Collarless, Close-in, Shaped Iron Aperture Designs for the SSC Dipole[†]

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Abstract

The nominal-design SSC (Superconducting Super Collider) dipole encloses the coil in an iron yoke having a circular aperture. The radial gap between the coil and the iron is about 15 mm to provide space for a strong annular collar around the coil, and also to reduce the effects of iron saturation on central field harmonics. The 15 mm gap also reduces the desirable dipole field contributed by the iron. The present paper gives a coil and aperture configuration in which the gap is reduced to 5 mm at the midplane, in which the aperture is shaped to reduce the unwanted effects of iron saturation. The transfer function is increased about 5% at 6.6 Tesla and the unwanted harmonics are within SSC tolerances at all field levels. These designs would require that the yoke and containment vessel absorb the stresses due to assembly and magnetic forces. A short magnet is being built with a close-in shaped iron aperture and existing coil geometry to assess the benefits of this concept.

Introduction

It has been shown previously[1,2] that an elliptical iron aperture (instead of a conventional circular one) allows one to bring the iron closer to the coil with the ellipticity reducing the change in sextupole harmonic due to iron saturation. Closer iron with the same amp-turns gives a significantly higher transfer function at all field levels. The elliptical shape of the aperture can further be modified in a systematic way to reduce the variation in higher order harmonics as well.

Procedure

The procedure used to perform this analysis and to come up with a design satisfying the required performance is basically the same which was used[3] for "Single Layer Coil 6.1 Tesla SSC Dipole". A combination of the coil and aperture parameters are optimized with the aperture taking the shape of a distorted ellipse. The design process controls the harmonics at zero field (or injection field) and at a single high field, referred to here as B_{opt}. The optimization is done such that the net variation in harmonics is minimized at high field while making sure that the actual values of harmonics remain within the prescribed limit at all fields. The choice of B_{opt}, the field at which the harmonics are controlled, determines in part the size of the peak and the extent of drop from the peak. This is particularly important for the sextupole harmonic which drops rapidly in the vicinity of the maximum design field due to saturation of the iron yoke at the midplane. For the SSC Dipole, where the design field is 6.6 Tesla, we found that 6.3 Tesla is a good choice for B_{opt}.

Magnet Designs

In this section we shall discuss several optimized designs. The SSC Dipole at the time of this study had a circular aperture with an inner iron radius of 5.571 cm. The coil configurations C358A[4], and its modified version C358D, have two layers of conductors with a total of 36 turns in them - 16 in the inner layer and 20 in the outer.

For the elliptical aperture designs, we studied coil configurations with total turns ranging from 34 to 38. The cable specifications in these designs are basically the same as those used in the standard design. The iron outer radius is also kept the same as in the present design which is 13.336 cm. The main difference in these designs from the standard design is in the aperture. At the midplane the gap between the coil and iron is reduced from 15 mm to 5.07 mm. The actual shape of the optimized aperture turns out to be different for the coil configurations having different number of turns in them. This is due to the fact that the iron is much closer to the coil and the details of coil configurations makes a significant effect on the iron saturation and in turn on the field at the center of dipole. However, in each case we were able to reach to a satisfactory solution with a few iterations. A midplane gap smaller than 5 mm would have made this procedure much more involved besides compromising the electrical insulation due to such a small gap.

The designs with 37 and 38 turns, though giving a higher transfer function, gave little increase in the quench field. This is due to the fact that the present cable, made of NbTi, has a rapidly decreasing critical current density (J_c) at 7 Tesla field and 4.2° Kelvin bath temperature.

The design of a magnet with 36 turns in the coil, will be discussed in detail in the next section. The performance of the designs with 34 and 35 turns will be discussed briefly later in this paper. They are described in detail in reference 5.

Details of the Design

The details of the coil configuration for the 36 turn model, EL36, are given in table 1. The coil cross-section is shown in figure 1. It has four blocks in the inner layer and two in the outer. The tilt angle is the angle by which each block is tilted. The first block of each layer is placed such that its two lower corners are 0.0102 cm above the midplane. Tilt angles of these blocks are not used as the variables in the coil optimization program. The blocks are separated by insulated copper wedges. Column 4 of table 1 gives the angular extent of these wedges following each block.

Table 1: Coil configuration EL36

Layer	Turns	Tilt Angle	Next Wedge
Inner	4	-	1.4600°
Inner	5	5.8676°	1.5630°
Inner	4	3.8260°	3.8206°
Inner	3	0.0000°	none
Outer	7	-	0.9925°
Outer	13	1.8286°	none

The coil optimization program assumes a circular $\infty\mu$ iron aperture. For EL36, the design iron radius is 4.75 cm. The optimized values of field harmonics, as produced by this program, are given in table 2. Please note that we have optimized the coil for non-zero harmonics. These values are such that they produce zero harmonics when this coil is used with the optimized non-circular aperture.

