LBL-25139

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the 1988 Applied Superconductivity Conference, San Francisco, CA, August 21–25, 1988

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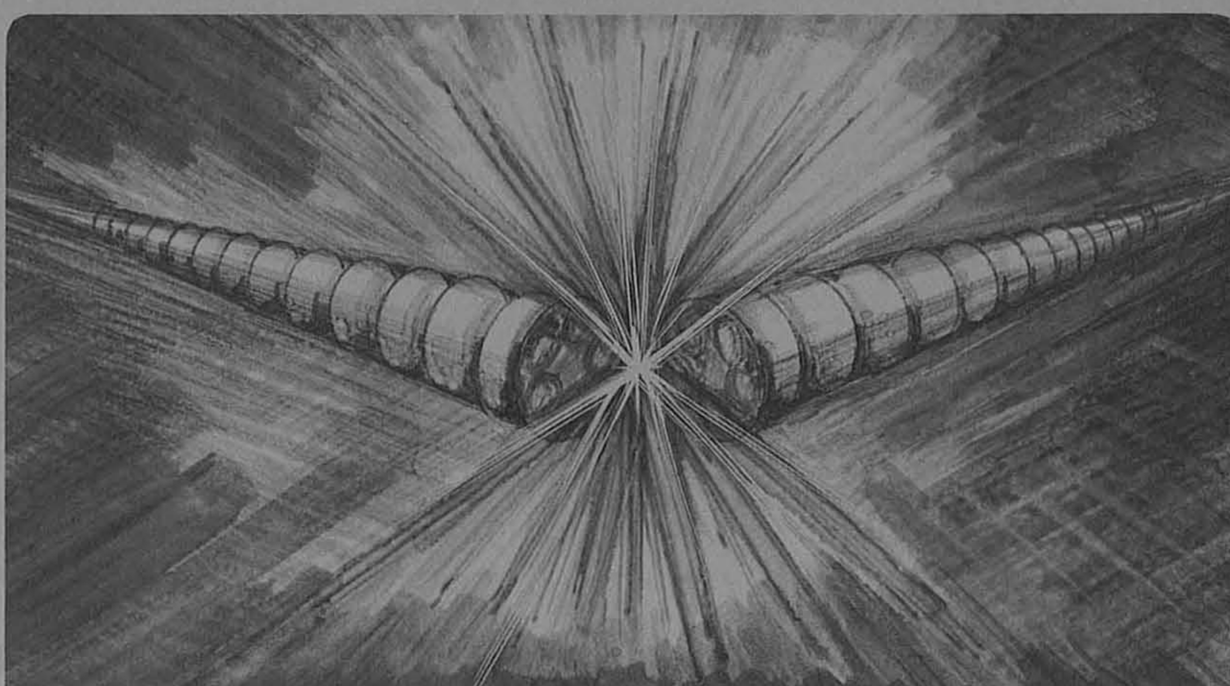
August 1988



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

SSC-MAG-194
LBL-25139

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

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Abstract

We have observed that some of our model SSC dipoles have long time constant decays of the magnetic field harmonics with amplitudes large enough to result in significant beam loss, if they are not corrected. The magnets were run at constant current at the SSC injection field level of 0.3 tesla for one to three hours and changes in the magnetic field were observed. One explanation for the observed field decay is time dependent superconductor magnetization. Another explanation involves flux creep or flux flow. Data are presented on how the decay changes with previous flux history. Similar magnets with different Nb-Ti filament spacings and matrix materials have different long time field decay. A theoretical model using proximity coupling and flux creep for the observed field decay is discussed.

Introduction

The quality of the magnetic field in the model SSC dipoles has been a major concern in that circulating beam can be lost if field imperfections exceed approximately 10^{-4} of the dipole field, especially at the injection field of 0.33 tesla or 1 TeV. Incorporated in the magnet test program has been an extensive magnetic field measurements program at all field levels. Because of magnetization currents flowing in the superconducting filaments, the exact field distribution depends on the path taken to reach a given field. We have been careful to follow a standard excitation path. An example is shown in Fig. 1, with the complete excitation and measurement cycle being from zero field to 6.6 tesla and then decreasing to zero.

