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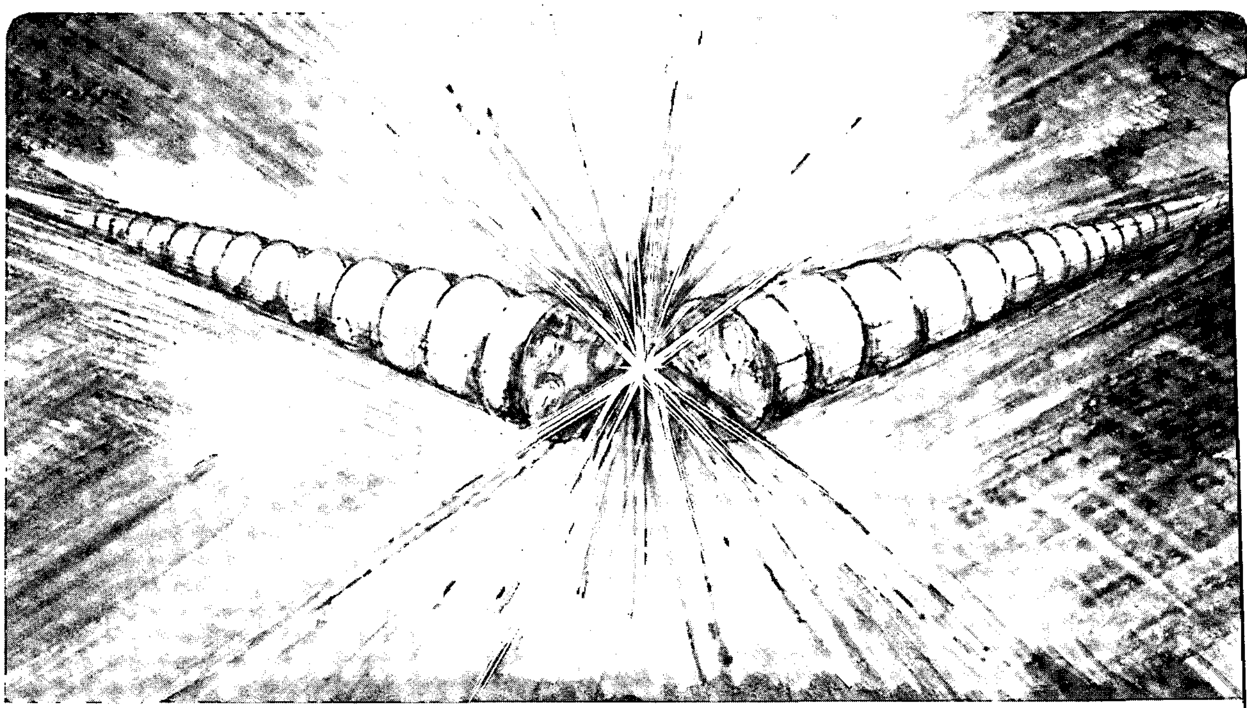

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ABSTRACT

Higher multipoles due to magnetization of the superconductor in superconducting dipole and quadrupole magnets has been observed for over twenty years [1,2]. This report presents measurements of the 12 pole and 20 pole multipoles in a model one-meter long four-centimeter bore SSC type quadrupole built at the Lawrence Berkeley Laboratory (LBL). The measurements were compared with calculations of the field structure using magnetization theory [3]. Good agreement was observed between the measured multipoles and the calculated multipoles. Under conditions equivalent to injection into the SSC at an energy of 2 TeV, about 1.0 unit of 12 pole was observed and 0.05 units of 20 pole was observed. (One unit of field error is a field error of one part in ten thousand.) Magnetization multipole measurements were also done on the first full length (5 meter) SSC quadrupole prototype. Measurements of flux creep decay were made on three one meter quadrupoles and the first five meter long quadrupole.

