CONF-890270--16

LBL-27062

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

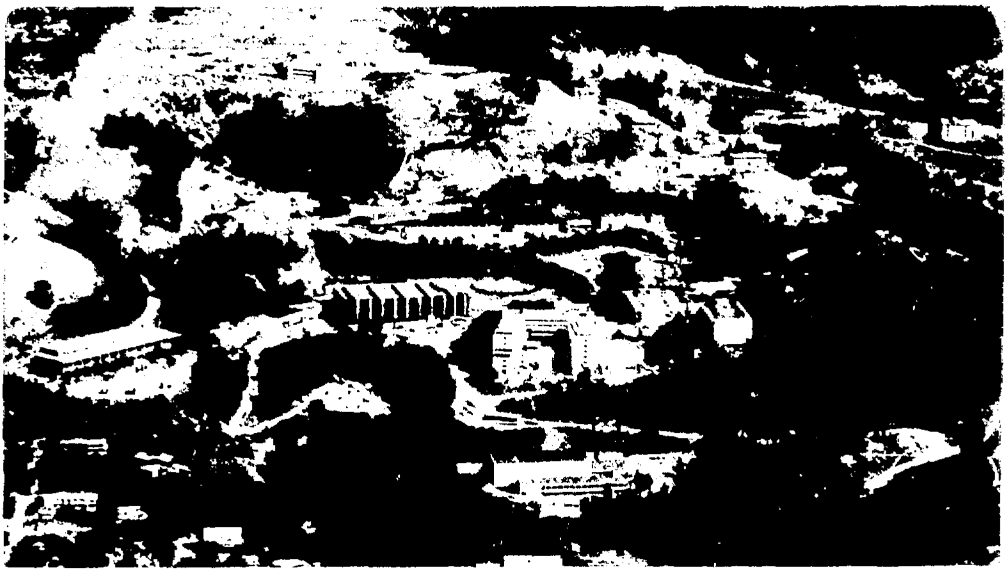
Engineering Division

Presented at the International Industrialization Symposium for the Super Collider, New Orleans, LA, February 9–10, 1989, and to be published in the Proceedings

Passive Superconductor: a Viable Method of Controlling Magnetization Multipoles in the SSC Dipole

M.A. Green

February 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

LBL-27062

LBL--27062

DE89 013432

Passive Superconductor: a Viable Method of Controlling Magnetization Multipoles in the SSC Dipole

Michael A. Green

Engineering Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

February 1989

Supported by the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

PASSIVE SUPERCONDUCTOR A VIABLE METHOD OF CONTROLLING MAGNETIZATION MULTIPOLES IN THE SSC DIPOLE

Michael A. Green

M/S 90-2148
Lawrence Berkeley Laboratory
Berkeley, CA 94720

ABSTRACT

At injection, the magnetization of the superconductor produces the dominant field error in the SSC dipole magnets. The field generated by magnetization currents in the superconductor is rich in higher symmetric multipoles (normal sextupole, normal decapole, and so on). Pieces of passive superconductor properly located within the bore of the dipole magnet can cancel the higher multipoles generated by the SSC dipole coils. The multipoles generated by the passive superconductor (predominantly sextupole and decapole) are controlled by the angular and radial location of the superconductor, the volume of superconductor, and the size of the superconducting filaments within the passive conductor. This paper will present the tolerances on each of these factors. The paper will show that multipole correction using passive superconductor is in general immune to the effects of temperature and magnetization decay due to flux creep, provided that dipole superconductor and the passive correction superconductor are properly specified. When combined with a lumped correction system, the passive superconductor can be a viable alternative to continuous correction coils within the SSC dipoles.

BACKGROUND

The effect of superconductor magnetization on the quality of the magnetic field in a superconducting dipole was observed almost 20 years ago.[1] It has been observed that superconductor magnetization will produce higher normal multipoles such as sextupole, decapole, 14-pole and so on, even though the magnet was designed to produce none of these multipoles. From the beginning, when LBL and others started fabricating accelerator types of dipoles, it was recognized that the higher multipoles generated by the superconductor magnetization would have an adverse affect on the performance of accelerators at injection, if the injection field is low enough.

On the Fermilab doubler saver, the higher multipoles generated by magnetization were not a problem until the machine was used as a storage ring.[2] When the Tevatron is used as a fixed target accelerator, the circulating beam current is low enough that the effects of magnetization could be corrected using lumped correction elements. Colliding beam storage rings are strongly affected by low level sextupole and decapole at injection. This effect grows worse as the beam size is reduced and more protons are packed into the beam.[3] The SSC and HERA have proposed to correct out the magnetization sextupole and decapole using continuous correction elements down the bore of each dipole. This solution is quite expensive.

