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Authors

Gilbert, W S
Althaus, R F
Barale, P J
et al.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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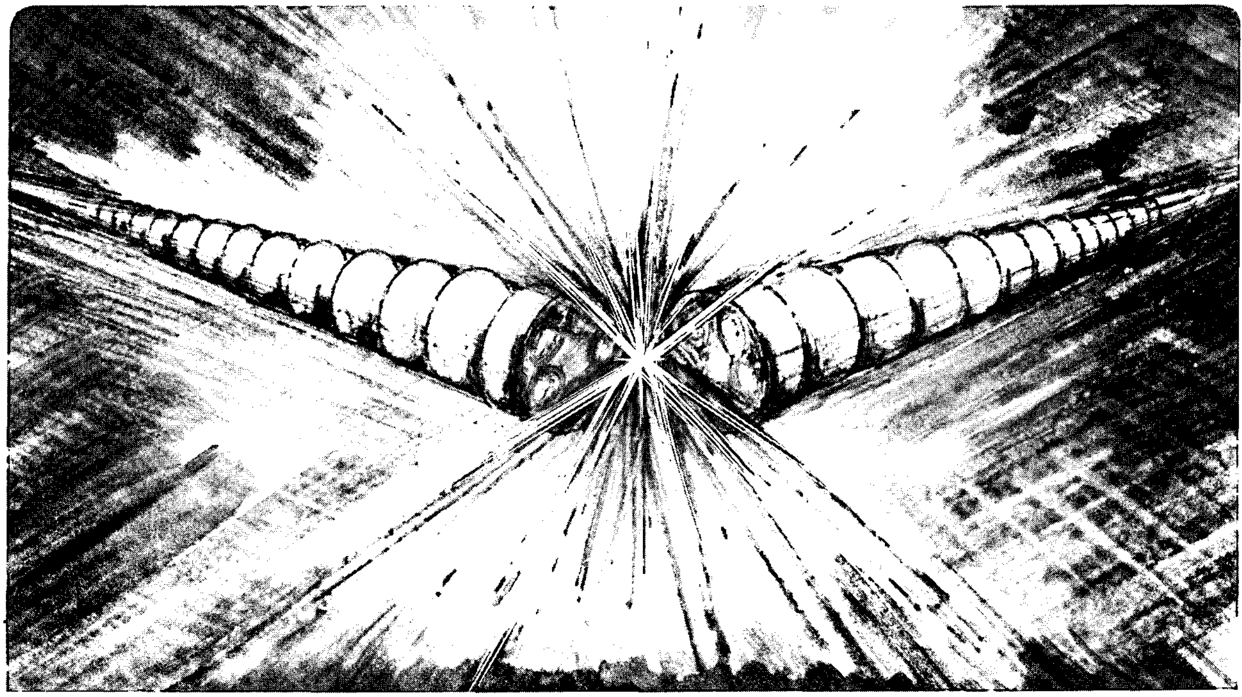

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Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

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ABSTRACT

The sextupole fields of model SSC dipole magnets have been observed to change with time when the magnets are held at constant current under conditions similar to injection into the SSC accelerator. The changes in the sextupole component have close to a linear log time dependence, and is felt to be caused by flux creep decay of the magnetization currents in the superconductor filaments. Measurements of this decay have been made under various conditions. The conditions include various central field inductions and changes of field prior to when the decay was measured. The measured field decay in the dipole's sextupole is proportional to the magnitude and sign of the sextupole due to magnetization which was measured at the start of the decay. This suggests that the decay is a bulk superconductivity flux creep. Proximity coupling appears to play only a minor role in the flux creep according to recent LBL measurements with a stable power supply.