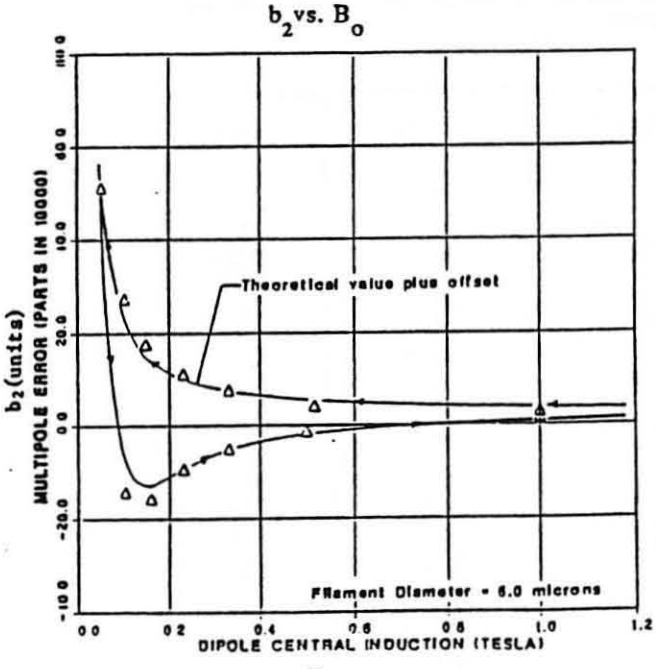

Fig. 1. Normal Sextupole Term

Generally, it was found that the magnetic field non-uniformities repeated quite well, but sometimes there were differences that were unexpected. These differences were traced to different delay times between the magnet excitation and magnetic field measurement; since no decay was expected, there was no standard delay time. When we looked for field decay with time, we found it. Several magnets with different superconductor designs were tested for magnetic field decay and some of that data is presented here. The largest effect is seen in the normal sextupole component, although it also appears in the other multipoles allowed in a dipole. In this paper, we will focus on the sextupole.

Figure 2 shows the effect of different excitation times. In the cycle case, the magnet is ramped to 6600 A at 16 A/S, back to 50 A, and up to 320 A at the same rate for a total of about 15 minutes before the decay measurements begin. When this cycle is interrupted to make magnetic measurements on the upramp and downramp, the time is increased to about 120 minutes. We call this a "sweep". The decay after the fifteen minute cycle is roughly linear on a semi-log scale, the first three measurements which take six minutes not lying on the straight line. For the two hour sweep, the first ten measurement, which take about twenty minutes, do not lie on the straight line which applies for the next hour of decay. The straight line slopes for the cycle and sweep modes are the same. The significance of this linear semi-log behavior is discussed below in the Explanation section.

