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CONTROL OF THE FIELDS DUE TO SUPERCONDUCTOR MAGNETIZATION
IN THE SSC MAGNETS*

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ABSTRACT

Field uniformity of better than one part in 10,000 is required for the dipole magnets for the Superconducting Super Collider (SSC). The high field dipole and quadrupole magnets proposed for the SSC generate higher multipole components of field due to magnetization (persistent currents) in the superconductor. When the superconductor filament diameter is of the order of 20 μm , the sextupole term alone is about 17 parts in 10,000 at an injection induction of 0.3 tesla in the SSC dipole magnets at a radius of 1 cm. This paper shows calculations of the magnetization phenomena which agree very well with magnetic measurement. Several passive methods for removing the sextupole component and higher components of the field generated by magnetization of the superconductor in the SSC dipole magnets are presented in the paper.

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BACKGROUND

The field due to circulating currents flowing within the superconductor of superconducting dipole magnets was observed as early as 1970.¹ This magnetic field was observed to be rich in higher multipoles even though the magnet was designed to eliminate these multipoles. From the very beginning, it was recognized that these higher multipoles would adversely affect the operation of a superconducting synchrotron or storage ring at injection if the field at injection was low enough.

Until recently, the field due to superconductor circulating currents has not been a problem. The injection field of superconducting machines such as the Fermilab Doubler-Saver and HERA are high enough that the sextupole and other higher multipoles are of minimal concern because they can be corrected out by the means of lumped correction elements. While the residual field has not been a problem with the Fermilab Doubler-Saver², the Superconducting Super Collider (SSC) is another matter. This machine, which will have a circumference of over 60 km, will have a low injection field 0.3T, and it requires much better field uniformity (better than one part in 10^4) than any machine designed before it.³ At injection the sextupole component is projected to be 17 parts in 10^4 when the superconductor filament diameter is 23 μm . This sextupole is not correctable using lumped correction elements.

This paper will present three methods for passively reducing the high multiples produced by the superconductor circulating currents. The methods presented here include: 1) passive pieces of superconductor arranged about the beam tube, 2) passive pieces of ferromagnetic material arranged about the beam tube and 3) pieces of oriented magnetized material arranged about the beam tube. The paper will present computer simulations of these correction methods using the LBL-SCMAG04 computer code.

BASIC THEORY

The field generated by circulating currents in a single filament of superconductor can be represented by the classical hydrodynamic doublet equation.⁴ In complex form this equation takes the following form:

$$H^{**}(Z) = \frac{\Gamma e^{i\alpha}}{2\pi i (Z - Z_c)^2} \quad -1-$$

where H^{**} is the complex conjugate of the field $H^*(Z)$ at a point Z generated by a current doublet with strength Γ and doublet angle α at a location Z_c . Γ is nothing but the product of the circulating current and the average distance between the circulating currents. (For a fully penetrated round beam model conductor, the distance is 0.423 times the filament diameter.) Γ is proportional to superconductor magnetization and α is the angle of the flux line which generated the circulating current minus $\pi/2$. Both Γ and α are functions of the previous flux history of the superconducting filament.

Equation 1 can be expanded into a Taylor series about the origin. Since superconducting dipoles and quadrupoles of interest are symmetrical (they are symmetrical about the axes which are at $\theta = 0$, $\theta = \pi/2T$, π/T , and so on to 2π , where T is the fundamental multipole of the magnet in question ($T = 1$ is a dipole magnet and $T = 2$ is a quadrupole magnet)). The power series takes the following form:

$$H^{**}(Z) = \sum_{N=1}^{\infty} a_N^* Z^{N-1} \quad -2-$$

where

$$a_N^* = -\frac{2\Gamma}{\pi i} N \cos((N+1)\theta_c - \alpha) r_c^{-(N+1)} \quad -3a-$$

when $N = T(2P+1)$, $p = 0, 1, 2, \dots$ and

$$a_N^* = 0 \quad -3b-$$

when $N \neq T(2P+1)$, $p = 0, 1, 2$. We define θ_c as the filament angle from the x axis, r_c is radius from the origin to the filament and N is the series multipole ($N = 1$ is dipole, $N = 2$ is quadrupole, and so on). T , Γ , and α are previously defined. There is a similar power series for the image doublet in the iron, but it is not very important for this discussion.