INTRODUCTION

At the 1988 Applied Superconductivity Conference, we presented data on the decay of magnetic field harmonics, at injection, of four model SSC dipole magnets.[1] One of these magnets, D15A-4F, had the power supply drifting at 5A/hr. during the decay. We have since shown that this drift causes an error in the measured field decay and that magnet has been remeasured with a low drift power supply. An additional five magnets have been measured in the past year and this report includes data on the sextupole field decay for all nine magnets. (The 12-pole field decay in the tested quadrupole). The other multipoles will be included in a more comprehensive LBL report.[2]

These measurements are extremely sensitive to details of set up cycles, ramp rates, power supply overshoot and stability. Some of these details are included here and others will be in the more complete report. The measurements with model dipoles are so time consuming and subject to unavoidable small variations in power supply repeatability that small changes in field decay in different magnets wound from superconductors of different designs are likely to be masked. Large variations in field decay were not observed.

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The association of the magnetization field decay with bulk flux creep is most strongly suggested by the linear log time behavior, but we are not aware of any theory that predicts this decay from first principles. Through the use of composite billets with different filament-matrix geometry, we have some data on the behavior of the composite decay with and without proximity coupling.

THE MAGNETIZATION PROBLEM IN SSC OPERATION

Fig. 1 shows the sextupole field at the reference radius of 1 cm as a function of magnet excitation. The current is ramped at approximately 6A/s from some low current, say 50A, to the injection current of 320A (approx. 0.33 tesla). The current is held constant from one to three hours while protons are injected into the two main rings. Then the ramp is resumed until the operating field is reached at 6600A. The stored beams interact for about a day, at which time the current is ramped down to near zero, the beams are dumped and the entire process is repeated. The reason the sextupole field changes with magnet current is the presence of magnetization currents in the superconducting filaments; otherwise the field shape would be constant and determined only by the transport currents flowing in the magnet coils. The observed slow decay of the magnetization sextupole can result in beam loss during the extended injection period. When ramping is resumed, the sextupole suddenly regains its pre-decay value, resulting in rapid beam loss.

Powered correction elements can correct for the magnetization sextupole if it is accurately known. The time decay of the field complicates this problem and if different magnets made from different superconductors were to have fields decay at different rates, the problem would be even more difficult. One of our goals was to see if there were differences in field decay for different conductors designs.

