A SINGLE LAYER COIL SUPERCONDUCTING MAGNET FOR SSC*

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Introduction

The superconducting magnet under consideration for the proposed Superconducting Super Collider[1] (SSC) uses a two layer coil geometry and is optimized for 6.6 T central field. In this paper we assess if it is possible to design a dipole having a realistic single layer coil configuration, using a cable having the same size as that used in the present SSC outer layer coil, can achieve a central field of about 6 T. The affirmative answer assumes a superconductor current density approaching the best achieved thus far in production, close-coupled cold iron with at most a very thin collar, a high but not unreasonable current density in copper at quench, and operation below 4.2 K. The performance under other operating conditions will also be discussed.

We shall first describe the cable used in this design. We shall discuss the optimization procedure of the iron shape, particularly in the aperture region to minimize the effects of iron saturation. We shall outline the design of a realistic single layer coil geometry. Finally we shall discuss various operating parameters from the quench protection point of view.

Cable

The present SSC outer layer utilizes a cable having 30 strands of 0.65 mm diameter. The cable is keystoned to 1.2 degree. The wire has a copper-to-superconductor ratio (CSR) of 1.8:1 and the 6504 A required for 6.6 T in the present 2-layer SSC design implies a current density S in the copper of 1024 A/mm^2 immediately following quench. For the present study, two values of S are used, 1100 A/mm^2 and 1500 A/mm^2. The latter is thought to be safe if active quench protection is used, and the former if passive is used. At a given field and current, S determines the actual copper area present, but the superconductor area and hence CSR vary with the critical current density in standard conditions (4.2 K temperature, 5 Tesla field). The finished cable thickness (including insulation) is 1.317 mm, and width is 10.06 mm. Except where indicated, the actual value of superconductor current density is not given in the figures which follow but rather the performance under standard conditions required to give the stated performance is given.

Elliptical Aperture Design

It has been shown[2] that the effect of iron saturation on the field harmonics can be substantially reduced by modifying a normal circular aperture to a somewhat elliptical shape. The change in sextupole harmonics can be minimized by making a perfectly elliptical aperture, however, the reduction in the change of higher harmonics require the elliptical shape to be further modified. The procedure of obtaining the aperture is summarized as follows. First an elliptical aperture is obtained which gives low shift in harmonics for a coil which has all harmonics zero for a circular aperture. A crude single layer coil geometry with non-integer turns is then designed for the above elliptical aperture which produces zero harmonics for infinite permeability iron. Following this procedure, an aperture and a coil geometry combination is obtained which gives both low harmonics and a low change with field in these values of harmonics. The values of semi-minor and semi-major axes of the ellipse are 35.86 mm and 44.84 mm, respectively. The size of the decapole bump (deformation) in the elliptical aperture shape is 1.53 mm and it was required to reduce the change in decapole harmonic due to iron saturation. No other higher order deformation in the aperture was required. A 5 mm coil-to-iron gap at the midplane is used to allow for a 5 mm thick collar. The strength of this collar will not be sufficient for full coil prestress and the Lorentz forces must be transferred through the iron to an outer stainless steel jacket; a cold iron design must be used for this magnet. The outer radius of the iron is taken to be 116 mm. The outer radius is 133 mm in the case of magnet using a two layer coil geometry.

Coil Design

The coil used in the last section although producing the required harmonics, did not satisfy the other criteria of an actual design. It was accepted there because a real coil design optimization, described in this section, requires too much computer time. The computer programs[3,4] which optimize a coil geometry to produce required harmonics, design the coil for a circular aperture. However, as described in last section, our aperture is not circular. If a coil geometry optimized to produce zero harmonics is used with this (non-circular) aperture, the field calculations will produce non-zero harmonics. Therefore, to cancel these harmonics the coil for circular aperture should be designed to have the harmonics of same magnitude but opposite sign. Several structures have been examined for a total number of turns ranging from 16 to 19. The attempt was to maximize the transfer function with the maximum pole angle remaining close to 70° and with the coil geometry producing the required harmonics. The chosen coil structure is shown in Fig. 1.