INTRODUCTION

The LBL SCMAGØ4 computer code has been used to calculate the magnetization multipoles in dipole magnets [4]. The multipoles generated in dipole are the normal symmetric ones; N = 1 (dipole), N = 3 (sextupole), N = 5 (decapole), and so on. (Note: the terminology is different from the one used by the beam dynamics physicists. Normal N = 1 is b_0; normal N = 3 is b_2; normal N = 5 is b_4; and so on.) The multipoles generated within a quadrupole will also be the normal symmetrical ones; normal N = 2 (b_1 or quadrupole, normal N = 6 (b_5 or 12 pole), normal N = 10 (b_9 or 20 pole) and so on.

A cross-section of the 4 centimeter bore LBL quadrupole [5] is shown in Fig. 1. The magnet is symmetrical about the four poles, located at 45 degrees from the x and y axes. Each conductor shown in Fig. 1 is a 30 strand outer SSC cable which has a copper to superconductor ratio of 1.8 in each of the 0.648 mm diameter strands. The SCMAGØ4 program divides each conductor into six parts. The magnetization field is calculated at the center of each of these parts.

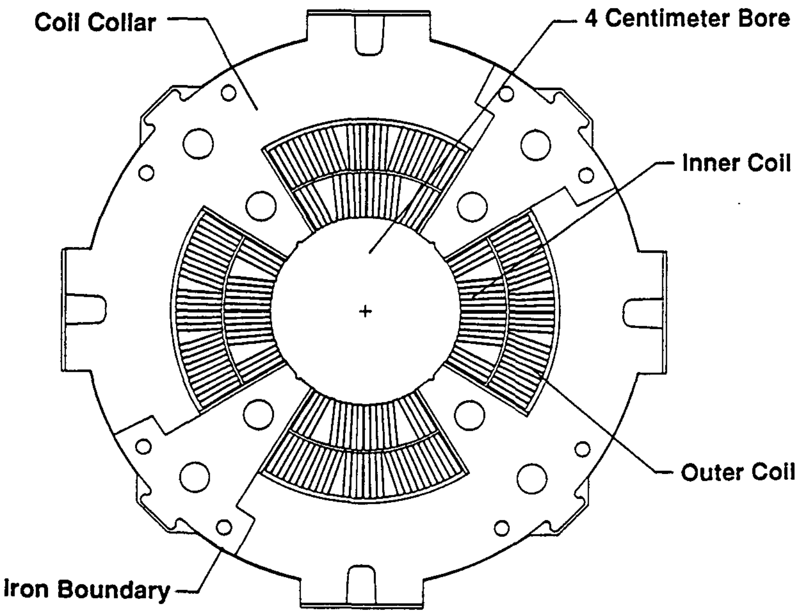

Fig. 1 A Cross-section Coils and Collars of the QCC-401 Four Centimeter Quadrupole

COMPARISON WITH MEASUREMENTS IN THE QSC-401 SHORT QUADRUPOLE

Measurements of the N = 6 (b_5) and N = 10 (b_9) made in the first QC cross-section quadrupole shown in Fig. 1 showed that, at intermediate currents (about 3000 amperes), the N = 6 offset was about -0.38 units. At the same current, the N = 10 offset was about +0.10 units. Figures 2 and 3 compare the measured N = 6 (12 pole) and N = 10 (20 pole) with the calculated N = 6 and N = 10 with the appropriate offsets subtracted from the measured data. The data in Figs. 2 and 3 is plotted in terms of the multipole ratio versus the magnetic induction at a 10 mm radius. The transfer function at a 10 mm radius is 0.332 tesla per 1000 A. The calculated magnetization multipoles assume that the critical current density of the superconductor at 5.0 T and 4.2 K was 2750 A mm-2.

Figure 2 compares the measured N = 6 with the -0.38 unit offset (the inverted triangles) with the calculated N = 6 (the solid line). Figure 3 compares the measured N = 10 with the +0.10 unit offset (the inverted triangles) with the calculated N = 10 (the solid line). In both figures, the filled inverted triangles indicate that the field is going up, and the open inverted triangles indicate that the field is going down.

The width of the N = 6 measured magnetization curve compare favorably with calculation, but there is additional offset in the negative direction at lower fields. It is almost as if there is a small amount of ferromagnetic material present in the magnet. (We have noticed a similar slope in some of the dipoles.) The width of the N = 10 measured magnetization curve is quite consistent with the calculated value. The apparent slope found in the N = 6 measured curve is not present in the N = 10 measured curve.