Beam dynamics studies by the SSC-CDG suggest that if the magnetization sextupole can be reduced to 2 units (1 unit equals 1 part in 10,000) at an injection induction of 0.33T, the effects of magnetic field error on the stored proton beam can be controlled using lumped correction elements in each half cell of the machine lattice.[4] Another correction scheme proposed by Neuffer[5] would allow for the correction of sextupole up 5 or 6 units using lumped elements every three dipole magnets. If the magnetization sextupole can be reduced to one or two units in each dipole, the expensive continuous correction elements can be replaced by the lumped correction elements which are already needed to control the tune of the SSC.

BASIC THEORY

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

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

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:

$$H^{**}(Z) = \sum_{N=1}^{\infty} a_n^* \; Z^{N-1} \qquad -2-$$

where

$$a_n'' = \frac{2\Pi\Gamma}{\pi i} N \cos((N+1)\,\theta_c - \alpha)\, r_c^{-(N+1)} \qquad \text{-3a-}$$

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

$$a_n'' = 0 \qquad \text{-3b-}$$

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:

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

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 four basic terms: 1) The bulk magnetization of the superconductor is proportional to filament diameter and J_c. 2) There is a magnetization due to surface effects such as h_{c1} and the vortex current.[7] This term is independent of J_c and filament diameter. 3) Coupling due to eddy currents between superconducting filaments and cable strands manifests itself as a flux change rate dependent term.[8] This term can be controlled by the twist pitch of the multifilamentary conductor and the transposition pitch of the cable. 4) There is magnetization due to tunneling between superconducting filaments which are in close proximity.[9,10]

For a superconductor with fully penetrated filaments which are spaced far enough apart to avoid proximity effects, the magnetization M will take the following form:

$$M = M_{f1} + M_{f2} \qquad \text{-5-}$$

where

$$M_{f1} = \frac{2}{3\pi} D_f J_c [1 - \delta] \qquad \text{-5a-}$$

and where

$$M_{f2} = H_{c1} - \frac{\ln[(H - H_{c1}/2)\phi]}{\ln[(H_{c2} - H_{c1}/2)\phi]} H_{c1} \qquad \text{-5b-}$$

D_f is the filament diameter, J_c is the critical current density of the superconductor in the filament at a field H; H_{c1} is the lower critical field; H_{c2} is the upper critical field; δ is the fraction of the conductor current carrying capacity carrying transport current (δ cannot be larger than 1); and $\phi = \lambda/(2.07 \times 10^{-15})$ with λ the superconductor penetration depth (λ is about 2500 angstroms for Nb-Ti).

All of the magnetization terms except the h_{c1} and vortex effects will decay with time. Flux creep decays of long time constants have been observed in both the bulk magnetization and the proximity coupling terms.[11,12,13] The decay time constants for the filament twist pitch and cable transposition pitch dependent magnetization are generally short. Since these terms are small, this type of decay is not of concern in a magnet. The decay associated with flux creep is of concern because as much as half of the bulk magnetization can decay during injection into the SSC. This decay has a log time dependence.

The effects of magnetization on the magnetic field in an SSC dipole magnet was modeled using the LBL SCMAGØ4 computer program. This program shows good agreement with measurements of magnetization in dipole magnets.[14] Figures 1 and 2 show a comparison of the measured sextupole and decapole with normal sextupole and decapole calculated by the SCMAGØ4 code. The SCMAGØ4 has been used to calculate the effects of nonsymmetric magnetization and currents.[15] The asymmetries appear as skew terms and even normal terms in the magnetic field expansion.

ELIMINATION OF MAGNETIZATION SEXTUPOLE AND DECAPOLE WITH PASSIVE ELEMENTS

The concept of using passive elements to eliminate the sextupole and the decapole in a dipole magnet is not new. The use of passive superconductor was first suggested by H. E. Fisk of Fermilab.[16] Ferromagnetic passive correction and correction using oriented permanent magnet materials has also been studied.[17] The oriented permanent magnet materials are expensive and difficult to manufacture so that the magnetization points in the correct direction.

Ferromagnetic correction using Mu metal (which has a saturation induction of about 0.65T) and soft iron (which has a saturation induction of 2.0T) is simple and not much metal is required to correct out the sextupole and decapole. The disadvantages of this approach are: 1) There is an offset in the sextupole and decapole at magnetic inductions above 0.5T. This offset is at its worst at a central induction of about 2T. 2) Ferromagnetic correction does not respond to changes in magnetization due to changes in temperature. 3) The decay of superconductor magnetization is not compensated for by ferromagnetic correction.