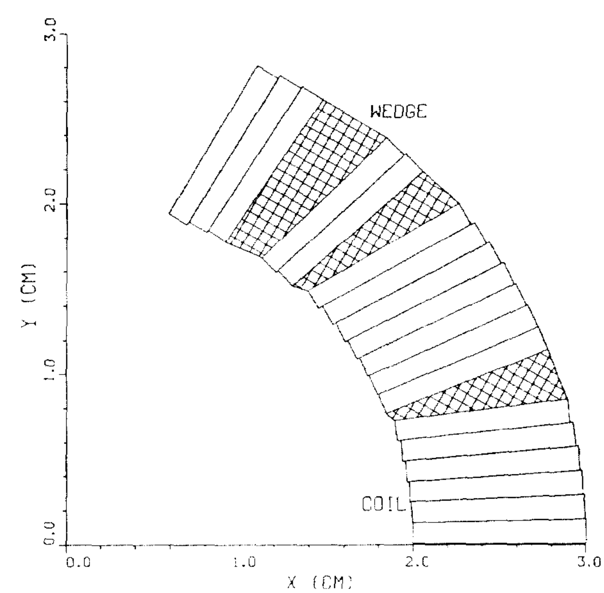

Fig. 1. The optimized coil structure

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It has four blocks with a total of 18 turns in them. The pole angle is 70.4 degrees. The number of turns in each block, the tilt angle by which each block is tilted and the value of wedges between the two consecutive blocks is given in Table I.

Table I

Block No.	Number of Turns	Tilt Angle (degree)	Wedge Angle (degree)
1	6	0.00	
			1.60
2	7	8.65	
			2.47
3	2	10.00	
			6.43
4	3	10.00	

The Magnet

The complete dipole magnet cold mass, based on the aperture and coil geometry discussed in the last two sections, is shown in Fig. 2. This is the model on the code MDP[5] and the picture is obtained from the same code. The performance of this model is summarized in Table II. We observe a very small shift in the harmonics — within 0.01 in all harmonics except in sextupole where it is 0.1 up to a field level of 6.1 Tesla. The stored energy at 6.1 Tesla is 0.7 MJ for a magnet of length 17.35 m.