It was said earlier that the doublet strength factor Γ is proportional to the superconductor magnetization. This relationship is as follows:

$$\Gamma = \frac{\pi D_f^2 M}{4} \quad -4-$$

where D_f is the superconducting filament diameter, M is the magnetization (Am^{-1}) and Γ is the Id product for the doublet (Am).

The magnetization of the superconductor contains two basic terms: 1) a bulk magnetization which is proportional to filament diameter, and 2) a magnetization due to surface effects such as H_{c1} and the vortex currents, which is independent of filament diameter.⁵ The SCMAG04 code models both effect from first principles.

The magnetization generated by the SCMAG04 closely approximates that which has been measured by A.K. Ghosh and others.⁶ Figure 1, a magnetization curve generated from basic superconductor data such as J_c vs H , H_{c1} , coherence distance, H_{c2} and penetration distance, very closely predicts the type of magnetizations which have been measured. The slight skew in the magnetization loop shown in Figure 1 is due to H_{c1} surface current effects.

Figure 1. A Magnetization Curve for a Typical Superconductor

Elimination of Residual Field with Passive Elements

The elimination of higher multipoles using passive elements has its roots in Equation 3a. (Note the iron image term is small compared to the term given by Equation 3a.) A study of passive methods of eliminating the higher multipoles of the residual field indicates that this must be done in the region between the coil and the useful aperture bore if the greatest effect for the least amount of passive material is to be achieved. For all practical purposes, the best place to put passive material is just inside the dipole coils. Three methods of passive reduction of higher multipoles of residual field have been studied. They are: 1) passive pieces of superconductor which carry no transport current, 2) passive pieces of ferromagnetic material, and 3) passive pieces of oriented permanent magnet materials such as samarium cobalt.

a) Correction with Passive Superconductor

The idea of using a passive superconductor was postulated by H.E. Fisk of Fermilab.⁷ To see how a passive superconductor might work, look at Equation 3a when the superconductor is in nearly a perfect dipole field ($\alpha = 0$).

$$a_N^* = -\frac{2\Gamma}{\pi i} N \cos((N+1)\theta_c) r_c^{(N+1)} \quad -5a-$$

This equation says that the sextupole will vary as $\cos 4\theta_c$ and Γ . (Note: Equation 3b still applies.) In order to achieve an elimination of the residual field sextupole over a wide range of fields in the magnet, one must manipulate Γ by choosing the correction superconductor filament diameter, and right angle θ_c . Other higher multipoles can be manipulated by varying θ_c as well.

Figure 2 shows SSC dipole 12-C which has 23.2μ filament conductor on the two inner three block layers and 18.6μ filament conductor on the two outer two block layers. The pieces of superconductor inside the coil symmetrically placed about angles $\theta_c = 12, 82, 22.5$ and 67.5 degrees contain 35μm filaments. The total amount of superconductor in these pieces is about 6.5 percent of the total superconductor in the magnet. The design will reduce the $N = 3, 5$ and 7 (sextupole, decapole and 14 pole) to less than 1 part in 10^4 at central inductions of 0.3 tesla on up. See Figure 3 for a comparison of the sextupole term in Dipole 12C with and without the passive superconductor.

b) Ferromagnetic Correction

Substantial reductions of higher multipoles of the residual field can be made using ferromagnetic materials. One can look at Equation 5a, but instead Γ has a different functional relationship with the field, and it is of opposite sign. The effects of ferromagnetic material can be modeled by SCMAG04 if the pieces are small compared to the coil radius.

