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THE IRONLESS COSθ MAGNET OPTION FOR THE SSC

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Abstract

The Fermilab design of a 5 T, 5 cm aperture superconducting dipole is described, that attempts to integrate essential cryogenic details with a low cold mass, low heat leak magnet containing a coil surrounded by aluminum collars. Operating characteristics of coils made with aluminum collars are presented along with harmonic data obtained from 1 meter long 5 cm aperture collared coils. A summary of results obtained from cold tests of a 7.6 cm aperture, 6 m long aluminum collared coil in an iron vacuum vessel cryostat are reviewed. Results from the measurement of heat leak to 4.5K, 10K, and 80K are discussed for a 12 m prototype cryostat. Calculations are summarized for passively correcting the persistent current sextupole fields.

Introduction

There are a number of important requirements that need to be incorporated in the design of SSC magnets. Fortunately experience with the first large superconducting prototype synchrotron, the Tevatron, provides a good basis for making cost effective and technically wise decisions. Among the most important considerations are those having to do with: field level; magnet style, i.e. one in one or two in one; conductor specifications including filament size, copper to superconductor ratio and cable dimensions; coil cross section including aperture, number of layers of conductor, collar material and thickness; the use of iron for field shaping and increased central field; the magnet cooling scheme including the number of pipes and coolant channels and the use of intermediate temperature shields to intercept thermal radiation; the cryostat and mechanical support of the coil; the quench protection system; etc. The choice of alternatives, of course, must satisfy operational requirements having to do with field quality, cost, reliability, heat leak, quench performance and protection, etc.

Reference Design B, the ironless cosθ dipole differs in three significant ways from the other two options, A and C.[1] Those differences are:

(1) one in one magnets;
(2) minimal iron;
(3) 5 cm aperture.

The rational for these choices is summarized as follows. The one in one magnet style choice, with the consequence of two separate rings, is based on several arguments, none of which by itself is overwhelming, but when taken as a whole seem to be best. With the side by side two in one magnet there is common flux through both apertures. Thus a quench in one aperture causes the other to quench or at least abort. Furthermore there are iron saturation effects that result in sextupole moment b_2 variation of several units from injection to full field, while other multipoles that vanish on average in the one in one case are usually present for two in one magnets. For the over and under, two in one magnets, where the magnet flux in the two apertures is not generally linked, the cryogenic operation may become difficult when one magnet aperture quenches and redirects 10 He to the cold aperture. In any case two in one magnets require iron and a Design B goal was to minimize iron and the consequent cold mass. One motivation for reduced cold mass was the time and/or refrigeration and power required to cool-down and warm-up.

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The 5 cm aperture was selected to significantly reduce the amount of superconductor needed in SSC dipoles compared to that used in Tevatron dipoles. The basic goal is a cost reduction of 50% per unit length from the Tevatron experience. This factor is achieved by making the aperture smaller and the unit magnet length longer (few ends per unit length). Although the choice of a 5 cm aperture is not guaranteed to yield the quality of field that is required, the change from 7.6 to 5.0 cm is significant enough to make later adjustment to a different aperture an understandable task.

Design

A cross-sectional drawing of the Design B dipole is shown in Figure 1. The displayed section is cut through a support location to illustrate the first version of the post support used in constructing the Magnetic Effects Model magnet. The outer iron shell serves as a vacuum vessel and returns magnetic flux and also acts as a shield from leakage flux presented by the second ring.