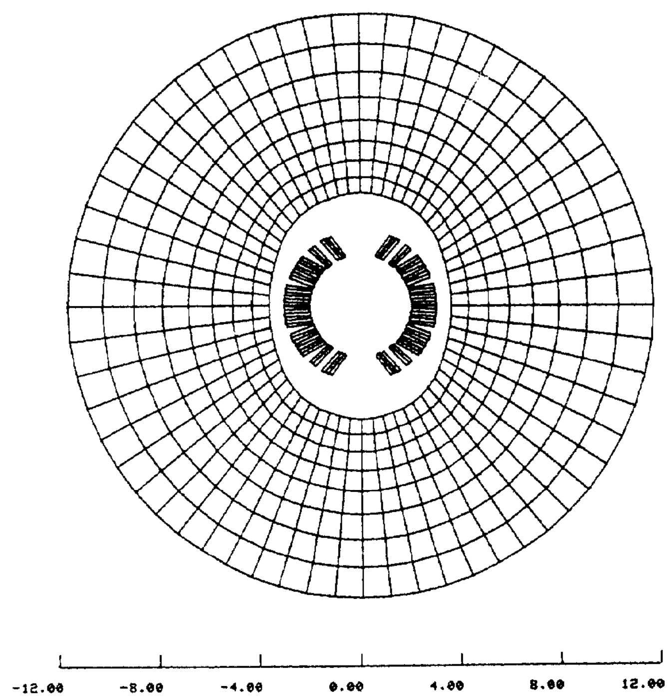

Fig.2 The complete magnet geometry and its model on MDP

Table II

I (Amps)	B (T)	B/I (G/A)	b'_2 10^{-4}	b'_4 10^{-4}	b'_6 10^{-4}	b'_8 10^{-4}
1000	0.614	.6143	-0.27	0.20	0.17	0.24
5000	3.072	.6143	-0.26	0.20	0.17	0.24
7000	4.300	.6143	-0.29	0.20	0.17	0.24
8000	4.912	.6141	-0.31	0.20	0.17	0.24
9000	5.521	.6135	-0.32	0.21	0.17	0.24
10000	6.120	.6120	-0.24	0.19	0.18	0.24
10700	6.524	.6097	-0.49	0.21	0.18	0.24

The harmonics are defined as follows:

$$B = B_0 + B_0 \sum_n b'_n \left(r/r_0\right)^n , \quad (n = 1, 2, 3, \ldots)$$

where B_0 is the field at the center, B at a radius r on the midplane and the harmonics b_n are normalized to a radius r_0. These harmonics have been computed for 1 cm normalization radius.

Quench Limit Parameters

The critical current density depends on the bath temperature and on the peak field in the cable. We plot the first two quantities required to produce specified values of central field with the current density in copper being 1500 A/mm^2 (Fig. 3) and 1100 A/mm^2 (Fig. 4), respectively. From these figures one can obtain the bath temperature required for the available value of critical current density in standard conditions (4.2 K, 5T), at a particular design value of central field. Along with these parameters a particular choice of current density in copper determines the required cross-sectional area of copper and superconductor and the copper to superconductor ratio CSR, in the cable.

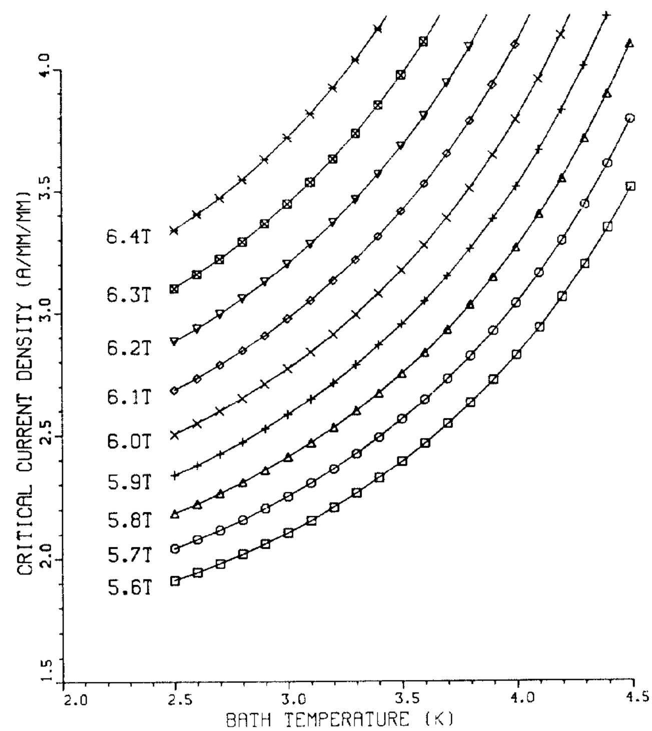

Fig.3. The required specifications for the critical current density, J_c(at 4.2 K and 5 T), and the operating bath temperature to obtain the field indicated on the curve for active quench protection scheme.