Small pieces of iron behave like tiny dipoles with a cosine theta distribution on the surface which draws magnetic flux into the dipole. In other words, the dipole is a flux sucker which has the following characteristics: 1) at external fields below $B_{sat}/2$, the flux within the dipole is twice the external flux, (note: B_{sat} is the ferromagnetic material saturation induction), and 2) when the external field reaches $B_{sat}/2$ the dipole strength is maximized such that an additional flux of $B_{sat}/2$ is created within the dipole regardless of how high the external field becomes (in other words, the field inside the dipole is $B_{sat}/2$ higher than the field outside the dipole a long distance away).

Figure 4 shows the D-12C dipole (with 23.2μ and 18.6μ filaments) with ferromagnetic passive correction using small pieces of Mu metal with $B_{sat} = 0.65$ tesla. The pieces of metal are sized and symmetrically located at angles $\theta_c = 21.9, 47.0$ and 66.9 degrees such that the $N = 3, 5$ and 7 are kept low over a wide range of central inductions. Figure 5 compares the sextupole terms in Dipole D12-C with and without ferromagnetic correction.

c) Correction with Oriented Permanent Magnet Material

A small piece of oriented magnetized material can be used to correct the residual field as long as the axis of magnetization is perpendicular to the magnetic field direction. Thus, one finds that Equation 3a will take the following form:

$$a_N^* = \frac{-2\Gamma}{\pi i} N \cos((N+1)\theta_c \pm \frac{\pi}{2}) r_c^{(N+1)} \quad -5b-$$

Compared to the passive superconductor, Γ for oriented magnetized materials, such as samarium

cobalt, is large. Very small pieces of this material are needed in order to achieve a correction of the residual field. In order to achieve correction of $N = 3, 5$ and 7 , one has to put the oriented material at various angles θ_c with doublet angles of either $+\pi/2$ or $-\pi/2$. (Any other α angle can result in the demagnetization of the permanent magnet material.)

Figure 6 shows the D12-C dipole (with 23.2μ and 18.6μ filaments) with oriented permanent magnetic material at two locations within the magnet. The pieces of material are very small (about 0.3 mm by 0.7 mm). The permanent magnet material at $\theta_c = 25^\circ$ has an α of $+\pi/2$, and the material at $\theta_c = 70^\circ$ has an α of $-\pi/2$. The material assumed has a magnetic moment of 1 tesla (this is close to the value found in oriented samarium cobalt). The theory has the material behaving like a dipole which generates an induction of 1.0 T within it. Figure 7 compares the sextupole from a corrected and uncorrected dipole D12-C. The oriented magnetic material and ferromagnetic material methods of correction greatly reduce the sextupole at an injection induction of 0.3 T, but the sextupole component is over-corrected at higher central inductions.

SUMMARY

The higher multipole generated by circulating currents in the filaments of the SSC Superconductor can ruin the field quality of an SSC dipole or quadrupole. Reduction of the filament diameter improves the situation, but it does not eliminate the problem. (As the filament diameter goes down surface H_c effects become more important, and proximity effects may come into play.) This paper illustrates that SSC magnets with large filaments (23.2 and 18.6μ) can be corrected using passive methods.

The passive superconductor method yields the best results. Not only is the correction more uniform and complete over a wide range of fields, but the temperature dependence of the correction is the same as the temperature dependence of the residual field being corrected. From Figure 3 one can see that both

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Figure 2. SSC-Dipole D12-C with Passive Superconductor Correction

legs (going down and going up) of the field are corrected, whereas the other correction methods will correct a rising field and make the falling field worse. Ferromagnetic correction and oriented magnetized material may be more useful for correcting magnets with fine filament superconductors.

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Figure 3. The Ratio of Sextupole to Dipole in SSC Dipole D12-C with and without Passive Superconductor Correction

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Figure 4. SSC Dipole D12-C with Passive Ferromagnetic Correction

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Figure 5. The Ratio of Sextupole to Dipole in SSC Dipole D12-C with and without Passive Ferromagnetic Correction

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Figure 6. SSC Dipole D12-C with Passive Oriented Permanent Magnet Correction

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Figure 7. The Ratio of Sextupole to Dipole in SSC Dipole D12-C with and without Passive Oriented Permanent Magnet Correction

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