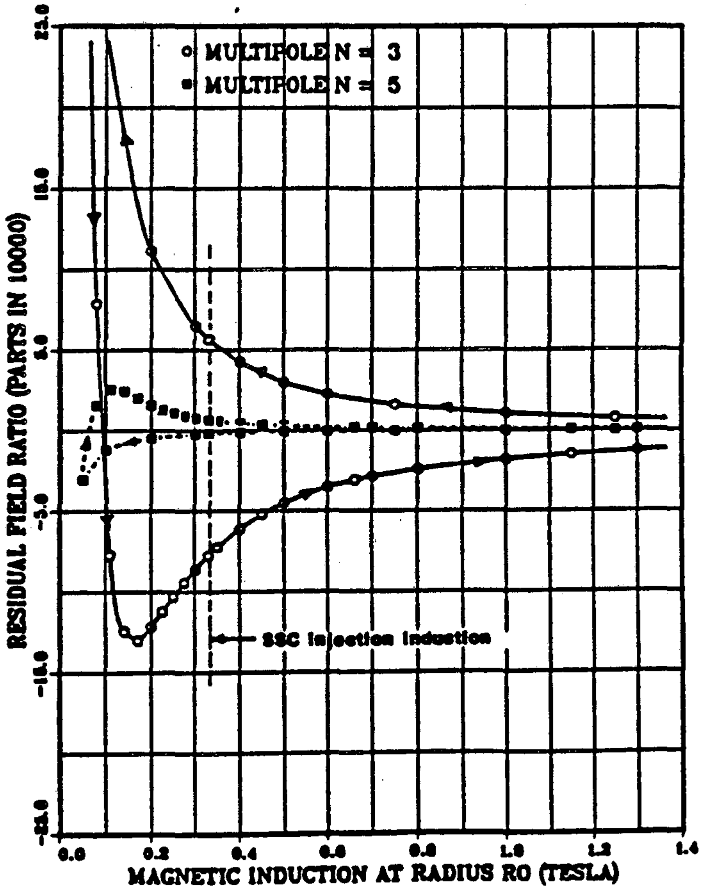
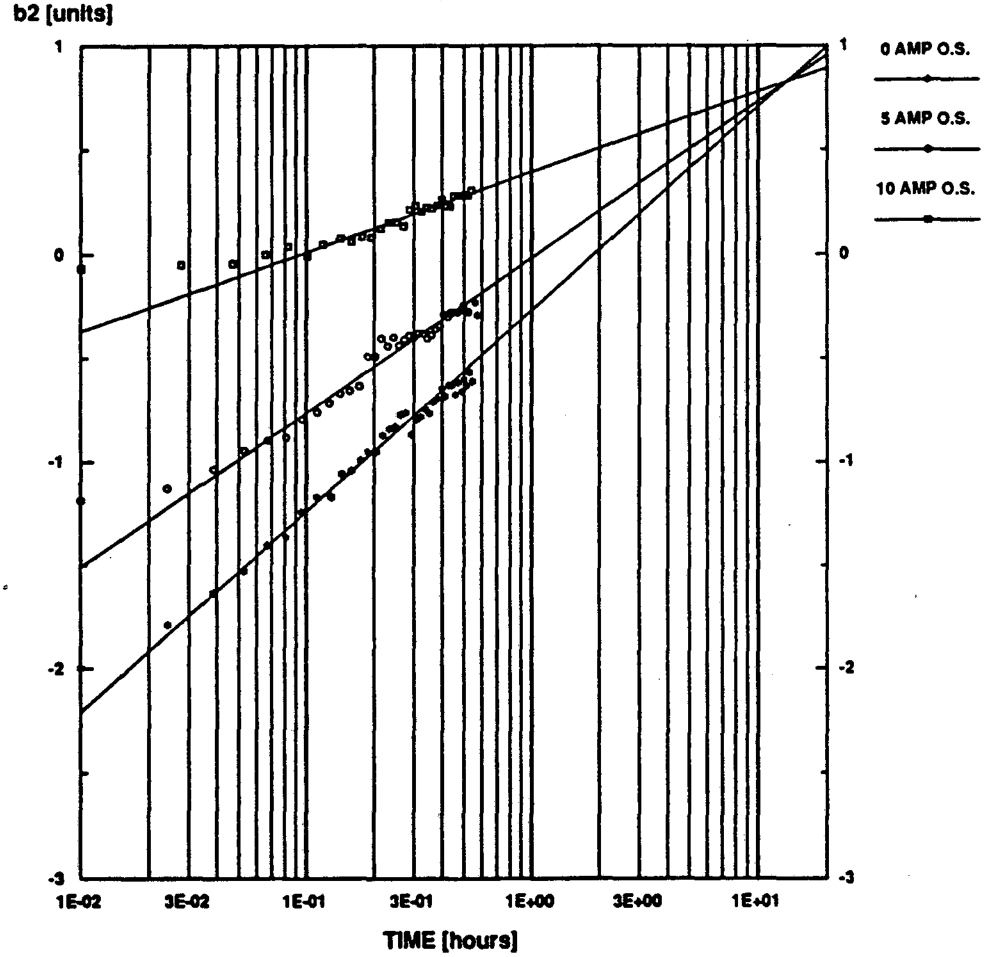


Fig. 1 The ratio of magnetization sextupole and decapole to the transport current dipole as a function of dipole central induction.

EFFECT OF POWER SUPPLY OVERSHOOT ON DECAY

When the current ramp is smoothly stopped at 320A, we get the sextupole decay curve shown in Fig. 2. The linear log time relationship indicates a flux creep behavior.[3] Current overshoot was simulated in other runs by allowing the ramps to proceed to either 325A or 330A and then decreasing the currents to 320A before the decay data were taken. One can see that the overshoot reduced the initial sextupole fields and the subsequent decay rates.