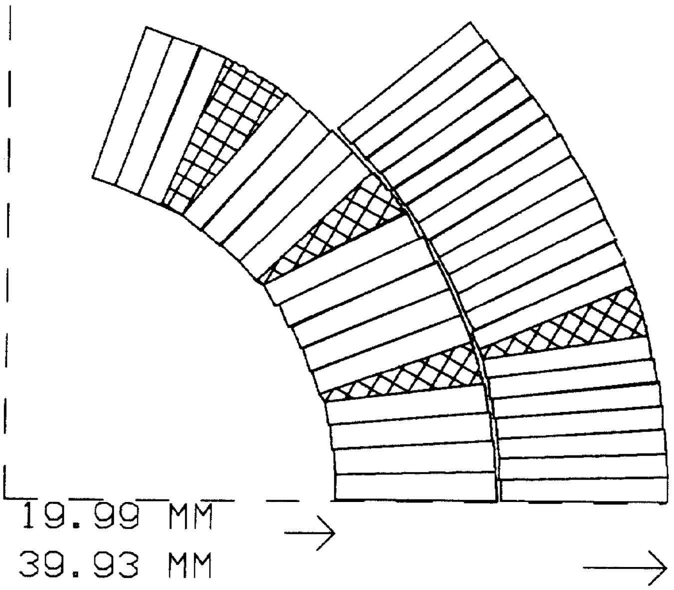

Figure 1: Coil EL36 for the elliptical aperture

The field harmonics are defined in the following relation:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} \left[b'_n + ia'_n\right] \left[cos(n\theta) + i\ sin(n\theta)\right] \left(\frac{r}{R_0}\right)^n ,$$

where B_0 is the field at the center, B_x and B_y the components at (r,θ), R_0 the normalization radius. a'_n are the skew harmonics and b'_n are the normal. In this paper R_0 is 1.

Table 2: Harmonics for coil EL36 and circular iron aperture of radius 4.75 cm; Harmonics are normalized to 1 cm radius and are in units of 10^{-4}

b'_2	b'_4	b'_6	b'_8	b'_{10}
-16.70	-0.68	0.02	0.01	0.07

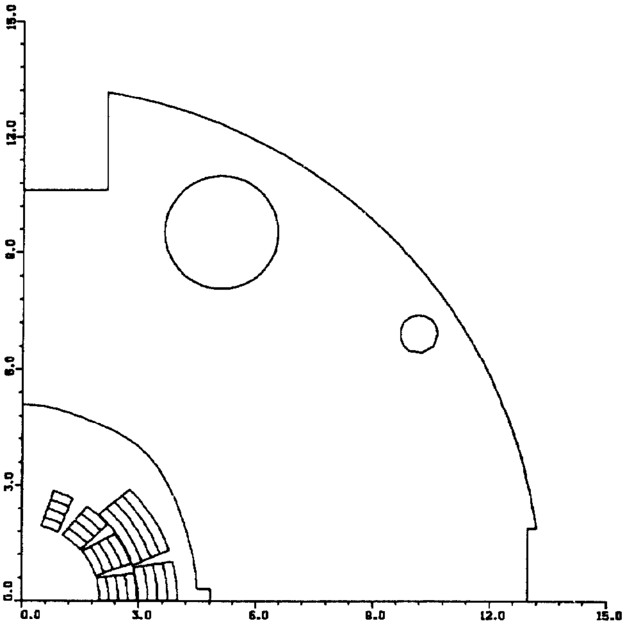

Figure 2: Elliptical aperture magnet with coil EL36

The optimized aperture is non-circular, the shape of which is defined by the semi-minor axis a, semi-major axis b, and b_4 and b_6 bumps (b-a can be regarded as a b_2 bump). The bumps, as defined in reference 2, describe the deviation from the circular aperture. The details of this aperture are given in table 3. The model of the first quadrant of this magnet is shown in figure 2.

Table 3: Aperture dimensions in cm for EL36 (a is the semi-minor axis and b semi-major)

a	b	b_4	b_6
4.500	5.090	0.219	-0.122

Performance

In table 4 we give computed harmonics for 1 cm normalization radius as a function of current in each turn for EL36. These computations have been done with the modified computer code POISSON[6] which now permits an analytic user-defined curve to be specified in AUTOMESH. Harmonics higher than b'_6 usually remain within $\simeq 10^{-6}$. We plot these harmonics as a function of the central field B_0 in figure 3.