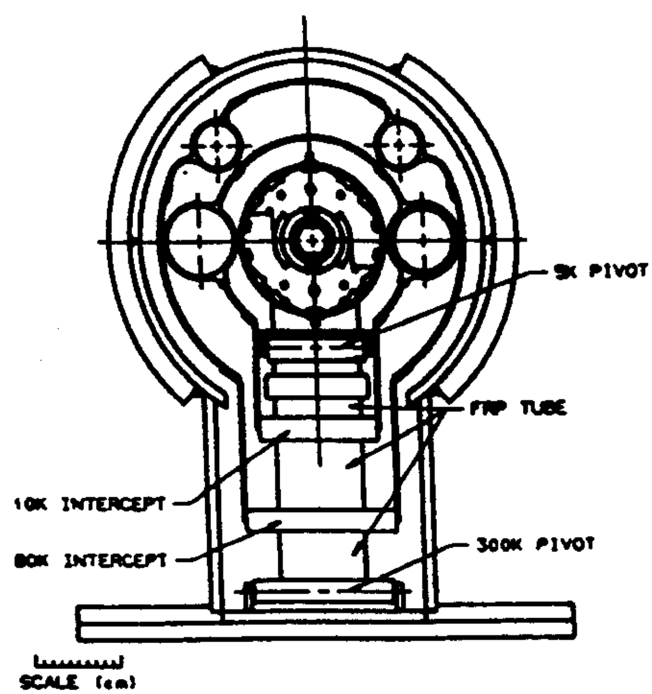

Figure 1 - Design B 5 cm Dipole Cross Section. The single phase assembly containing the aluminum collared coil is shown along with the 10K and 80K heat intercepts, G-10 support post, and external iron vacuum vessel.

There are two intermediate temperature shields, one at 80K N_2 and one at 10K (He gas) each with their corresponding layers of super-insulation. The intermediate 10K shield (a slightly higher temperature may be desired) exists to intercept radiation from the 80K system that would otherwise end up in the 4.5K system, with a consequent saving in overall refrigeration costs. The cost effectiveness of this design is partially justified by the need to return gaseous He to the refrigeration system for reliquefication. One optional pipe is shown that would be used if there were a decision to collide protons and anti-protons in a single magnet ring. This extra pipe would return N_2 if there were only a single ring. Further details that more fully describe the cryogenic system can be found in the Reference Design Report.[1]

The interior assembly that consists of the magnet coils, aluminum collars, and vacuum tight stainless steel skin around the collars is referred to as the single phase assembly. Inside the coil there is a cold beam pipe and there may be correction magnet windings in the single phase He flow channel between the coils and the beam tube.

The parameters that describe the single phase assembly and conductor are given in Table 1. Short sample measurements of the critical current for cables from reels 2674 (inner) and 2669 (outer) at 6T are 8100 A and 7375 A, respectively. The equivalent current densities are 1900 A/mm² at 6 T and about 2400 A/mm² at 5 T. These current densities are somewhat greater than was expected for high homogeneity NbTi superconductor.

Table 1
Reference Design B Parameters

Field(B min, B max)	0.25 T, 5.0 T
Maximum Current	6000 A
Aperture	5 cm
Collars	Aluminum 16.5 cm O.D.
Radial Collar Thickness	4.0 cm
Conductor Strand	0.75 mm diameter
Inner Cable(25 strands)	1.175 mm x 1.50 mm x 9.1 mm
Outer Cable(23 strands)	1.175 mm x 1.50 mm x 8.375 mm
Filament Diameter	17.5 µm
Cu/SC Ratio Inner	2.0 (1.8)
Cu/SC Ratio Outer	3.0 (1.8)

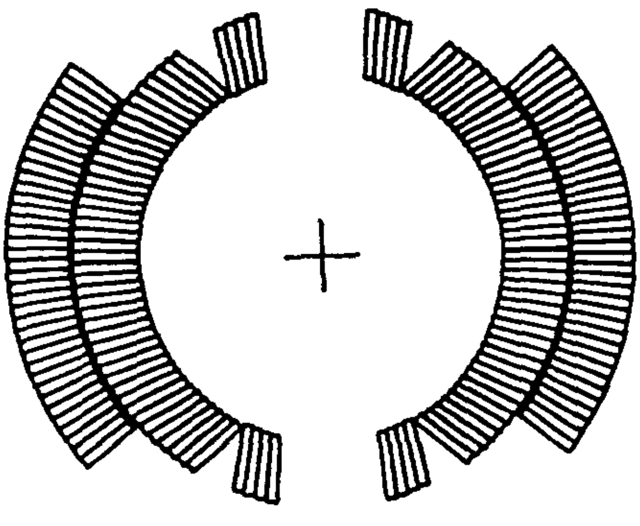

Figure 2 - Reference Design B Coil Configuration. The design employs a single Cu wedge in each quadrant on the inner turn.