Figure 1

A COMPARISON OF MEASURED ERROR AND THE THEORETICAL ERROR PLUS THE OFFSET AS A FUNCTION OF CENTRAL INDUCTION ON LBL DIPOLE D-15A-5 NORMAL SEXUPOLE TERM

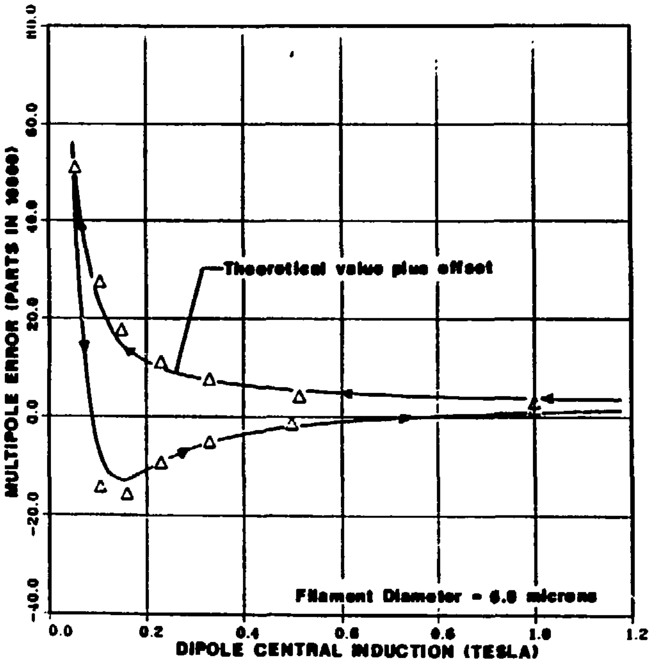
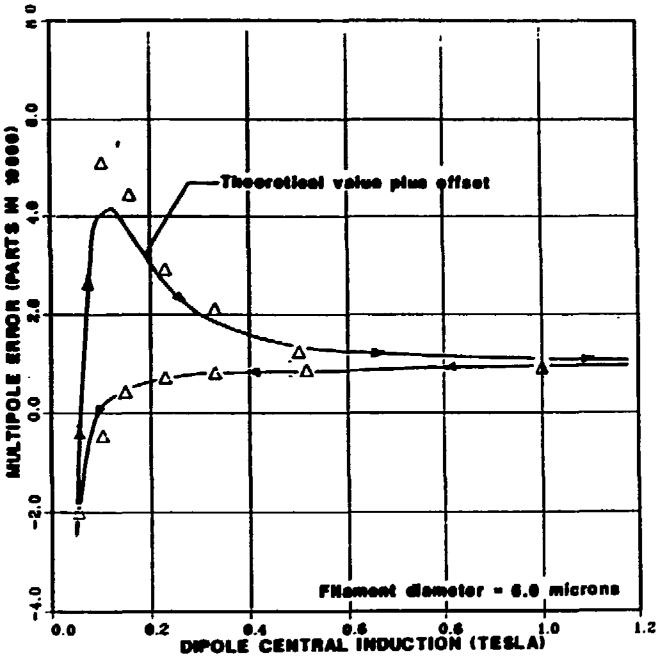


Figure 2

A COMPARISON OF MEASURED ERROR AND THE THEORETICAL ERROR PLUS THE OFFSET AS A FUNCTION OF CENTRAL INDUCTION ON LBL DIPOLE D-15A-5 NORMAL DECAPOLE TERM



Compensation using passive superconductor works over a wide range of dipole central inductions whether the field is rising or falling. Compensation of the magnetization induced sextupole and decapole using a passive superconductor continues even when the temperature changes. It is probable that passive superconductor will compensate for the flux creep decay of the sextupole and decapole produced by magnetization.

Correction of dipole NC-9 with passive superconductor

Figure 3 shows the LBL NC-9 dipole cross-section with flux lines and the ratio of the magnetization sextupole and decapole to the central dipole induction for an uncorrected NC-9 dipole with superconductor which has 5 micron filaments. In Figure 4 one can see the positive magnetization sextupole as the central induction is reduced from 6.6T. When the central induction is reduced to zero and then increased, the positive sextupole decreases and becomes negative. When the central induction increases from zero to 0.1T (after coming down from 6.6T to zero), the magnitude of the negative sextupole decreases. At an injection induction of 0.33T, the sextupole ratio at a radius of 10 mm is -7.126 units (one unit is 1 part in 10,000). The decapole ratio at injection is about +1 unit.

