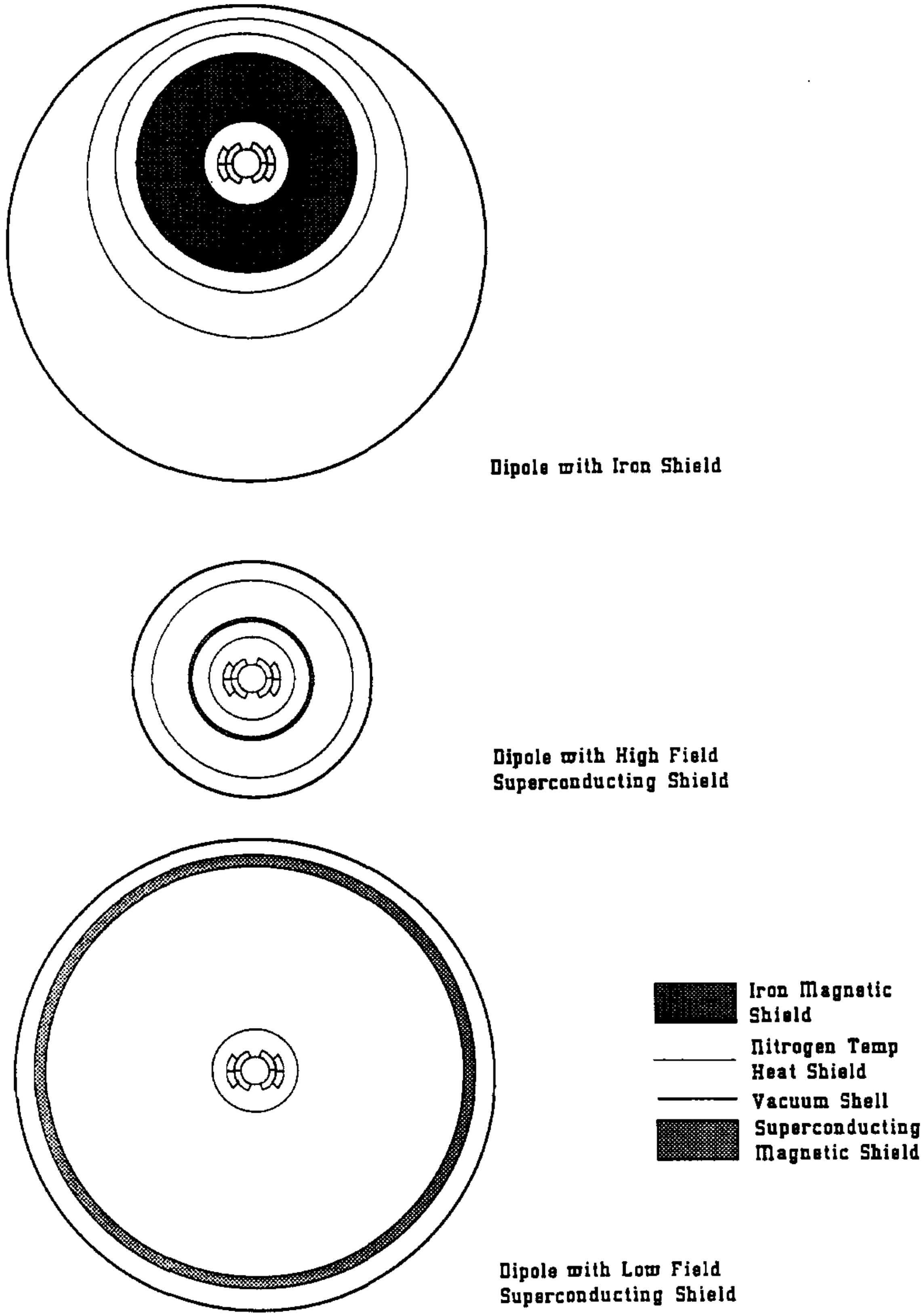


Figure 4: Comparison of Cross Sections for Dipoles with Iron shields and with high or low field Superconducting Shields. The coils shown have 4 cm diameter and the larger vacuum shells have a 61 cm diameter.

The low field design illustrates the use of $0.2T$ superconducting shells. It is nearly as large is the designs with Iron shields, but the weight and magnetic properties will have the differences outlined above.

6 Cryostat Issues

The cryostat designs which have been recently developed provide support to the magnet thru a series of support posts which penetrate the thermal shields in order to provide the support required for the massive iron shield. The current design of cryostats is dominated by the requirement that the weight of cold iron be stably supported in the cryostat. The proposed superconducting shield will have to be supported and will in turn have to support the coil assembly without allowing large holes thru which field would penetrate. Since the weight involved will be 4 to 10 times less than in comparable cases with iron shields, the cryostat can be re-optimized to utilize this as an advantage. The design shown for a low field shield allows a large radial distance, such that the cryostat design can be completely different than the folded posts which are needed to support the large iron mass. It may be possible to take advantage of the lower weights and large radial space to create designs in which the heat path can include long longitudinal distances as well as long radial ones. The much smaller mass of cold (helium temperature) materials may prove to be an very important operational advantage of this design option.

7 Issues about Superconductor Properties

Several issues which might be of concern need to be addressed for this system and should be examined in any proposed test. First, it is understood that, unlike Type I materials, Type II superconductors can allow flux penetration. This design presumes that one can avoid serious flux leakage by a suitable choice of materials and a sufficiently conservative shield thickness. Beyond this quasi-static description, one also experiences flux creep phenomena in Type II superconductors. These effects have proved to be significant in accelerator dipoles[5][6]. We note that for this shielding case, we have sought to reduce the significance of the shield on the useful field of the magnet. Thus any effect of flux creep in the shield will have a correspondingly reduced importance. Furthermore, the flux creep effects on the dominant field are not important (not yet observed) whereas the effects of flux creep on field distortions (sextupole and decapole errors) have been significant. For a large radius shield, any field shape effects of flux creep will be very small, indeed.

A concern which must be addressed in designing a superconducting shield is the flux jump instability. This phenomena can occur when the volume of superconductor thru which flux can move is large enough that the heat caused by flux motion cannot be removed sufficiently quickly by the combination of cryogen and metalic conduction. For $NbTi$ one is required to have small filaments (about $40\mu m$ diameter). This consideration will likely demand that the shield be construction with a series of layers whose thickness is prescribed by the heat conduction and capacity of the superconductor and the host metal in which it is embedded.

8 Suggested Test of Superconducting Shields

Before embarking on a program to construct magnets which incorporate high temperature superconducting shields, it seems appropriate to consider a test configuration in which the essentials of the problem can be addressed. At least one vendor has been located who might be interested in (and able to) fabricate a several cm diameter tube of high temperature superconducting material. If we install such a tube in a suitable hollow (variable temperature) cryostat, we can create a coil inside which will provide an external dipole field suitable for tests.

9 Conclusions

The possibility of a superconducting shield for accelerator dipole and quadrupole magnets has been explored. We find that the de-centering instability associated with iron shields is avoided by the strong diamagnetic shield. In addition, the shield can be much thinner, occupying less radial space in the cryostat. We recognize that by avoiding the weight and decentering forces of the iron shield, we can re-optimize the cryostat design and substantially reduce the mass which must be cooled to helium temperatures.

Promising applications in which these advantages are important have been identified:

1. p-p Collider Interaction Region Quadrupoles
2. Corrector Dipoles for Collider Detectors
3. High Field Accelerator Dipoles

Perhaps this will prove to be a practical use for the new high temperature superconductors.

10 Acknowledgements

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