Since the Rutherford style cable cannot be keystoned sufficiently to allow the cables to lie on radii of constant azimuth, copper wedges are installed in the winding as shown in Figure 2. This feature allows one to significantly reduce undesirable multipoles in the magnet design.

The aluminum collars surrounding the two layer coil are thick enough to permit the magnet to reach 6 T if further improvements are realized in the manufacture of superconductor. There are two major reasons for using Al collars instead of stainless steel. The use of Al would significantly reduce the magnet cost and the preload required to collar the coils is significantly less with Al since it shrinks more than stainless steel in the transition from room temperature to 4.5K.

To fully test the performance of Al collars, cable was procured with more superconductor than was indicated in the Design Report. This resulted in a Cu/SC ratio of 1.8 instead of the planned values of 2.0 and 3.0. To avoid the cost associated with procuring two different kinds of strand, both the inner and outer cable were fabricated from the same 0.030" diameter wire although the inner strand was pulled through a final die to slightly reduce its diameter.

Design B Prototypes

To judge the field quality and performance of Design B dipoles a number of short collared coil prototypes have been built and tested. The test magnets are 81 cm in overall length. The scope of the R & D effort involves the construction of both 4 and 5 cm aperture magnets so that a comparison can be made of the field quality attainable in Designs B (5 cm) and D (4 cm).

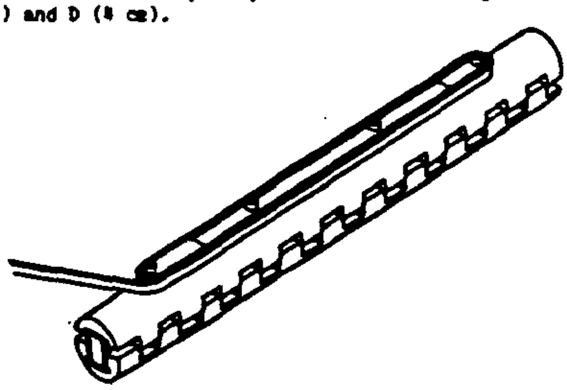

Figure 3 - Winding Mandrel. The split mandrel used to make the dry wound coils is shown.

The coil winding in the Fermilab models does not use epoxy impregnated fiberglass with subsequent heat treatment in a press to produce molded half coils. Instead the kapton insulated cable is wound onto a precisely dimensioned mandrel to form a coil that can then be collared immediately after winding. To facilitate the winding process the mandrel is vertically split open as shown in Figure 3 which allows turns to be inserted on the midplane of the magnet. Collaring is accomplished by placing collar packs over the coil and then simultaneously closing the mandrel and the collars. This results in a coil with conductors held in place solely by the collars without any epoxy. We refer to this type of coil winding as being a dry technique. Design B molded coils made with epoxy coated kapton but without fiberglass are also being constructed. They are known as wet coils.

Since superconducting cable with the Design B dimensions was not immediately available, two short dipoles, SC1001 and SF1001 were built with non-standard conductor and cold tested. They performed adequately although specific changes in the tooling were indicated during the winding. Following the arrival of SSC conductor the winding of SC1001 and SG1002 commenced. Upon completion of SG1001 a turn to turn short was discovered and SG1002 was a failure because the bus turn pulled out of the coil as the winding mandrel was being extracted. With subsequent changes in the ground wrap insulation scheme four magnets have been successfully built. They are designated SG1003, SG1004, SG1006, and SJ1003.

SG1003, SG1004, and SG1006 have been cold tested and SJ1003 is awaiting cold tests. The cold tests include quench performance and measurement of harmonic field content in the body of the magnet. The load line for the high field point is shown in Figure 4 for SG1004 as well as the short sample performance of the cable that was used in the magnet. The magnet reached 6700A on the seventh quench at 4.2K and reached about 7100A at 4.2K after being cooled to 3.2K and quenched. With the expected 15% increase in J_c at 3.2K the high field point load line intercept with the anticipated short sample implies the magnet should reach 7500A. The maximum quench current at 3.2K was 7420A.