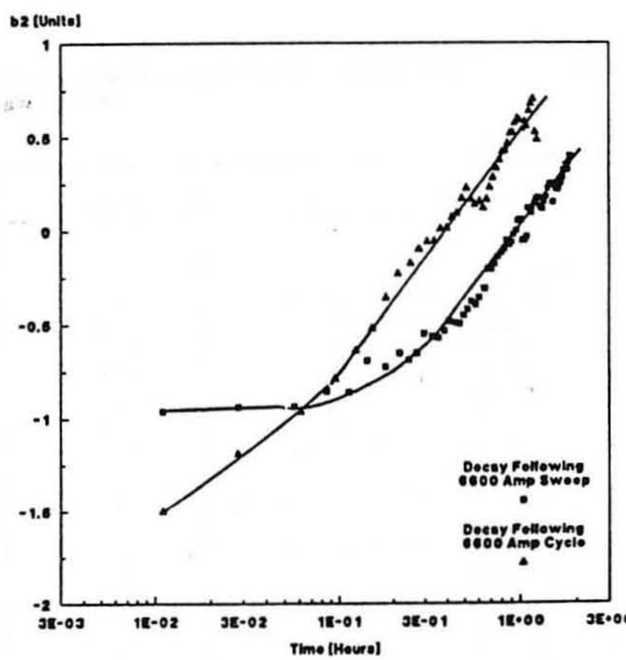

Fig. 2. 320 A Sextupole Decay; Magnet D-15A-6
Cycle ≈ 15 min. 0A → 320 A decay
Sweep ≈ 120 min. 0A → 320 A decay

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

Manuscript received August 22, 1988.
Revised October 25, 1988.

Figure 3 shows that the decapole also changes with time. Figures 4 and 5 show the injection sextupole field decays for four different magnets at 4.3 K. The magnets are almost identical except for their superconductors, which are listed in Table I.

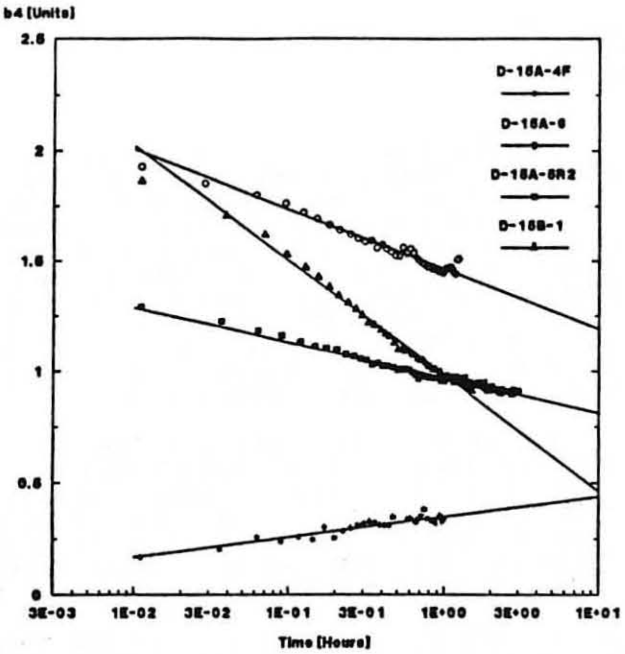

Fig. 3 Decapole Decay - Four Magnets

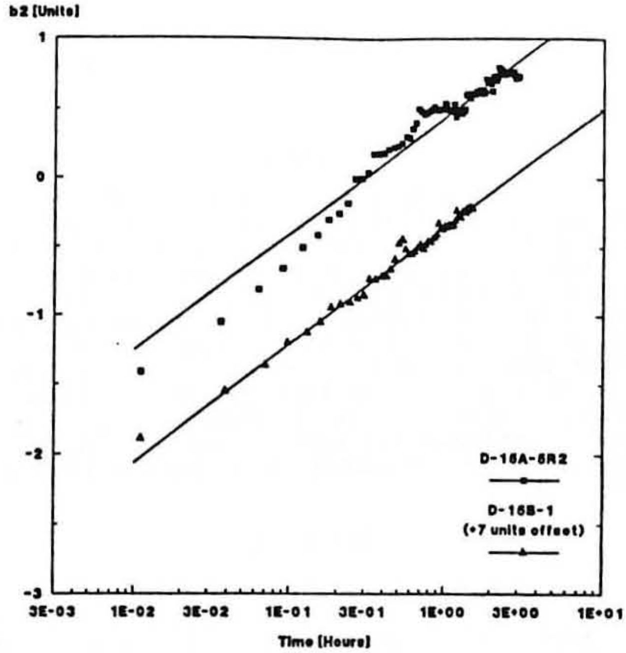

Fig. 4. Sextupole Decay - Two Magnets, Flux Creep Only

Table 1. A Comparison of the Superconductor in Four LBL Dipoles in Which Long Time Constant Field Decay was Measured.