The agreement between the measured and calculated N = 6 and N = 10 is quite good. The cycle to cycle variation of the N = 6 term can be as much as 0.3 units at an injection energy of 2 TeV depending on the previous flux history of the magnet. The cycle to cycle variation of the N = 10 is between 0.01 and 0.02 units depending on the history of the magnet. The minimum current for the two cycles varied by a couple of amperes (about 5%).

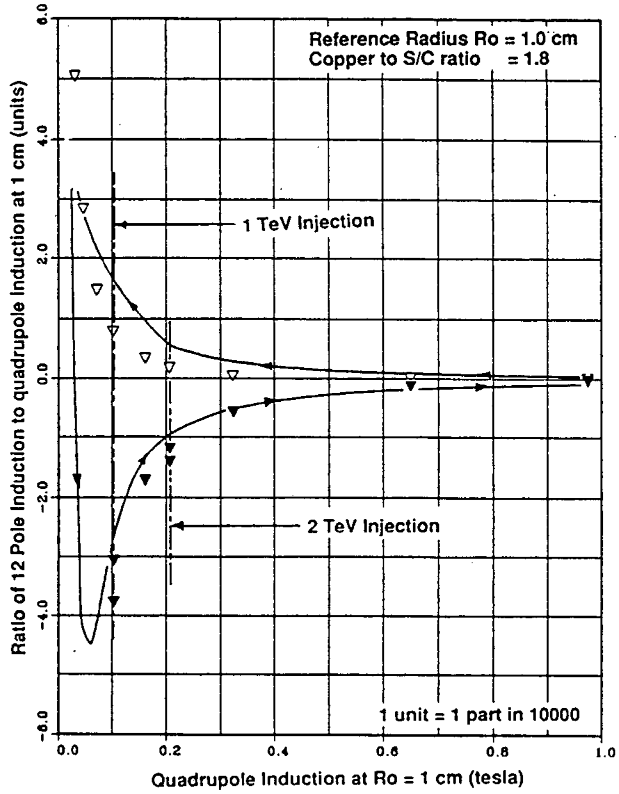

Fig. 2 A Comparison of Measured and Theoretical Magnetization 12 Pole in the QSC-401 Quadrupole versus Quadrupole Induction at R = 1 cm (-0.38 Unit Offset Removed)

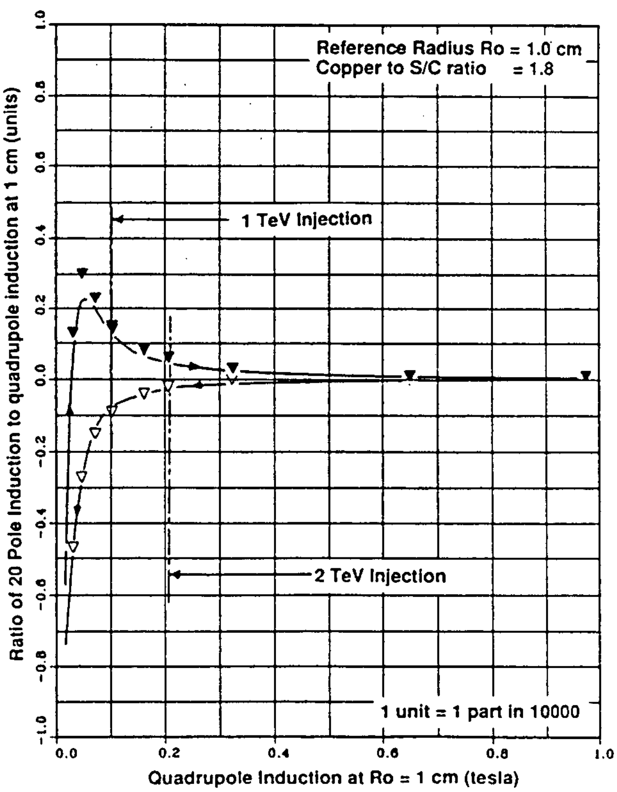

Fig. 3 A Comparison of Measured and Theoretical Magnetization 20 Pole in the QSC-401 Quadrupole versus Quadrupole Induction at R = 1 cm (+0.10 Unit Offset Removed)