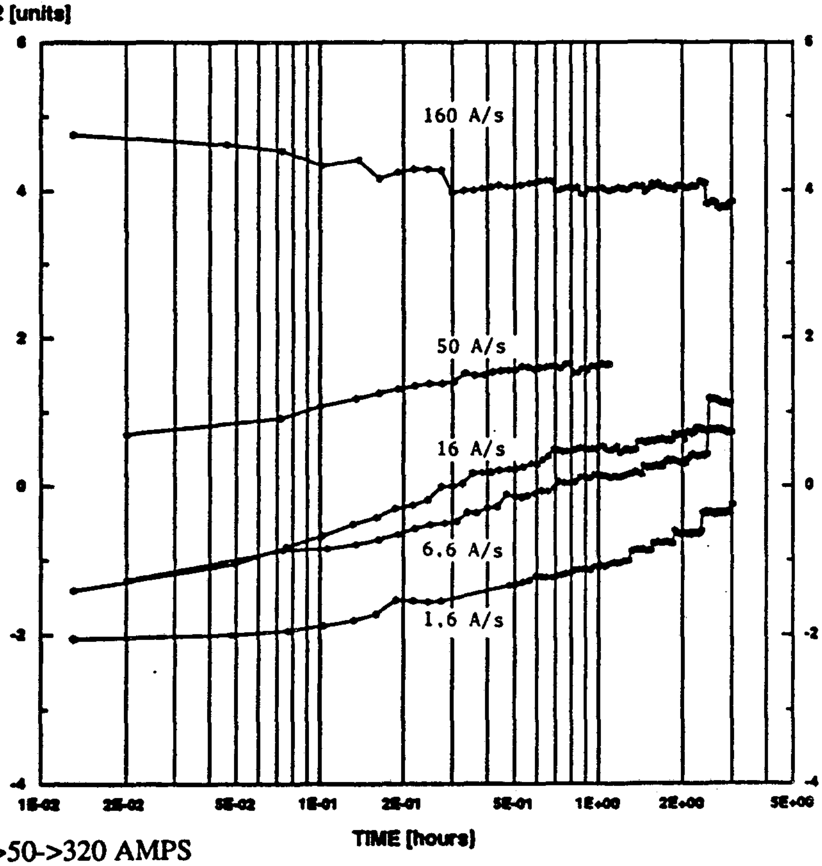


CYCLE 1: 0->6600->50->320 AMPS AT 16 A/S
CYCLE 2: 0->6600->50->325->320 AMPS AT 16 A/S
CYCLE 3: 0->6600->50->330->320 AMPS AT 16 A/S

Fig. 2 LBL 1 Meter Model Magnet D-15A-5R3 320 A Decay @ 4.3K with overshoot.

EFFECT OF RAMP RATE ON DECAY

In Fig. 3 are shown the sextupole field decay curves at 320A for excitation ramp rates of 160, 50, 16, 6.6, and 1.6 A/s. The excitation cycle is from 0 to 6600A, 6600 to 50A, and 50 to 320A, which is then maintained for the one to three hour decay. Fig. 1 shows that the equilibrium sextupole field, in going from 50A to 320A, goes from more than positive 25 units (a unit is 10^{-4} of the dipole field) to a negative 7 units, going through a minimum of negative 12 units at 150A. It is clear that the magnetization currents take tens of seconds to stabilize. This could be a measure of the field diffusion time or an inward flux creep. Most of our data have been taken with a ramp rate of 16 A/s and the decay data are close to those taken at the projected SSC ramp rate of 6.6 A/s.



CYCLE: 0->6.6K->50->320 AMPS

Fig. 3 D-15A-5R2 - Cold Measurements, 320 amp decay @ 4.3K varous ramp rates.

TEMPERATURE EFFECT ON DECAY

Fig. 4 shows sextupole decay at 4.3K and 1.8K for magnet D15A-5R2. The greater magnetization sextupole at injection field is expected as the conductor J_c is greater at the lower temperature. The 1.8K decay seems to be slightly slower. Similar data for magnet D15C-1 appear in Fig. 5. Here the 1.8K decay seems to be considerably slower than at 4.3K.