Passive superconductor must create a positive sextupole of +7.16 units at injection. (The sextupole generated by the magnet coil should be corrected out by the sextupole created by passive superconductor.) A negative decapole of about one unit must be produced by the passive superconductor. To see how the passive superconductor works, look at Equation 3a. The passive superconductor, which is mounted inside the coil (in order to minimize the amount of passive superconductor needed to correct the field), sees nearly a perfect dipole field such that $\alpha = 0$ or $\alpha = \pi$. when $\alpha = 0$ Equation 3a takes the following form:

$$a_n^* = \frac{2\Gamma}{\pi i} N \cos((N+1)\,\theta_c)\, r_c^{-(N+1)} \qquad \text{-6-}$$

This equation says that the sextupole term (N = 3) will vary as $4\theta_c$ and Γ. (The decapole term will vary as $6\theta_c$ and Γ.) In order to achieve an elimination of the magnetization field over a wide range of fields in the magnet, one must manipulate Γ by choosing the correction superconductor filament diameter, and the correct angle θ_c. Other higher multipoles can be manipulated by θ_c as well.

Two correction methods

Two correction schemes studied at LBL are presented here. In order to get the desired positive sextupole in the NC-9, dipole pieces of passive superconductor should be placed symmetrically about $\theta_c = 0$, 90, 180, and 270 degrees (see Equation 5). If one wants to create a negative decapole as well as a positive sextupole, the passive superconductor at the midplane $\theta_c = 0$ and $\theta_c = 180$ must be split symmetrically with space between the conductor.

Figure 3

SSC DIPOLE CROSS-SECTION LBL NC-9

SHOWING MAGNETIC FLUX LINES

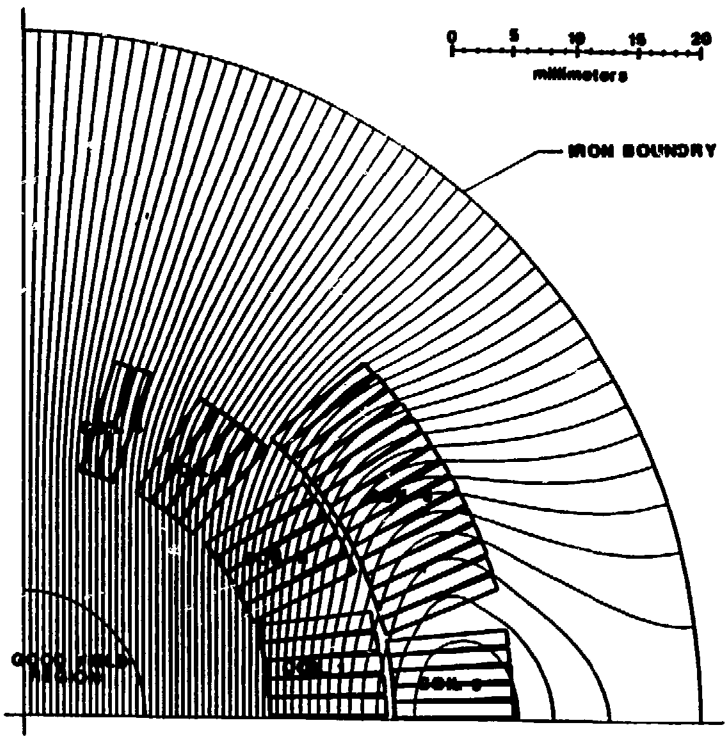
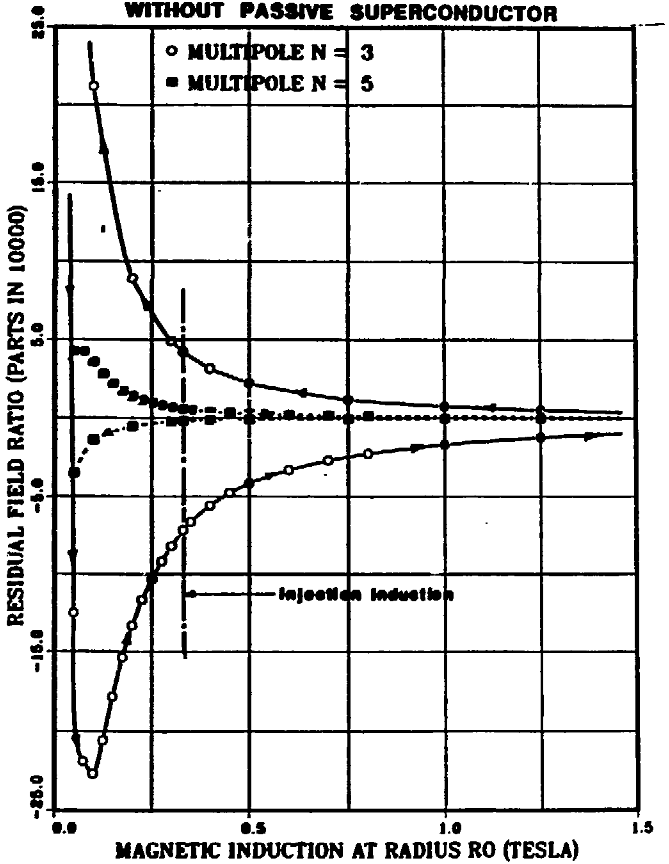