COMPARISON WITH MEASUREMENTS IN THE LONG QCC-401 QUADRUPOLE

The QCC-401 quadrupole and its cycle is somewhat different from the QSC-401 quadrupole. The QSC-401 quadrupole measurements were compared to the standard (2750 A mm-2 at 5.0 T and 4.2K) SSC conductor. The conductor in the QSC-401 magnet was quite close to the SSC standard cable. The cable in the QCC-401 quadrupole is different. The inner layer has a critical current density of 2750 A mm-2; the outer layer critical current density was 2620 A mm-2. The minimum current for the QSC-401 test was 97A. The minimum current in the QCC-401 test was 59 A.

In the QCC-401 quadrupole, the measured offset for the N = 6 at 3000 A was about -3.62 units. The N = 10 offset was about +0.19 units. Figure 4 compares the corrected measured N = 6 with the calculated N = 6; Figure 5 compares the measured N = 10 with offset with the calculated N = 10. In both figures, the filled inverted triangles apply to measurements with the field going up, and the unfilled inverted triangles apply to measurements with the field going down.

Width of the measured N = 6 and N = 10 magnetization curves compares very favorably with the previous case, the lower field part of the measured magnetization curve is offset about a half a unit as compared to the calculated value. There is a particular jump toward positive 12 pole at an induction of 0.66 T at a radius of 10 mm. This hump occurs both when the field is rising and when it is falling.The origin of the hump is being investigated, but appear that the hump is unrelated to the superconductor magnetization. Despite the hump, the agreement between measurement and calculation is not too bad.

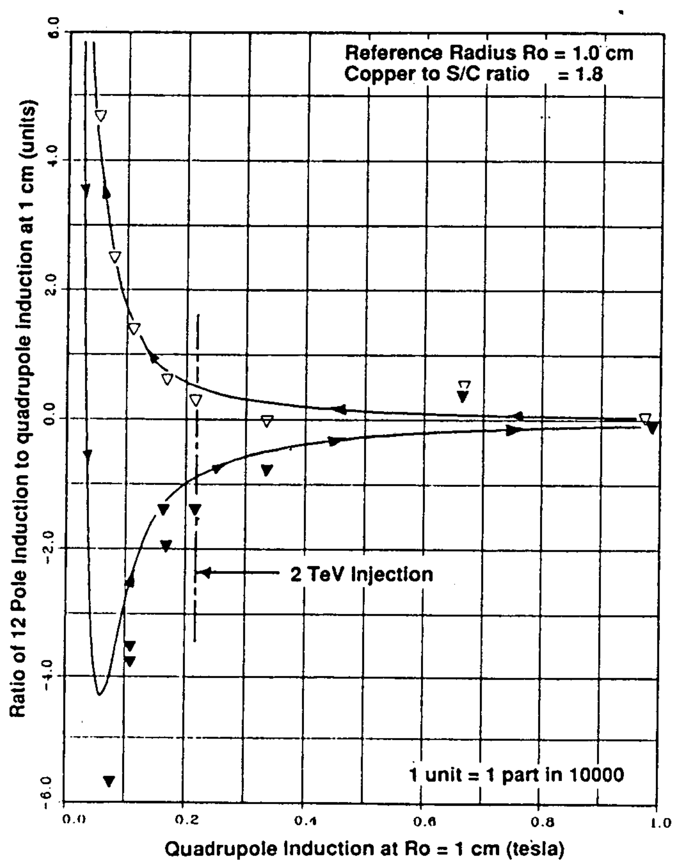

Fig. 4 A Comparison of Measured and Theoretical Magnetization 12 Pole in the QCC-401 Quadrupole versus Quadrupole Induction at R = 1 cm (-3.62 Unit Offset Removed)