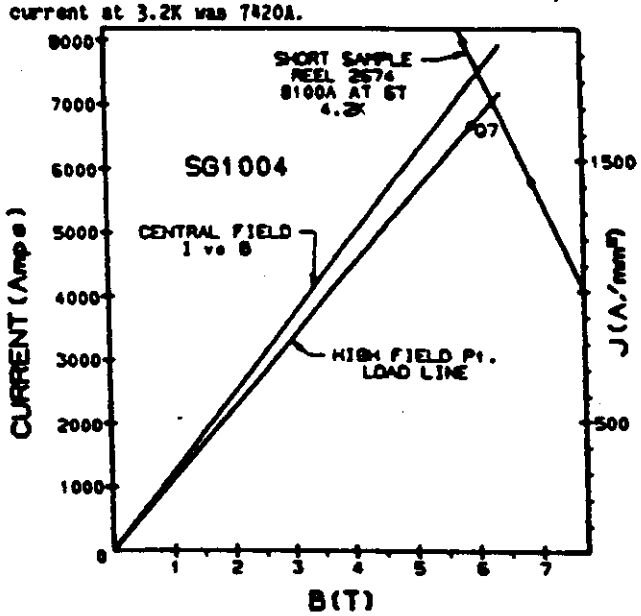

Figure 4 - Load Line, Conductor Short Sample and Magnet Performance for SG1004.

The harmonic content of the dipole's body field is given by the measured normal and skew coefficients in the expansion:

$$B_y + i B_x = B_o \sum_{n=o} c_n z^n \text{ where}$$

$c_n = b_n + i a_n$ and $z = x + iy$. Both warm and cold measurements have been made to determine these coefficients. The cold results are found by rotating a Morgan coil at 6 Hz in the bore of the magnet and measuring the induced voltage at the harmonic frequency of interest. The voltage measurements are performed using either a magnetometer based on a Brookhaven design[3] or a lock-in amplifier. The warm measurements use a Morgan coil and lock-in amplifier, but in this case the induced voltage is generated by powering the magnet with 10A of 11 Hz alternating current. The voltage at a fixed Morgan coil angle is measured and recorded before the measuring coil is rotated to a new fixed angle position. The voltage recorded at 64 fixed positions (5.625° increments) is Fourier analyzed to give the measured harmonic coefficients. A comparison of warm and cold harmonics for Tevatron dipoles and quadrupoles has shown good agreement as does the warm and cold data taken on the SSC prototypes. The warm measurement coefficients for SG1003, SG1004, and SG1006 are given in Table 2 and they are plotted in Figure 5. Also shown in Figure 5 are the predictions for 5cm aperture dipoles based on extrapolations from CBA (13.2 cm) and Tevatron magnets (7.6 cm).[3]

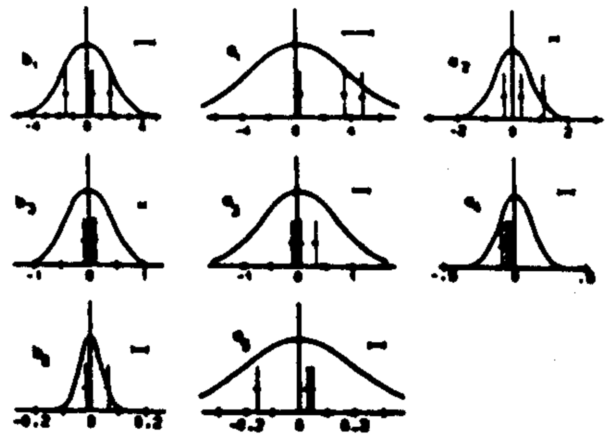

Figure 5 - Skew and Normal Multipoles. The values given in Table 2 are plotted here along with the RMS gaussian width predictions based on extrapolations of Tevatron and CBA dipole data.