Magnet --->	D-15A-4F	D-15A-5R2	D-15A-6	D-15B-1
Inner Layer				
Number of Strands in Cable	23	23	23	23
Strand Diameter (mm)	0.808	0.808	0.808	0.808
Normal Metal to S/C Ratio	1.26	1.3	~1.35	1.52
Filament Diameter (μm)	4.7	6.0	5.3	5.0
Filament Spacing (μm)	0.4*	1.5	0.53	1.2
Material Between Filaments	Cu*	Cu	Cu-Mn**	Cu
J_c at 5 T and 4.2 K (A mm^{-2})	2600	~ 2700	~2700	2650
Strand Twist Pitch (twists per in.)	2.0	2.0	2.7	0
Cable Twist Pitch (twists per in.)	2.0	1.6	2.2	1.6
Outer Layer				
Number of Strands in Cable	30	30	30	30
Strand Diameter (mm)	0.648	0.648	0.648	0.648
Normal Metal to S/C Ratio	1.76	1.8	~1.35	1.61
Filament Diameter (μm)	4.7	6.0	4.3	5.0
Filament Spacing (μm)	0.4*	1.5	0.43	1.0
Material Between Filaments	Cu*	Cu	Cu-Mn**	Cu
J_c at 5 T and 4.2 K (A mm^{-2})	2618	~ 2700	~2700	2600
Strand Twist Pitch (twists per in.)	2.0	2.0	5.4	2.0
Cable Twist Pitch (twists per in.)	2.0	1.6	4.9	1.6

*This superconductor is quite complex. The conductor consists of 52 μm diameter bundles of superconductor with 0.4 μ spacing between filaments within the bundle. The filaments are not round. The spacing between the filament bundles is about 3.5 μm.

**The filaments are nearly round and uniformly distributed in the conductor with manganese doped copper between filaments.

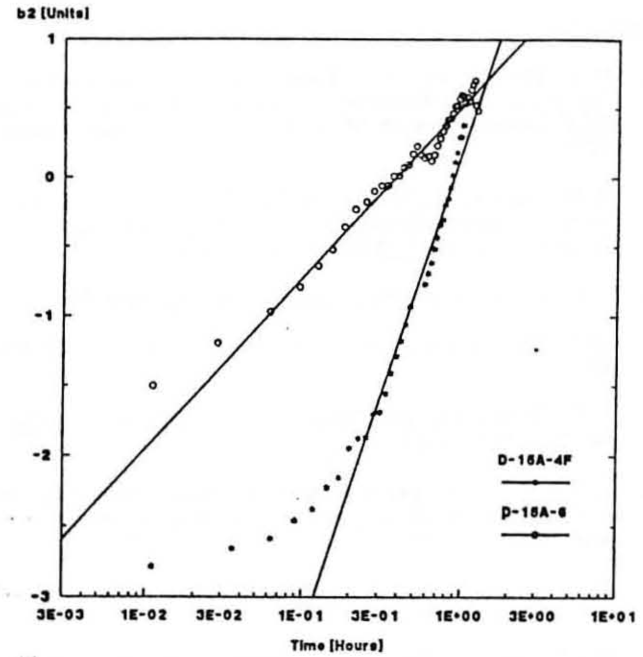

Fig.5 Sextupole Decay - Two Magnets, Flux Creep Plus Proximity Coupling

Explanation for the observed Field Decay

Long time constant decays of the sextupole component of field are observed in all of the dipole magnets tested, when a quiet power supply was used. All decays which were observed occurred in a direction which is consistent with a reduction of magnetization. In magnets D-15A-5R2 and D-15B-1, the decays exhibited a log t time dependence (see Figure 4) which is similar to the decay time dependence observed by Fermilab[1,2] in the Tevatron magnets.