Table 4: Computed field harmonics for EL36 at 1 cm radius

I kA	B_0 Tesla	T.F. T/kA	b'_2 10^{-4}	b'_4 10^{-4}	b'_6 10^{-4}
$\infty\mu$	$\infty\mu$	1.105	0.02	0.00	0.03
2.950	3.2419	1.099	-0.01	0.00	0.03
4.720	5.1580	1.093	0.54	0.03	0.03
5.310	5.7557	1.084	0.68	0.06	0.03
5.900	6.3251	1.072	-0.21	0.06	0.03
6.136	6.5445	1.067	-0.92	0.05	0.03
6.490	6.8632	1.058	-2.35	0.02	0.03

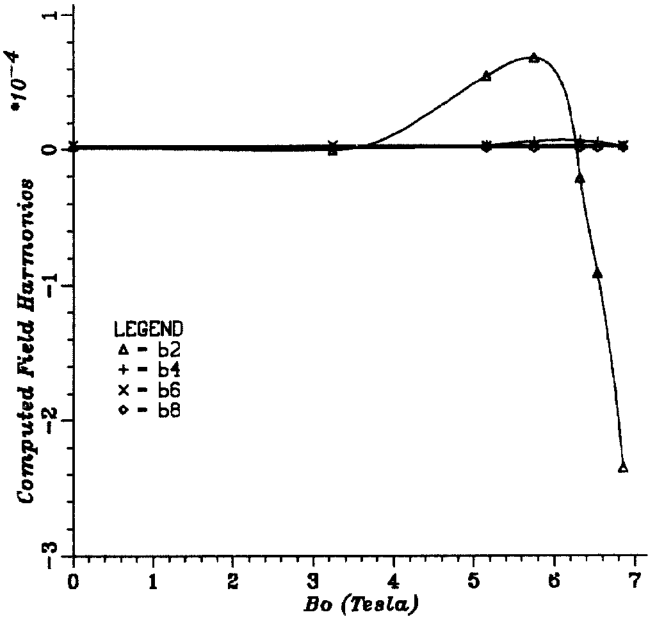

Figure 3: Harmonics as a function of central field for EL36

In table 5, we list the ratio of peak field (the maximum magnetic field in the coil) to central field in the inner and outer layers. The quench performance of a magnet depends on these peak fields, operating temperature and current density in the superconductor. The critical field can be computed with the help of these parameters.

Table 5: Ratio of peak field to central field in EL36

B_0 (Tesla)	Inner layer	Outer layer
6.5445	1.0473	0.8476
6.8632	1.0480	0.8475

In table 6, we compare the performance of the elliptical aperture magnets designed with the number of turns ranging from 34 to 36 with the present circular aperture SSC magnet having C358A. We compare the critical field, transfer function at 0.3 T and 6.6 T, stored energy (E) at 6.6 T, current (I) in each turn to produce 6.6 Tesla central field, and percentage of safety margin (in current) available in the outer layer. In all designs we have considered a copper to superconductor ratio of 1.3 in the inner layer and 1.8 in the outer. We also assume a critical current density at 5 Tesla and 4.22° kelvin, $J_c(5, 4.22)$, to be 2475 $Amps/mm^2$.

Table 6: Comparison of elliptical aperture designs v/s the present circular aperture SSC dipole with C358A coil

Coil Turns	EL34 34	EL35 35	EL36 36	C358A 36
Critical field, T	6.844	6.948	6.955	6.867
TF@0.3T, T/kA	1.047	1.077	1.105	1.039
TF@6.6T, T/kA	1.011	1.041	1.065	1.016
E@6.6T, kJ/m	63.5	62.8	63.3	66.1
I at Quench, kA	6.813	6.730	6.592	6.788
% Margin	3.64	3.49	3.74	3.49

Discussion

The gain in transfer function obtained by the use of the elliptical aperture can be utilized in either of the following two ways. (1) For the same number of turns, greater field from the elliptical aperture design; (2) Fewer turns required in the elliptical aperture case to produce the same design goals as those produced in the standard design having 36 turns in it.

For the first case, we compare the designs EL36 and C358A (column 3 and 4). We realize a gain of about 1 kGauss (or 1.3%) in the critical field. In transfer function we observe a gain of 4.8% at the design field of 6.6 Tesla. The safety margin in the outer layer is about the same. The reduction in stored energy by 4.2% means that the axial forces on the coil ends will be less by the same amount.

For the second case, we compare EL34 and C358A (column 1 and 4). EL34 has 34 turns in the coil and C358A has 36. We observe that we get about the same performance in the two designs, except that the stored energy is reduced by 3.9% in EL34. Since the total superconductor cost in the SSC dipole is $250 million, a reduction of 2 turns per quadrant gives a saving of ≃$14 million; magnetization effects are also reduced in the same ratio.

Short Dipole Program

A short dipole magnet with elliptical aperture is being built at the Brookhaven National Laboratory. The magnet, known as DSS015, is actually being rebuilt from an earlier circular aperture magnet. This will have an elliptical iron insert in an old circular aperture. The iron insert will provide the contour shape in the aperture designed for EL36. To minimize construction, coil C358D, which has 36 turns in it, will be used instead of EL36. This means that there will be non-zero harmonics. The expected performance of this magnet is discussed in detail in reference 7. Nevertheless, the gain in transfer function, critical field, stored energy, etc. should verify the benefits of such designs and the reliability of the computer methods used in these designs.

References

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