Table 2

Multipoles for 5 cm Dry Wound Coils (at 1 cm)

	SG1003		SG1004	SG1006
b_1	1.60	± 1.5	-1.42	0.069
a_1	3.38	± 2.0	0.69	4.78
b_2	43.18	± 0.5	43.44	43.81
a_2	0.37	± 0.15	1.14	-.397
b_3	0.13	± 0.10	-0.12	.115
a_3	-0.11	± 0.30	0.035	.422
b_4	2.29	± 0.20	2.32	2.30
a_4	-0.10	± 0.10	-0.040	-.066
b_5	-0.009	± 0.05	0.062	-.007
a_5	0.046	± 0.05	0.036	-.165
b_6	-0.464	± 0.05	-0.470	-.433
a_6	0.004	± 0.02	-0.019	-.004
b_8	0.042	± 0.05	0.045	.046
a_8	0.0003	± 0.005	0.001	.0002

Variation of the normal sextupole moment b_2 with magnet current is shown in Figure 6. The magnetization currents are responsible for the sextupole moment difference of 20 units between full field and injection. This difference is larger than anticipated in the Reference Design because the filament size is larger and the Cu/SC ratio is smaller than the design calls for. The larger percentage of SC in the outer shell is especially significant since the magnetization sextupole moment is entirely negative for that layer of conductors. Although an explicit calculation has not been done to predict the persistent sextupole field for the conductor used in the magnet, the measurements when scaled by filament size and Cu/SC ratio are within 20% of Reference Design predictions. A specific comparison will be possible when measurements of the cable magnetization are complete.

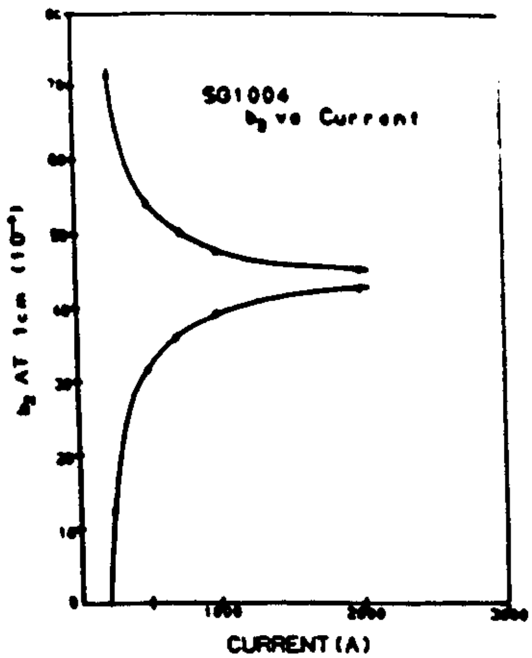

Figure 6 - Sextupole Hysteresis due to Persistent Currents.

Magnetic Effects Model

To test and prove the cryostat and vacuum vessel concepts embodied in the reference design a 6m long model was constructed.[4] The features tested include: single phase assembly and cryostat construction techniques, support posts, off-centering forces, shield heating and deformation during quenching and general warm-up and cool-down procedures.

The magnet was specially equipped with carbon resistors for thermometry and linear variable differential transformers (LVDT) actuated by quartz rods that penetrated the insulating vacuum to measure single phase assembly and shield positions. A cross section showing the locations of three of the LVDTs is given in Figure 7. The LVDT sensitivity was about 1 mil. During cool-down and power tests the LVDT position and temperature were monitored with a Fast ADC system that accumulated data at a 10KHz rate.

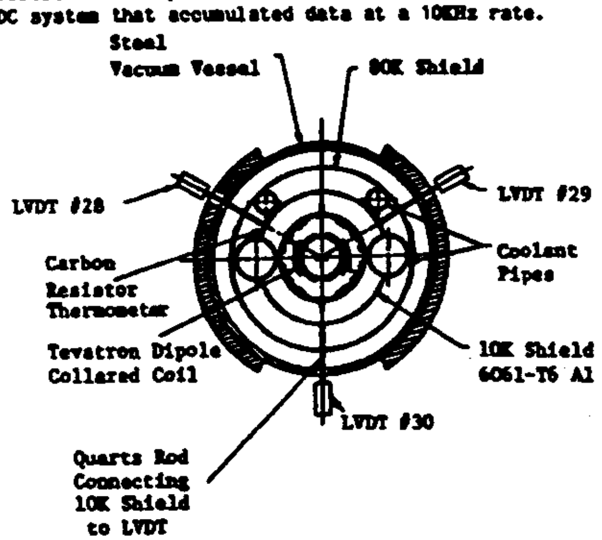

Figure 7 - LVDT Locations Relative to the Single Phase Assembly and Exterior Vacuum Vessel.