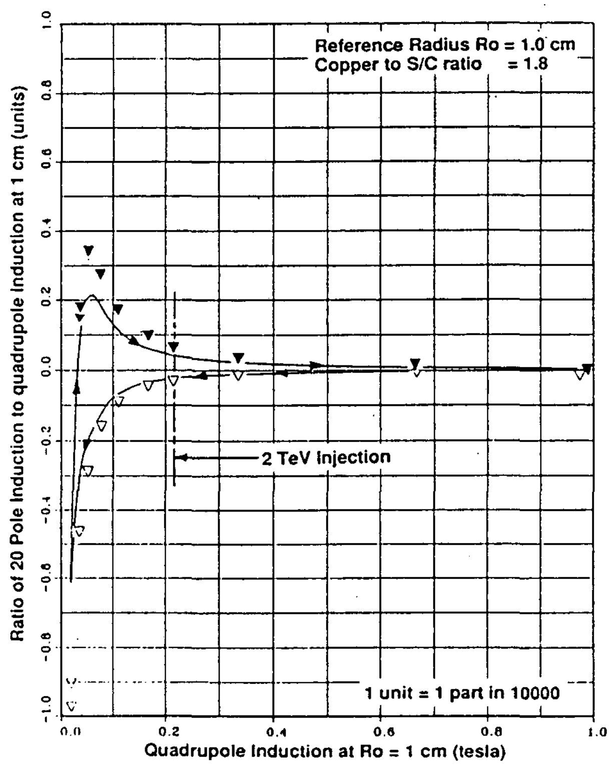

Fig. 5 A Comparison of Measured and Theoretical Magnetization 20 Pole in the QCC-401 Quadrupole versus Quadrupole Induction at R = 1 cm (+0.19 Unit Offset Removed)

MEASURED 12 POLE AND 20 POLE DECAY IN THE QSC-401, QSC-402, QSC-403, AND QCC-401 QUADRUPOLE MAGNETS

The flux creep decay of the magnetization 12 pole and 20 pole was measured in the QSC-401, QSC-402, QSC-403, and QCC-401 magnets. In QSC-401, about 0.1 units of 12 pole decay was observed per decade of time (see Fig. 6), just over 10% of the observed 12 pole decayed per decade. The 20 pole decay rate was about 0.06 units per decade (see Fig. 7). The QCC-401 decay was almost identical to the QSC-401 decay (0.095 units of 12 pole decay and -0.008 units of 20 pole decay) in both the QSC-401 magnet and the QCC-401 magnet. The decay acted in a direction which reduced the amount of the magnetization multipole. QSC-402 had observed 12 pole and 20 pole decay rates which were similar to those observed in the QSC-401 magnet [6]. The 12 pole decay was about 0.15 units per decade; the 20 pole decay rate was about -0.006 units per decade.

Figure 8 shows the 12 pole decay measured by the improved LBL magnetic measurement system. The apparent jump in the decay rate at 4000 seconds is real. The new measurement system can take a complete set of multipole data in about 2.5 seconds. The apparent jump in the 12 pole takes place in about 10 seconds. The same jump is also seen in the 20 pole decay data. The cause for the sudden increase in the rate of decay is under investigation. This type of jump in the measured magnetization multipole has been observed in earlier dipole magnetization decay measurements [6,7].

The QSC-403 measurement of flux creep decay is quite different from the decays measured for the QSC-401, QSC-402, and the QCC-401 magnets. The 12 pole started decaying in the normal way (in the direction where the magnetization 12 pole is decreased). Later, the 12 pole decay changed sign. This decay pattern is similar to that observed in dipole magnets in which the magnet operating temperature was lowered [6] (see Fig. 9). The 20 pole decay appeared to be normal except that the decay rate was faster (about -0.025 units per decade) than was observed in the QSC-401, QSC-402, and QCC-401 magnets.