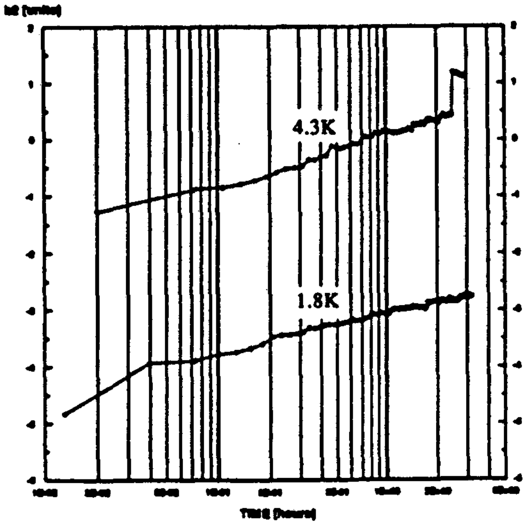


Fig. 4 D-15A-5R2 - Cold Measurements
320 amp decay @ 1.8K vs 4.3K comparison.

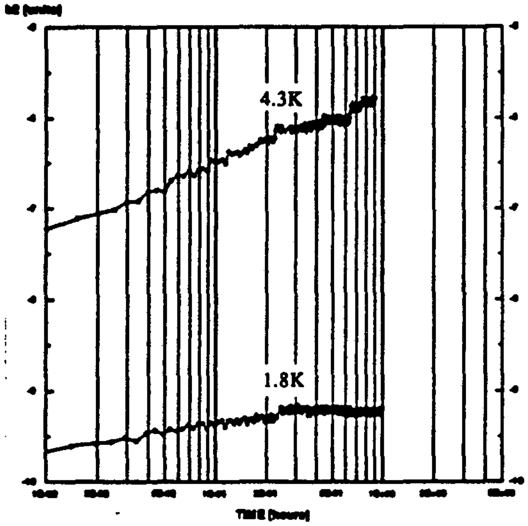


Fig. 5 D-15C-1 Cold Measurements
320 amp decay, 1.8K vs 4.3K comparison.

REPRODUCIBILITY OF DECAY RATES FOR SAME MAGNET

Magnet D15A-5R2 had six sextupole field decays measured under similar set up conditions. For each decay a straight line slope was fitted to the roughly linear log time data. The early, less that 0.1 hour, data usually lie above the fitted slope (slower decay). Often a sudden jump is observed. For these decays, the slopes yield 1.2 ± 0.1 units/decade. This spread is due not only to the data not lying on a perfectly straight line, but on different set up cycles. The 10,000 A power supply sometimes has a variation of a few amperes at the 50A turnaround and at the 320A levels. One wouldn't expect the reproducibility of the set up conditions to be any better for other magnet tests which are at least one month apart. Therefore, our present accuracy on sextupole decay slope is roughly ± 0.1 units/decade. Magnet D-15A-5 was run three different times in a five month period with slightly different pole shims. This should not influence the magnetization effects. The three different configurations are referred to as R1, R2, and R3. All the decay measurements compared below had the same set up cycles at a ramp rate of 16 A/s.

R1 has one decay with slope = 1.20 units/decade
R2 has six decays with slope = 1.18 ± 0.07"
R3 has three decays with slope = 0.98 ± 0.09"

PROXIMITY COUPLING - SMALL FILAMENT SPACING

Proximity coupling, which effectively increases the magnetization by coupling small diameter filaments together, occurs when the filament spacing is too small, less than 1μm. The conductor in magnet D-15A-4FR1 (see Table 2) has a spacing of only 0.4 μm, and has been measured to have a large magnetization at 0.3 tesla.4 The decay data, tentative at this time, show a sextupole decay rate of 1.00 unit/decade, which is about the same as that for other conductors. There is some evidence that the proximity coupling portion of the magnetization decays faster than the bulk property flux creep.