Figure 5 shows the response of the bottom LVDT on the 10K shield during a current extraction from the magnet without a quench. While calculations of induced eddy currents and subsequent deformation of the shields are difficult, due to the complicated shape of the shields with their component pipes, the predicted motion is for the shield to stretch vertically while it shrinks horizontally, to return to a circular configuration, and finally to stretch horizontally while shrinking vertically. Time constants are such that the first part of the motion just described is caused by the interaction of the decaying magnet current with the induced eddy currents while the later described motion results from eddy current interactions alone. If the shields are off center relative to the magnet coil the shields also translate slightly thus making the shield motion at a given point fairly complicated. Although there are not enough LVDTs to prove this is happening the data are consistent with such a hypothesis. The real situation is even more complicated since the shields are physically connected to the single phase assembly which moves because of magnetic off-centering forces.

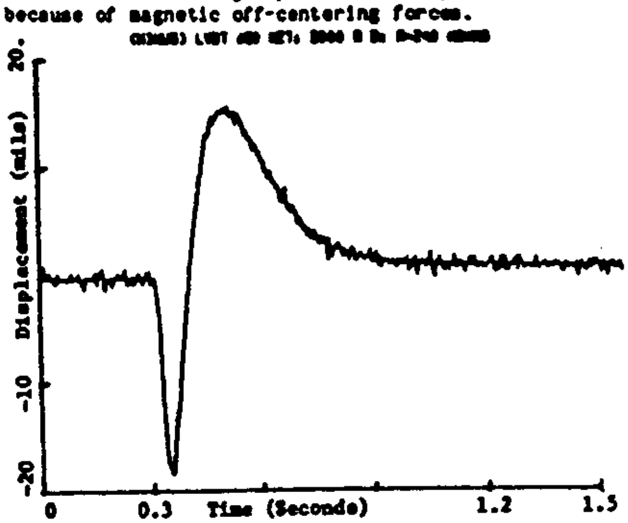

Figure 8 - 10K Shield Response as Measured with the Bottom LVDT. The vertical scale extends over the range ± 20 mils while the horizontal axis represents 1.5 seconds total time.

Analysis of the LVDT data indicates that when quenching occurs the shields flex elastically about 1mm. Since the single phase assembly also moves less than 1mm during ramping and quenching and returns to its original position one concludes there are no particular reasons for concern with Design B relative to off centering, eddy current caused shield deformation, shield heating during quenches, support post failure, etc.

Heat Leak Model

To achieve reasonable operating costs, the SSC magnets must have a small heat leak. The goal is a reduction to about one tenth (one fifth) the Tevatron static heat load at 4.5 (80)K. At this level the heat load due to synchrotron radiation ~1W/m will dominate the refrigeration load. While this goal is substantial, low heat leaks of 40 mW/m(5K) and 600 mW/m(80K) have been achieved in the Tevatron transfer lines compared to the Tevatron magnet system heat loads of 1.5 to 2.0 W/m(5K) and 7.5 W/m(80K), respectively. While it was not possible in the limited time available to specify and design the ultimate cryostat, testing an early prototype, to see if the goals were realistic, seemed to be necessary. Construction of a cryostat also allowed development of assembly procedures, mechanical engineering of support posts, tests of large multilayer insulation (MLI) thermal blankets, measurement of heat leak with variable insulating vacuum pressure, etc.