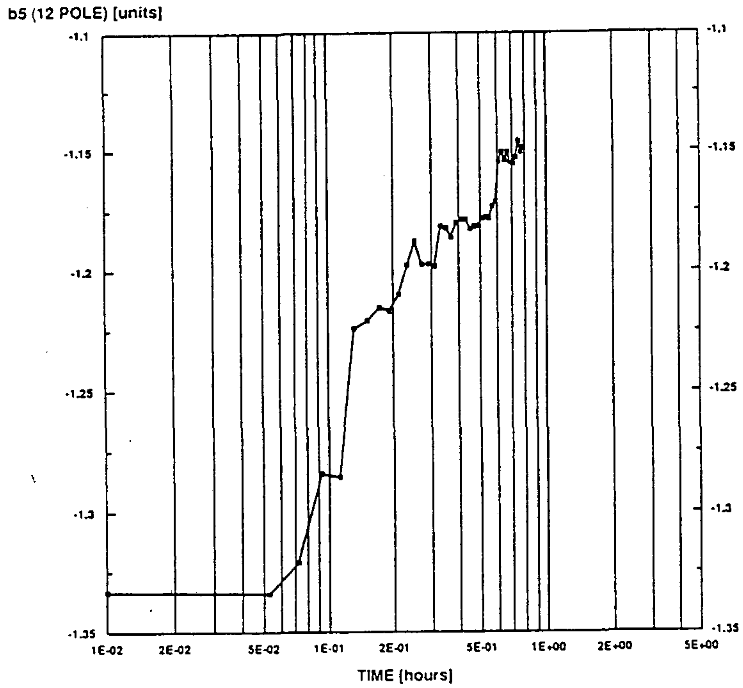

Fig. 6 A One Hour Decay 12 Pole at 640 Amperes in the QSC-401 Quadrupole After Three 6600 Ampere Setup Cycles

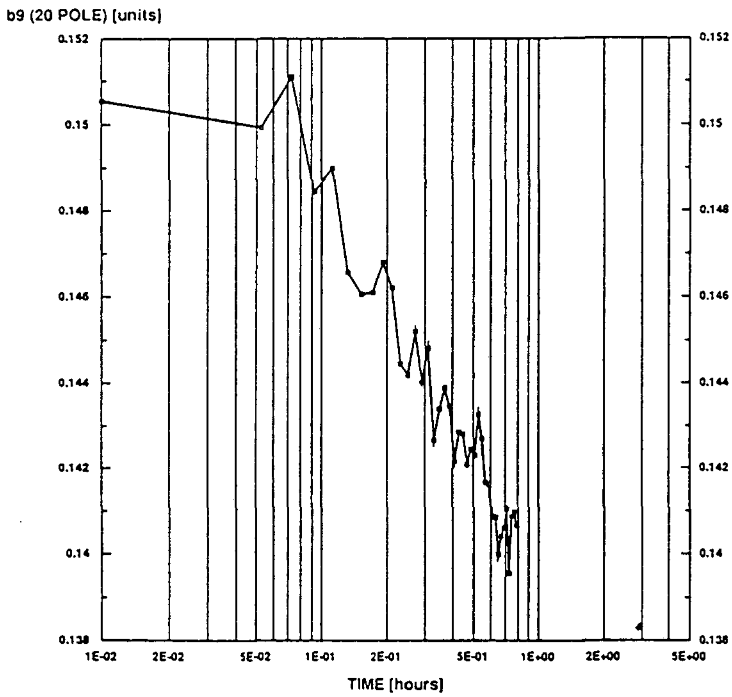

Fig. 7 A One Hour Decay of 20 Pole at 640 Amperes in the QSC-401 Quadrupole After Three 6600 Ampere Setup Cycles