Figure 4

THE RATIO OF MAGNETIZATION SEXTUPOLE AND DECAPOLE TO THE TRANSPORT CURRENT DIPOLE AS A FUNCTION OF DIPOLE CENTRAL INDUCTION WITHOUT PASSIVE SUPERCONDUCTOR



The first correction scheme, Case A, uses sixteen 9-strand cables with 9 strands made from inner cable strands (with a copper-to-superconductor ratio of 1.4 and 5 micron filaments). Figure 5 shows a quarter of the model NC-9 dipole with the correction, the Case A, passive superconductor. Figure 6 shows the ratio of magnetization sextupole and decapole to central dipole induction versus the central induction of the magnet. Table 1 shows the magnetization sextupole ratio for the dipole without passive correction cases A and B.

The second correction scheme, Case B, uses eight 14-strand cables with the 14 strands made from inner coil superconductor with 10 micron filaments and a copper-to-superconductor ratio of 1.4. Figure 7 shows a quarter of the model NC-9 dipole coil cross-section with the Case B passive correction superconductors. Figure 8 shows the ratio of magnetization sextupole and decapole to central dipole induction as a function of central induction. In both Case A and Case B the magnetization sextupole has been reduced by over two orders of magnitude at injection. In both cases, the sextupole and decapole are well within bounds so that the SSC accelerator can be corrected using lumped elements every half cell.

<u>The effects of temperature, conductor placement errors, magnetization mismatch, proximity coupling and magnetization decay</u>

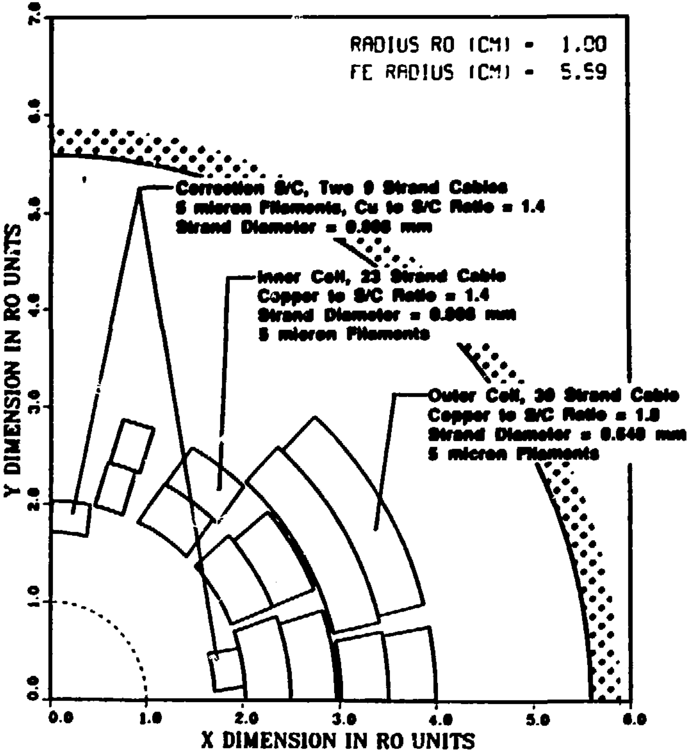
The superconductor used to correct the magnetization multipoles in the dipole react to temperature changes in much the same way as superconductor in the magnet coils. The value of dJ_c/dT divided by J_c is about 0.208 k^{-1} for all of the superconductor in the magnet. In the range of temperatures expected in the SSC (from 4.2K to 4.5K), the change in sextupole passive correction with temperature is less than 0.02 units. (See Table 2 for a comparison of temperature effect on the quality of corrected field.) Even at 1.8K, satisfactory passive correction can be obtained.

A symmetrical one-degree placement error changes the correction superconductor magnetization sextupole by about 0.2 units (at a radius of 10 mm). (A one-degree error corresponds to a placement error of 0.32 mm.) If a one-degree error occurs on one superconductor block, a skew quadrupole of about 0.07 units (at a radius of 10 mm) is produced. The normal sextupole produced by a single conductor motion is of the order of 0.03 units. The allowable error in the placement of the passive superconductor is about 5 degrees (about 1.6 mm).