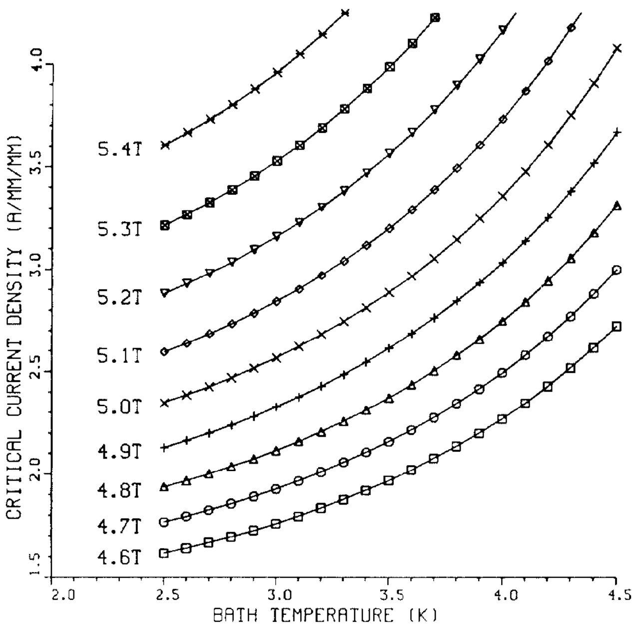

Fig.4. The required specifications for the critical current density, J_c(at 4.2 K and 5 T), and the operating bath temperature to obtain the field indicated on the curve for passive quench protection scheme.

Discussion

In Table III we list a few possible operating points which are of interest due to various reasons. Please also refer to Fig. 3 and Fig. 4 for the following discussion. The maximum field is obtained when the magnet is designed for the best but still realistic conditions. This means we use an active quench protection scheme allowing about 1500 A/mm^2 current density in copper, use the best superconductor cable available in production with J_c (4.2 K, 5 T) = 3200 A/mm^2 and operate at 2.5 K bath temperature. This gives us (column 1) 6.35 T central field with a total current in coil being 10.41 kA. If the same magnet is run at 9.97 kA current it will produce a 6.1 T magnetic field and will have a safety margin of 13.5% at quench; in the past, quench fields have been underestimated by 6%, suggesting that there is an additional safety margin of 12%. If operation at 4.35 K is desirable, the best that can be achieved is 5.6 T (column 2).

Table III. A few possible combinations of parameters for a single layer SSC magnet

Reference Column Number	1	2	3	4	5
B_o, Central Field (T)	6.35	5.6	5.3	5.0	4.7
Current, kAmp	10.41	9.13	8.64	8.14	7.65
Current Density in Cu at Quench, (A/mm^2)	1515	1500	1100	1100	1100
Copper to Superconductor ratio	2.3	1.6	3.9	3.0	2.45
Bath Temp (K)	2.5	4.35	2.5	3.2	4.35
J_c (at 5T, 4.2K), (A/mm^2)	3200	3200	3200	2750	2750

If the copper current density is restricted to 1100 A/mm^2 for passive quench protection schemes, then with the cable above J_c one can obtain 5.3 T at 2.5 K operating temperature (column 3). If we use the same cable as used in SSC with J_c (at 4.2 K, 5 T) = 2750 and operate at 4.35 K with current density in copper 1100 A/mm^2, again both same as in the SSC two layer dipole, the peak field will be 4.7 T (last column). However if the operation is done at 3.2 K temperature, a 5.0 T field can be realized (column 4).

References

[1] Superconducting Super Collider, Conceptual Design, SSC-SR-2000, March 1986.

[2] G. Morgan, "Use of an Elliptical Aperture to Control Saturation in closely-coupled, Cold Iron, Superconducting Magnets, 1985 Particle Accelerator Conference, Vancouver, BC, May 13-16, 1985.

[3] MAG2 is a computer program by R. Fernow for designing coils with non-integer turns. It was used in making a crude coil geometry. (No external report published.)

[4] PAR2DOPT is a computer program revised by P.Thompson. It uses a collection of routines called PARTIAL, mostly written by R.Fernow and some by G.Morgan. (No external report published.)

[5] MDP is modified version of the Program GFUN by C. Stewart. Reference for GFUN: M. J. Newman, C. W. Trowbridge and L. R. Turner, Proc. 4th International Conf. on Magnet Technology, Brookhaven (1972).