A 12m long thermal measurement model cryostat was designed and constructed. Since a 12m magnet coil was not available the 5K cold mass was faked by using a thick-walled aluminum cylinder of roughly equivalent size. The 5K and 80K thermal shields and their associated pipes were similar to those employed in the Magnetic Effects Model as were the support posts. Details of the geometry, insulation schemes, and preliminary results are given in the paper by Niemann et al.[4] To compensate for measurement effects due to the end cryogenic connection boxes, the end vessels were first butted together and sealed without the 12m model cryostat to determine the heat leaks of the end boxes alone. The 80K and 4.5K heat leaks of the fully assembled system (including the 12m cryostat and end boxes) were deduced by measuring the liquid N_2 and He boil-off to gas, while the 10K heat leak was determined by measuring the flow and temperature rise of the 10K shield gas stream.

After subtracting the measured heat load of the end vessels for the 80K and 4.5K systems the measured heat leaks at 80, 10, and 4.5K are 33.5W, 2.28W, and 510mW while the predictions are 29.5W, 2.28W and 425mW, respectively. In terms of watts per meter these become roughly 2.5W/m, 1.9W/m, and 35mW/m. While these numbers are ~ 50% larger than the SSC goals they are consistent with calculations based on the design of our test model. It is fully expected that with proper design the SSC heat leak budget will be met although cryostat designers will need to pay special attention to the conduction heat leak of supports and heat sinking of the shields to the supports.

Passive Correctors

It may be possible to avoid placing full length correction coils inside the SSC dipoles if the magnetization induced in strips of superconductor placed between the beam pipe and dipole coils can be used to cancel unwanted persistent current fields.[5]

The results of sample calculations are shown in Figure 9 for the Design D 4 cm aperture magnet. Since the magnetization sextupole moment generated by flux changes in the coil winding is negative, passive superconductor is placed in the regions ± 22.5° about the x and y axes. For the example where the Design D coil winding is made from 6μm filament wire with Cu/SC ratio 1.3 for the inner and 1.8 for the outer, the passive corrector can be about 2.5mm thick if its filaments are 8.7μm in diameter. A packing factor (metal area to total area) of 0.46 is assumed for the passive corrector to give this result as would be the case if insulated strands are used to make the corrections. Figure 9 also shows the normal sextupole field with and without the corrections.

A substantial cost saving may be possible if the passive superconductor can be imbedded in the outside of the beam pipe. Here it is assumed the passive superconductor can be drawn to make strips 3/4 mm thick and 3/4 cm wide with Cu/SC ratio 1.0 and packing factor 1.0. The beam pipe would be extruded with fins that collapse around the superconductor as both are drawn through a die to secure the superconductor.

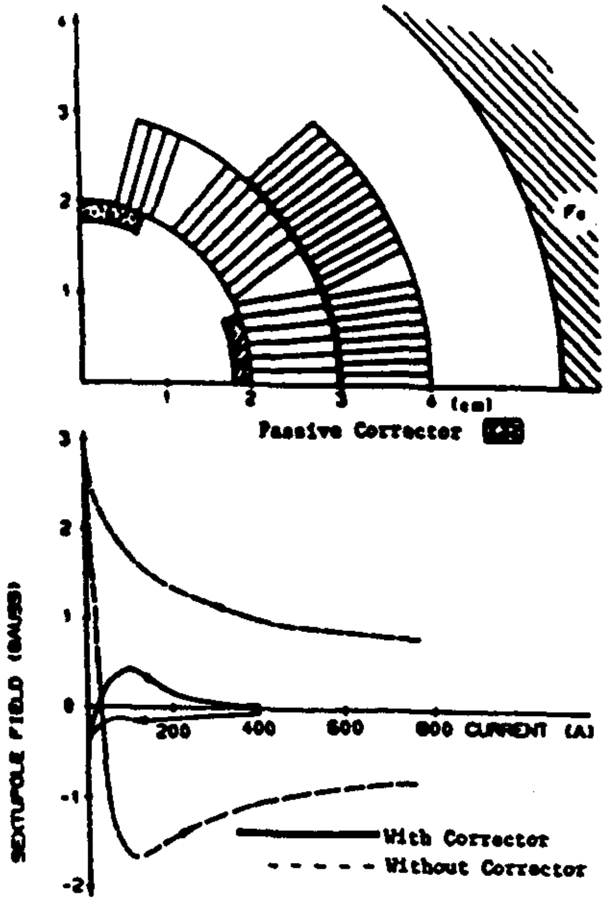

Figure 9 - Passive Correction Scheme & Predicted Sextupole Fields.