The magnet superconductor is expected to have a critical current density at 5 T and 4.2 K of 2750 Amm^{-2} ± 3 percent. The critical current density at 0.3 T is about 5.5 times larger than the critical current density at 5.0T.[18] Measurements on samples of many kinds of niobium titanium suggest that the variation of this ratio is about ±10 to 15 percent. If the superconductor is carefully selected so that the passive superconductor has the same metallurgical structure as the magnet conductor, this variation is much lower. The critical current density of the magnet superconductor and the passive superconductor should be specified to have the same value at two different inductions (say 2T and 5T). The diameter of the superconducting filaments is expected to vary from magnet to magnet by less than

Figure 5

THE LBL NC-9 MODEL SSC DIPOLE COMPUTER MODEL CROSS-SECTION PASSIVE SUPERCONDUCTOR CORRECTION CASE A



6

Figure 6

THE RATIO OF MAGNETIZATION SEXTUPOLE AND DECAPOLE TO THE TRANSPORT CURRENT DIPOLE AS A FUNCTION OF DIPOLE CENTRAL INDUCTION WITH PASSIVE SUPERCONDUCTOR CASE A

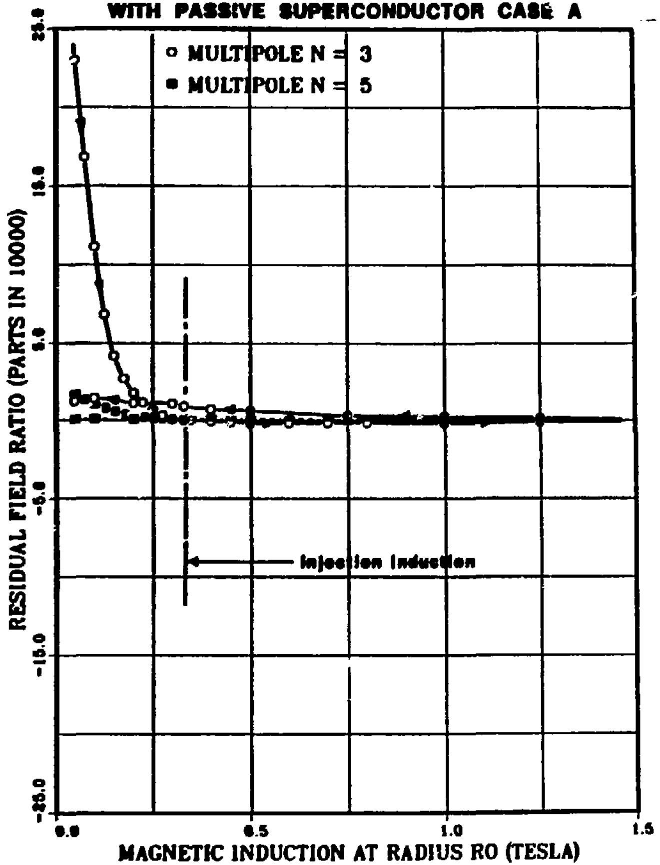


Figure 7

THE LBL NC-9 MODEL SSC DIPOLE
COMPUTER MODEL CROSS-SECTION
PASSIVE SUPERCONDUCTOR
CORRECTION CASE B

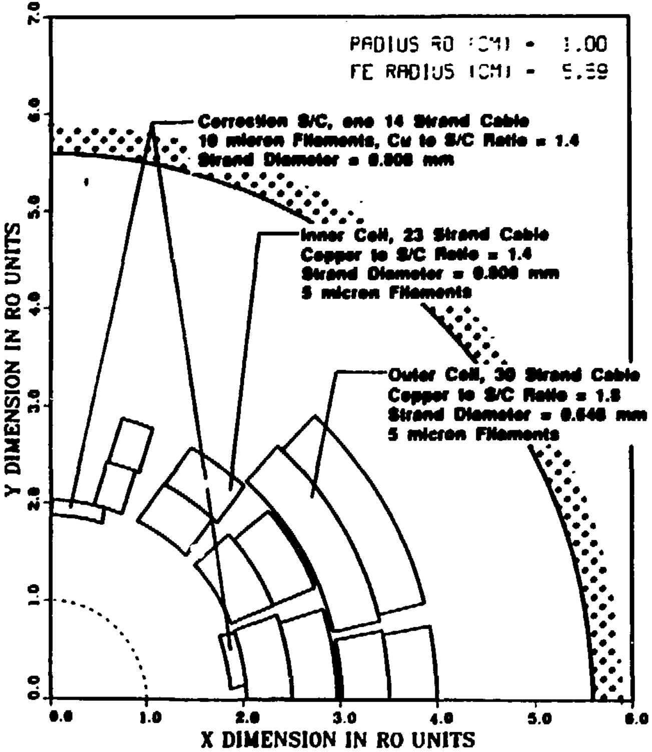


Figure 8

THE RATIO OF MAGNETIZATION SEXTUPOLE AND
DECAPOLE TO THE TRANSPORT CURRENT DIPOLE
AS A FUNCTION OF DIPOLE CENTRAL INDUCTION
WITH PASSIVE SUPERCONDUCTOR CASE B