Magnet D-15A-6 also has conductor with small filament spacing, 0.53 μm, but the normal copper is doped with Mn and doesn't show any measured increase in its 0.3 tesla magnetization.

DECAY RATES - DIFFERENT MAGNETS; DIFFERENT CONDUCTORS

In Table 2 are listed the conductor details for the various magnets in which field decay, at injection energy, was measured.

In Table 3 are listed the slopes of the various sextupole decays for similar set up cycles and ramp rate of 16 A/s. As discussed above, the data has enough scatter that one can't attribute the small differences in magnet decays to the conductor designs.

It is worth noting that a dipole magnet has conductor at various magnetic fields and effectively integrates the different magnetization cycles over the entire volume. Laboratory magnetization experiments on conductor at a single field possibly could more precisely probe the differences in field decay associated with different conductor designs.

Table 2 - A Comparison of the Superconductor in LBL Magnets in Which Long Time Constant Decay was Measured.

Magnet--->	D15A-4FR1	D15A-5R1, R2, R3	D15A-6	D15C-1	D15B-1 D15C-2	Quadrupole QA-1R1
				Inner Layer Cable Annealed	Inner Layer Cable Cold Worked	
Inner Layer						
Number of Strands in Cable	23	23	23	23	23	30
Strand Diameter (mm)	0.808	0.808	0.808	0.808	0.808	0.648
Normal Metal to S/C Ratio	1.26	1.3	~1.35	1.52	1.52	1.69
Filament Diameter (μm)	4.7	6.0	5.3	5.0	5.0	5.0
Filament Spacing (μm)	0.4*	1.5	0.53	1.2	1.2	1.2
Material Between Filaments	Cu*	Cu	Cu-Mn**	Cu	Cu	Cu
Jc at 5 T and 4.2K (A mm^{-2})	2600	~2700	~2700	2650	2650	2743
Strand Twist Pitch (twists per in.)	2.0	2.0	2.7	0	0	2.0
Cable Twist Pitch (twists per in.)	2.0	1.6	2.2	1.6	1.6	1.6
Magnetization data (H=0.3T)						
Inner Layer						
2M (mT)	25.6	21.4	16.2	17.1	15.4	15.6
2Me (mT)	3.6	1.3	0.9	0.8	0.6	1.6
Outer Layer						
Number of Strands in Cable	30	30	30	30	30	30
Strand Diameter (mm)	0.648	0.648	0.648	0.648	0.648	0.648
Normal Metal to S/C Ratio	1.76	1.8	~1.35	1.75	1.75	1.69
Filament Diameter (μm)	4.7	6.0	4.3	6.0	6.0	5.0
Filament Spacing (μm)	0.4*	1.5	0.43	1.2	1.2	1.2
Material Between Fialments	Cu*	Cu	Cu-Mn**	Cu	Cu	Cu
J_c at 5 T and 4.2K (A mm^{-2})	2618	~2700	~2700	2582	2582	2743
Strand Twist Pitch (twists per in.)	2.0	2.0	5.4	2.0	2.0	2.0
Cable Twist Pitch (twists per in.)	2.0	1.6	4.9	1.6	1.6	1.6
Outer Layer Magnetization						
2M (mT)	22.3	19.2	-	17.5	17.5	15.6
2Me (mT)	3.1	2.0	-	2.0	2.0	1.6
2 M = magnetization between upramp & downramp current sweeps $2M_e$ = Excess magnetization due to eddy currents						