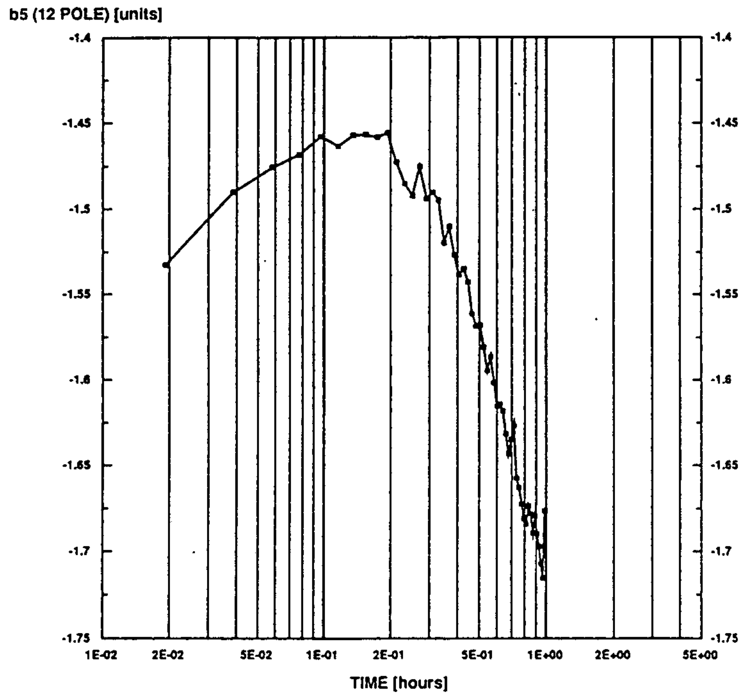

Fig. 8 A One Hour Decay of 12 Pole at 640 Amperes in the QCC-401 Quadrupole Following a 5000 Ampere Setup Cycle and a Staircase Cycle

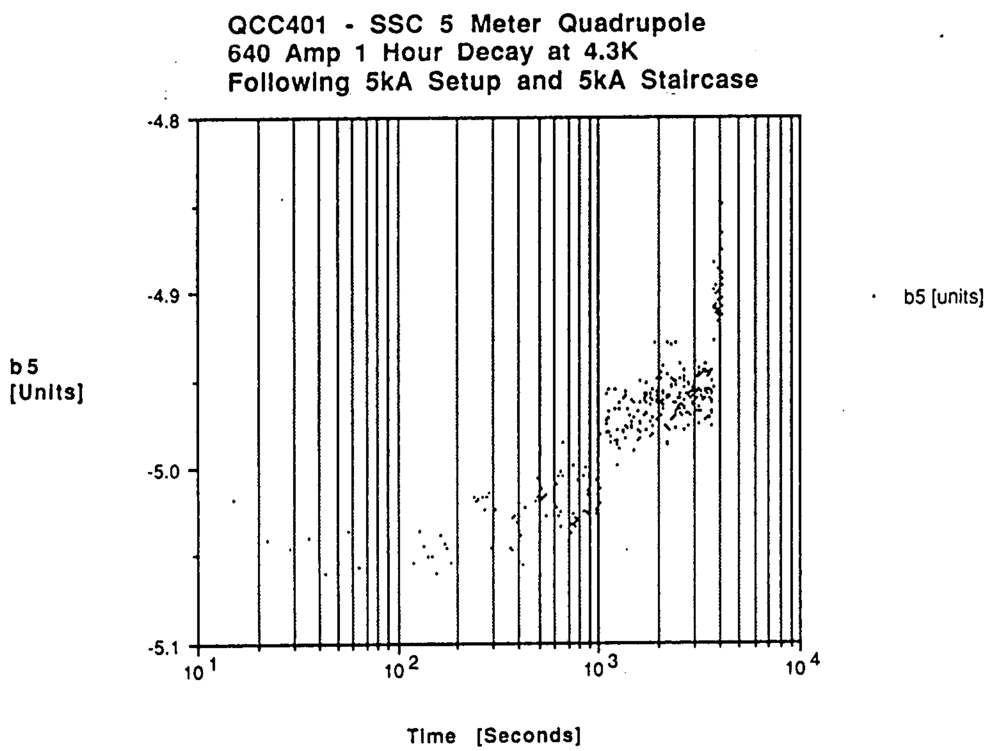

Fig. 9 A One Hour Decay of 12 Pole at 640 Amperes in the QSC-403 Quadrupole

SUMMARY

The magnetization multipoles measured in the LBL SSC quadrupole models QSC-401 and QCC-401 agree with calculated values reasonably well. The measured decay rates for QSC-401, QSC-402, and QCC-401 12 pole and 20 pole appear to be about 10 to 15% of the measured magnetization per decade of time. This rate of decay is similar to that observed in the LBL one meter long dipole magnets.

ACKNOWLEDGMENTS

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