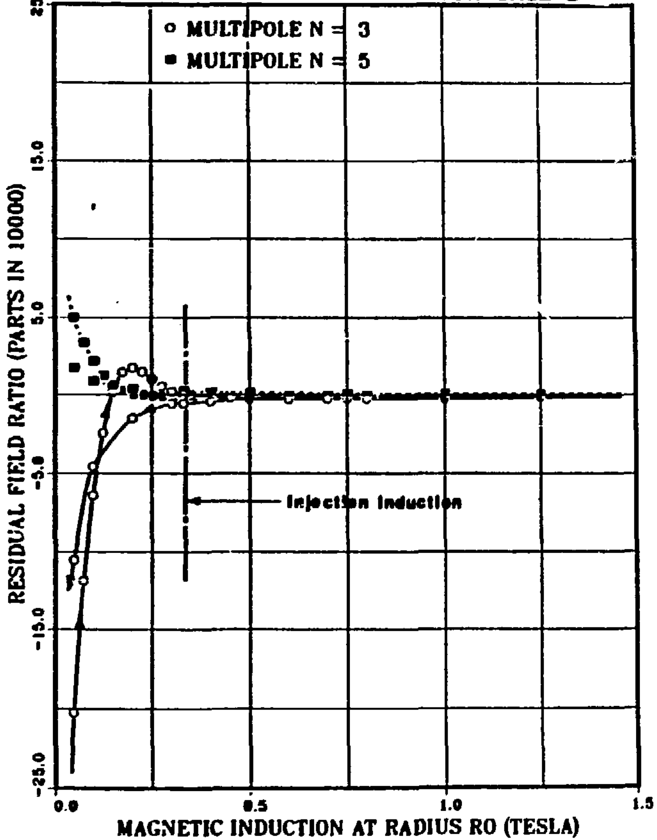


Table 1
A COMPARISON OF SEXTUPOLE RATIOS AT LOW FIELDS WITH AND WITHOUT PASSIVE SUPERCONDUCTOR CORRECTION

Central Induction# (tesla)	Sextupole to Dipole Ratio (units)*		
	without Correction	Correction Case A	Correction Case B
0.100	-22.69	11.14	-6.39
0.150	-17.85	4.17	0.17
0.200	-13.34	1.76	1.75
0.250	-10.30	0.67	1.00
0.300	-8.17	0.06	0.22
0.330	-7.16	0.01	0.04
0.350	-6.62	0.01	0.00
0.400	-5.57	-0.06	-0.10
0.500	-4.15	-0.19	-0.27
0.600	-3.30	-0.18	-0.27
0.800	-2.26	-0.15	-0.24
1.000	-1.68	-0.17	-0.25
1.250	-1.23	-0.10	-0.17
1.500	-0.94	-0.07	-0.13

Induction at the Dipole Center due to the Transport Current
* 1 unit = 1 part in 10000 taken at a 10 mm radius

Table 2
A COMPARISON OF SEXTUPOLE RATIOS AT LOW FIELDS WITH PASSIVE SUPERCONDUCTOR AS A FUNCTION OF TEMPERATURE

Central Induction# (tesla)	Sextupole to Dipole Ratio (units)*		
	Correction 1.8 K	Correction 4.3 K	Correction 4.5 K
0.100	16.45	11.14	10.48
0.150	8.83	4.17	3.81
0.200	3.88	1.76	1.61
0.250	1.70	0.67	0.59
0.300	0.62	0.06	0.03
0.330	0.38	0.01	0.00
0.350	0.31	0.01	-0.01
0.400	0.12	-0.06	-0.07
0.500	-0.12	-0.19	-0.20
0.600	-0.12	-0.18	-0.18
0.800	-0.14	-0.15	-0.15
1.000	-0.22	-0.17	-0.16
1.250	-0.13	-0.10	-0.10
1.500	-0.12	-0.07	-0.07

Induction at the Dipole Center due to the Transport Current
* 1 unit = 1 part in 10000 taken at a 10 mm radius

3 percent. It is reasonable to expect a magnet-to-magnet variation of the magnetization field multipole components to be about 5 or 6 percent. In a magnet system with passive superconductor the sextupole variation from magnet to magnet can be expected to be about 0.5 units.