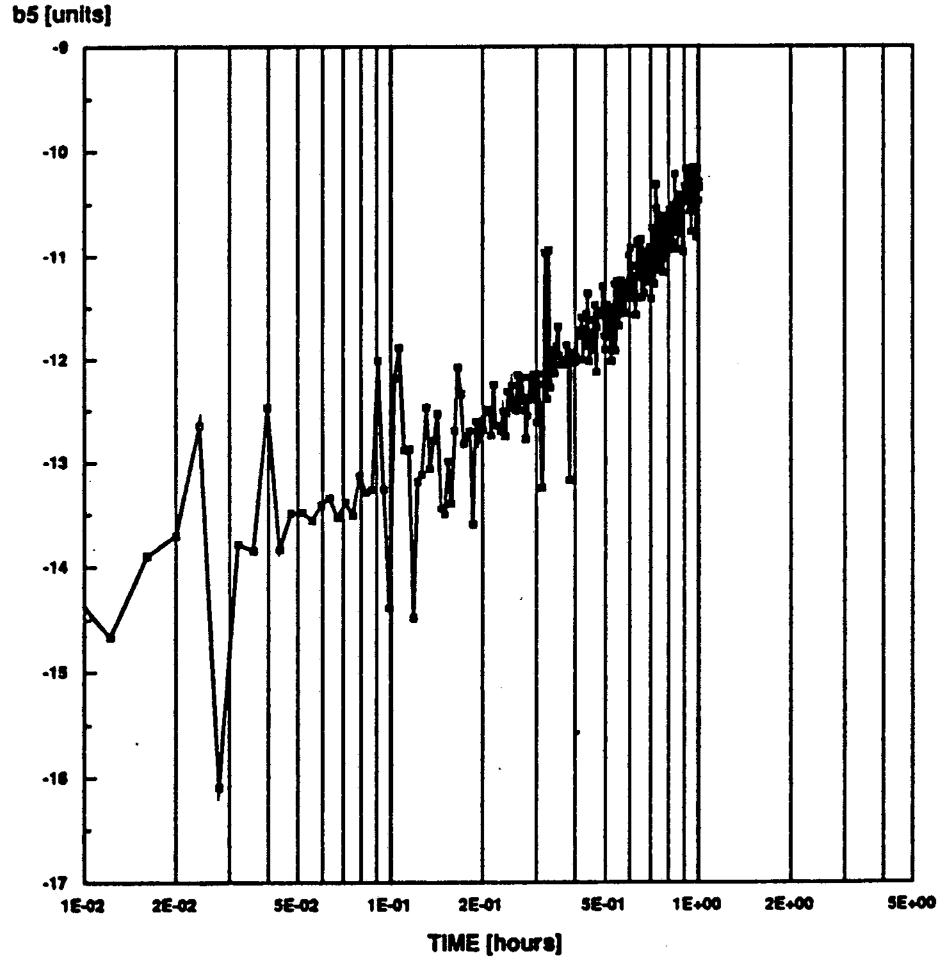
* & ** from page 2 of LBL-25139

Table 3 - b_2 decay @ 320 A, 4.3K

Magnet No.	Decay Slope (units/decade)
D-15A-5R1	1.20
D-15A-5R2	1.18 ± 0.07
D-15A-5R3	0.98 ± 0.09
D-15A-4FR1	1.00 (tentative)
D-15A-6	1.17
D-15B-1	0.85
D15C-1	0.80
QA-1R1 (Quad)	2.7 (b5)

QUADRUPOLE FIELD DECAY

QA-1R1 is a model SSC quadrupole built at LBL. The 12 pole magnetic field harmonic, called b5, is analgous to the sextupole field in the case of the dipoles already cited. The same set up cycle was used for the quadrupole and the decay of the 12 pole field is shown in Fig. 6. The magnetization offset at injection and the rate of decay are both about double that for the case of the dipoles.



CYCLE: 3X(50->6600->50)->320 AMPS @ 16 A/s

Fig. 6 QA-1R1 - Cold Measurements - TBL 35, 320 amp decay @ 4.3K

CONCLUSIONS

The decay of magnetization currents as observed in the LBL-SSC model dipoles is roughly a linear log time relationship, suggesting a flux creep lasting over several hours. We have also measured a surprisingly long time to stablize these fields, some tens of seconds. The decay seems to be a bulk property effect and not particularly sensitive to details of conductor design.

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720