The log t dependence indicates that the circulating current in the superconductor decreases with a log t dependence as long as there is no excitation of these currents by a flux change. The log t dependence of the circulating current decay suggests that the decay is due to flux vortex motion (or flux creep). Flux creep, studied in 1962 by Anderson[3], is explained as the thermally activated motion of flux quanta through the conductor pinning sites. Beasley et al.[4] have shown a number of important effects. The effect is a bulk pinning effect which is proportional to the volume of the conductor. The rate of decay also appears to be proportional to temperature and the magnitude of the critical current. As the circulating currents decay away from the J_c, H, B critical surface, the rate of decay is reduced.

Table 1 compares the superconductor in the four nearly identical, one-meter long dipole magnets. The superconductor in the inner coils of the magnet has a normal metal-to-conductor ratio of 1.26 to 1.35 with filament diameters of 4.7 μm to 6.0 μm and a critical current density at 5 T and 4.2 K of about 2650 A mm^{-2}. The outer layer superconductor has a wider variation of normal metal-to-superconductor ratio (1.35 to 1.8) and filament diameters (4.3 to 6.0 μm). The critical current density of 5.0 T and 4.2 K is the same as the inner layer superconductor. The factor which differs among the four magnets is the spacing between the filaments. Dipole D-15A-5R2 and D-15B-1 which exhibits the lowest decay have filament spacings of 1.0 to 1.5 μm. Dipoles D-15A-4F and D-15A-6 which exhibit higher rates of decay despite smaller filament diameters have filament spacings of 0.4 to 0.53 μm. The small filament spacings suggest that sextupole decay may also be related to proximity coupling.[5] The decay in proximity coupling between filament would also result in a decrease in superconductor magnetization.

According to E. W. Collings[6], one can argue for a faster rate of decay in the proximity coupling currents because the region between filaments behaves like a weakly pinned superconductor with a lower T_c than the superconductor within the filaments. The magnitude of the proximity coupling currents is related to filament spacing, the filament bundle size, and material between the filament.

To test the hypothesis of proximity coupling as one source of magnetization (which then decays away), the SCMAG04 computer code[7] was used to estimate the effect of superconductor magnetization (including proximity coupling) on the sextupole at a control induction of 0.33 T (when the magnet has been charged to high field, brought down to 0.05 T, then brought back up to 0.33 T). If one includes the extra magnetization due to proximity coupling measured by Brookhaven National Laboratory for the Furakawa cable used in magnet D-15A-4F[8] one gets an extra negative sextupole of 3.to 4 units at a central induction of 0.33 T. If one dopes the matrix material, one should also reduce the magnetization due to proximity coupling[9]. The addition of manganese to the copper in the superconductor of magnet D-15A-6 does reduce coherence of the copper, and it appears to reduce the proximity coupling between the filaments. The extra sextupole component at 0.33 T observed in dipole D-15A-6 is also reduced.

Unfortunately it is difficult to make a direct comparison between magnet D-15A-4F and D-15A-6 because the conductors in the two magnets are quite different in their structure. The conductor in magnet D-15A-4F is complex consisting of many 52 μm diameter bundles of 4.7 μm diameter filaments spaced 0.4 μm apart with copper between the filaments. The bundles of filaments are about 3.5 μm apart, and there is probably no proximity coupling between bundles. If the D-15A-4F magnet conductor had spacings between the filaments of 0.4 μm throughout the conductor (instead of in 52 μm bundles), the proximity coupling magnetization would be at least an order of magnitude more than that measured in the dipole D-15A-4F conductor. The Supercon conductor used in dipole D-15A-6, which has manganese doped copper between filaments, has a uniform filament spacing throughout the conductor, yet the measured proximity coupling magnetization is smaller than that measured in the D-15A-4F superconductor.[9,10] Magnet measurements suggest that the manganese doping does really reduce proximity coupling but not enough to completely eliminate it or the resultant field decay. Calculations using the SCMAGØ4 program suggest that most of the proximity coupling occurs in the outer layer of the magnet (where the filament spacing is smaller and the field is lower), and that there is almost no proximity coupling in the inner layer superconductor. The filament distribution in these two magnets are displaced in Figures 6 and 7.