Proximity coupling in either the magnet superconductor or the passive superconductor must be avoided. Proximity coupling can be eliminated by spacing the filament at least 1.2 microns apart in a copper matrix. If the matrix copper is poisoned with manganese, the filament spacing can be reduced. Recent experiments at the Brookhaven National Laboratory suggest that magnetization due to proximity coupling decays faster than does magnetization in the superconducting filaments by themselves.[19]

Recent experiments at LBL suggest that the magnetization decay rate is proportional to J_c and filament diameter. This suggests that the magnetization generated by the magnet superconductor and the passive superconductor will decay together. It is expected that the magnetization sextupole generated by the correction superconductor will continue to cancel the magnetization sextupole generated by the magnet coil superconductor as time progresses. This hypothesis has not been tested by an experiment.

CONCLUDING COMMENTS

Passive superconductor inside the coils of the SSC dipole can potentially greatly reduce the sextupole and decapole due to magnetization of the coil superconductor. This correction will occur over a wide range of magnetic inductions from 0.2 T to full field. (The 14-pole component can also be controlled by a more complex arrangement of the superconductor.) The passive superconductor should extend over the full straight section length of the superconductor dipole magnet. (There is no need to bring the passive superconductor over the dipole magnet ends.) The passive superconductor will increase the superconductor requirements of the SSC dipole by 4 to 5 percent depending on the case. (Less superconductor is required for passive correction than would be required to build powered continuous dipole correction coils.) The case of passive superconductor to correct the sextupole and decapole will permit one to eliminate the continuous powered correction coils down the bore of each dipole magnet.

ACKNOWLEDGEMENTS

The author thanks J. M. Peterson of the SSC-CDG for his many comments. The author also acknowledges the many conversations with W. S. Gilbert of the Lawrence Berkeley Laboratory and A. K. Ghosh of Brookhaven National Laboratory.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. M. A. Green, IEEE Transactions on Nuclear Science NS-18 (3), p. 664, June 1971.
2. H. C. Brown, et al, IEEE Transactions on Magnetics 21 (2), p. 979, March 1985.
3. H. E. Fisk, et al, "Magnetic Errors in the SSC", Report of the SSC Central Design Group SSC-7, April 1985.
4. A. Chao and M. Tigner, "Requirements for Dipole Field Uniformity and Beam Tube Correction Windings", SSC-N-183, May 1986.
5. D. Neuffer, "A Novel Method for Correcting the SSC Multipole Problem", SSC-172, April 1988.
6. M. A. Green, "Residual Fields in Superconducting Magnets", published in the Proceedings of the MT-4 Conference at Brookhaven National Laboratory, , p. 339, 1972.
7. W. J. Carr, IEEE Transactions on Magnetics, MAG-21 (2), p. 335.
8. M. N. Wilson, Superconducting Magnets, Clarendon Oxford Press, Oxford, UK, pp. 174-181, 1983.
9. E. W. Collings, "Stabilizer Design Considerations in Ultrafine Filamentary Cu/Ti-Nb Composites", Proceedings of the 6th Workshop on Niobium-Titanium Superconductors, University of Wisconsin, Madison, WI, 1986.
10. M. A. Green, Advances in Cryogenic Engineering 33, Plenum Press, New York, 1987.
11. D. A. Herrup et al., "Time Variations of Fields in Superconducting Magnets and their Effects on Accelerators", IEEE Transactions on Magnetics, MAG-25, No. 2, 1989.
12. M. R. Beasley et al., Physical Review 181, pp. 682-700, May 1969.
13. W. S. Gilbert et al., "Magnetic Field Decay in Model SSC Dipoles", IEEE Transactions on Magnetics, MAG-25, No. 2, 1989.
14. M. A. Green, "Field Generated Within the SSC Magnets Due to Persistent Currents in the Superconductor", Proceedings of the Ann Arbor Workshop on SSC Issues, LBL-17249, December 1983.
15. M. A. Green, "Aberrations Due to Asymmetries in Current, Filaments and Critical Current", LBL Engineering Note M6670, August 1987.
16. H.E. Fisk and A. D. McInturff, private communication on the use of a passive superconductor to correct the residual field higher multipoles.
17. M. A. Green, IEEE Transactions on Magnetics, Mag-23, No. 2, p. 506, 1987.
18. M. A. Green, "Calculating the J_c, B, T Surface for Niobium Titanium Using a Reduced State Model", IEEE Transactions on Magnetics, MAG-25, No. 2, 1989.
19. A. K. Ghosh, National Laboratory, private communication on the decay of proximity coupled currents, January 1989.
20. W. S. Gilbert, Lawrence Berkeley Laboratory, private communication on LBL measurements of magnetization field decay, January 1989.