A test of the passive correction scheme was performed using a standard Tevatron cross section dipole and a corrector made from 20 mil insulated wire. The results are shown in Figure 10. With the corrector the sextupole field was reduced although not as much as desired. The reasons for the weakness of the corrector are: (1) the packing factor assumed in calculating the amount of corrector wire needed was 0.70 instead of the achieved value of 0.46; (2) the measured bulk magnetization of the corrector wire was about half the value that was measured for the wire the magnet cable was made from.

Further tests will be done with either a 4 or 5 cm prototype dipole.

Conclusions

Work has progressed on both SSC magnets and cryostats. The dry winding technique for making 1 meter long coils seems to work although winding and collaring tooling improvements are still being made. Multipoles from the early 5cm coils are about as expected but more magnet data are needed to confirm this trend. No ill or unexpected effects were encountered in testing a 6m long (7.6 cm ID) aluminum collared coil that was assembled in an external iron vacuum vessel. Off-centering motion of the coil and intermediate temperature shields during magnet ramps and quenching were within the nominal expectation of 1mm. For a 12 meter long cryostat model the measured heat leak to the 80K, 10K, and 4.5K systems was approximately what was anticipated and there is good reason to expect future designs to achieve the heat

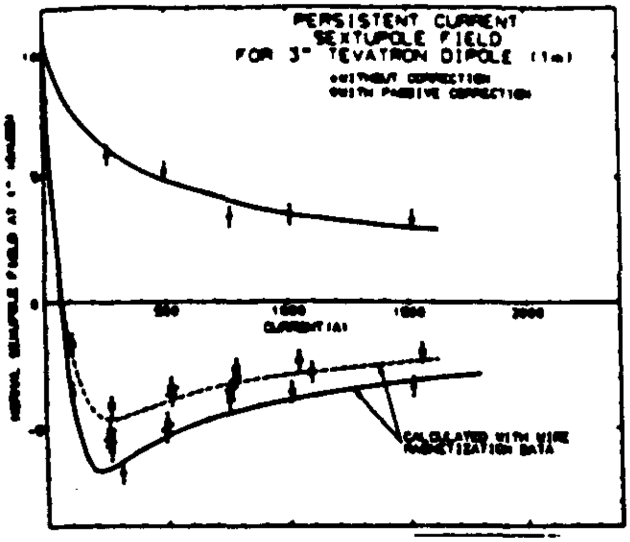

Figure 10 - Test Results for a 7.6 cm Coil with & Without Passive Correction.

leak budget that was suggested in the Reference Design Report. Activities over the next several months will center around construction of short coils of both 4 and 5cm inner diameter and the design of a 17m long cryostat that can accept a 4 or 5cm collared coil surrounded by cold iron.

<u>References</u>

[1] Superconducting Super Collider: Reference Designs Study for U.S. Department of Energy p 331 (May 8, 1984).

[2] C.H. Holbrow, An introduction to the Isabelle Harmonic Coil Magnetometer, Tech. Note 170 (1979) Brookhaven National Laboratory, Upton, New York.

[3] The predictions are the work of an Aperture Task Force subgroup on Magnet Errors; Jack Peterson, SSC Central Design Group, Lawrence Berkeley Laboratory.

[4] R.C. Niemann et al. "Experimental Evaluation of Design Features of a Cryostat for an Iron-less Cos θ SSC Magnet". Paper P28 of these proceedings.

[5] B.C. Brown and H.E. Fisk, "A Technique to Minimize Persistent Current Multipoles in Superconducting Accelerator Magnets". Proceedings of the 1984 Summer Study on the Design and Utilization of the Superconducting Super Collider, R. Donaldson & J.G. Morfin (ed). p 336 (1985).