In Table 2, we list the slopes of the linear portions of the sextupole vs. log time curves for the four magnets shown in Figures 4 and 5. The slopes are the sum of the flux creep and proximity coupling component, if any.

Table 2

Magnet	Slope b_2 (units)/decade (time)
D-15A-5R2	0.85
D-15B-1	0.85
D-15A-6	1.22
D-15A-4F*	3.47

* The power supply drifted some 5A/hour during this decay measurement. For the other three magnets, the current drift was less than 0.3A/hour. The decay of magnet D-15 -4F will be remeasureed with the improved power supply.

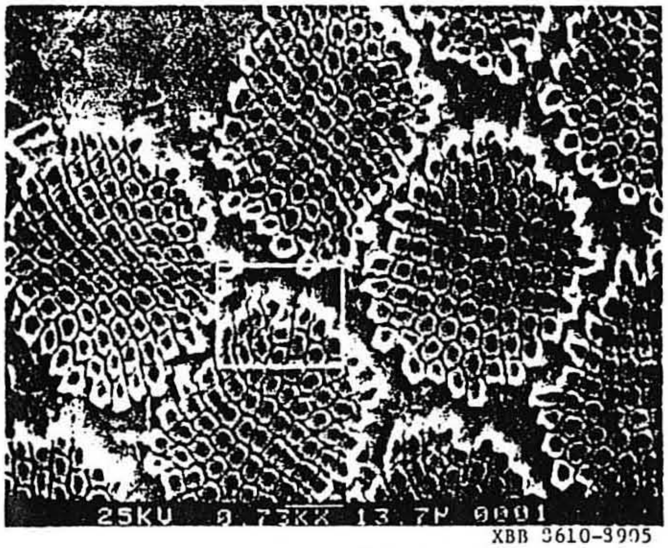

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Fig. 6 Photo - Furakawa

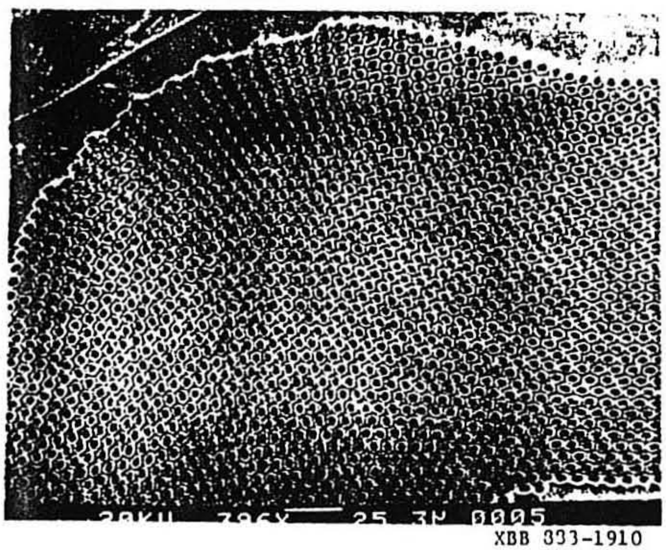

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Fig. 7 Photo - Supercon (Mn)

Conclusions

Slow magnetic field changes due to decay of magnetization current was observed in all of the magnets tested. The magnets with conductor which have filament spacings of 1.5 μm exhibited sextupole component decay with a log t dependence. When the filament spacing is reduced to 0.53 μm or below, the observed magnetization sextupole was increased and the subsequent decay was also increased. An explanation based on proximity coupled currents (for the cases with small filament spacings) and their decay of these currents seems qualitatively correct but quantitative predictions require more data on the candidate conductors. Doping of the copper in the interfilamentary region with 0.5% manganese does reduce the proximity effect.

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