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Abstract

Results are presented from tests of the first two full length prototype SSC dipole magnets. Magnetic field measurements have been made at currents up to 2000 A. The two magnets achieved peak currents at 4.5K of 5790 A and 6450 A respectively, substantially below the short sample limit of 6700 A. These peak values, however, could not be achieved reproducibly. Data are presented from studies performed to try to understand the poor quench performance.

Introduction

In this paper we present test results[1] from the first two full scale prototype magnets[2,3] for the proposed Superconducting Super Collider (SSC).[4] These magnets have a "cos(θ)" style coil with a 4 cm aperture and a magnetic length of 16.6 m. An iron yoke outside stainless steel collar laminations augments the field by about 20%. The test were carried out at the Fermilab Magnet Development and Test Facility. Details of the test facility, cryogenic and electrical instrumentation and magnetic measurement systems are presented elsewhere[1,5,6].

Magnetic Measurements

The harmonic content and vertical angle of the magnetic field is measured with a rotating coil probe called the "mole",[6] and the vertical field angle is independently measured with a probe using a gimballed permanent magnet and an electrolytic bubble level sensor.[7] The beam pipe of this magnet is in contact with 4.5K helium, requiring the use of a vacuum insulated "warm bore" tube to allow the use of room temperature probes. Because the relatively large heat leak caused by the warm bore[8] could adversely effect quench performance, the warm bore was not installed in the second magnet (D00002).

Harmonic Multipole Measurements

The field shape of accelerator magnets is generally expressed in terms of a two dimensional multipole expansion:

$$B_y + iB_x = B_o \sum_{n=0} (b_n + ia_n)\,((x + iy)/r_{ref})^n$$

where r_{ref} is the reference radius; r_{ref} is chosen to be 1 cm for SSC magnets. The harmonics allowed by the symmetry of the coil are b_n with n even. The allowed harmonics, particularly those of lower order, are expected to have larger systematic values and to display persistent current hysteresis effects.

The field quality of each magnet was measured at 10 A before the magnet was cooled and D00001 was measured at 2000 A at 4.6K The results are displayed in Table 1. Also shown for comparison are the specifications[9] given by the SSC Central Design Group. With the exceptions of a_1 and b_2, warm and cold measurements of D00001 agree within one or two tenths of a unit. The warm value of b_2 is 0.7 units larger than the cold value because, with the large filaments in the cable used in this magnet, (20 micron compared with 5 microns in the final design) there is still a non-zero persistent current contribution to the sextupole moment at 2000 A. The disagreement in a_1 is not understood. All harmonics in both magnets, with the exceptions of a_1, b_2 and b_8, are within the specifications. The large values of b_2 and b_8 result from known defects in the coil design and fabrication which will be corrected in later magnets. The values of b_2 and b_8 in the two magnets agree within the allowed random error, suggesting that reasonable manufacturing tolerances have been achieved.

Table 1

Harmonic multipole coefficients measured at 10 A with the magnet at room temperature ("warm") and at 2000 A with the magnet at 4.5K ("cold"), compared with specifications for random and systematic components. Units for a_n and b_n are 10^{-4} cm^{-n}.

	D00001		D00002	Specification	
	Warm	Cold	Warm	Random	Systematic
a_1	0.8	-0.8	1.6	0.7	0.2
a_2	-0.3	-0.3	0.0	0.6	0.1
a_3	0.0	-0.1	-0.1	0.7	0.2
a_4	0.0	-0.1	0.0	0.2	0.2
a_5	0.0	-0.1	0.0	0.2	---
a_6	0.0	0.0	0.0	0.1	---
a_7	0.0	0.0	0.0	0.2	---
a_8	0.0	0.0	0.0	0.1	---
b_1	0.1	0.1	0.4	0.7	0.2
b_2	-11.8	-12.5	-12.3	2.0	0.1
b_3	0.0	0.0	-0.1	0.3	0.1
b_4	0.1	0.4	0.3	0.7	0.2
b_5	0.0	0.0	0.0	0.1	0.02
b_6	0.2	0.1	0.2	0.2	0.04
b_7	0.0	0.0	0.0	0.2	0.06
b_8	0.8	0.8	0.8	0.1	0.1
B_o/I	10.33	10.25	10.23	G/A	
A_o/B_o	4.1	2.7	5.8	mrad	

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Vertical Field Angle

The vertical field angle has been measured both with the mole (warm and cold) and with a prototype device ("vertical tilt probe") which uses a gimballed permanent magnet to sense the field direction. Measurements with the vertical tilt probe have been made only at room temperature. The field angle of both magnets, as measured with the second device, is displayed in Fig. 1. Comparison of data taken at different times with the magnet mounted on different stands shows repeatability of this technique is better than ±0.5 mrad. Quasi-periodic structure is observed in both magnets which correlates well between the two, suggesting a common origin in the manufacturing process. Measurements made with the mole agree well in shape with these data (when the latter are averaged over 61 cm intervals corresponding to the mole length).

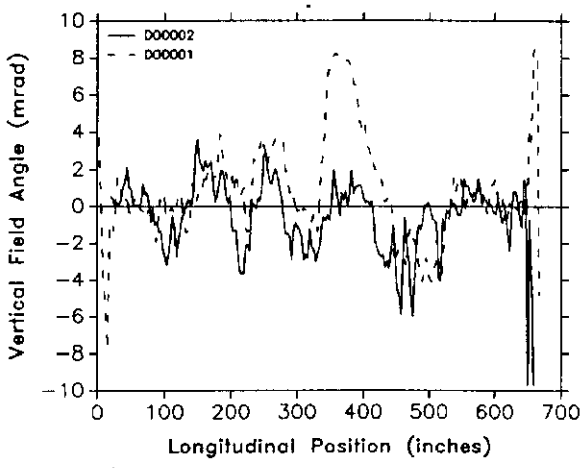

Figure 1. Vertical field angle versus position. The origin is at the non-lead end of the magnet.

Quench Behavior

The quench histories of the two magnets are displayed in Fig. 2. Their quench performance is rather disappointing both because of the low peak currents relative to the specification and because the results are not reproducible from one quench to the next. The design current for SSC operation is 6400 A and the estimated short sample limit for the conductor at 4.6K is 6700 A, while the quench currents range between 4920 A and 5790 A in D00001 and between 5220 A and 6450 A in D00002 when operated at 4.6K. Even after more than 50 quenches, no clear training towards higher current is observed. (The last quenches in D00002 were done at a temperature of 3.6K and so cannot be compared directly with the others.)

Quench Experiments

Numerous experiments have been done to attempt to learn the source of the low and erratic quench currents. No dependence of quench current on ramp rate is observed over the range 6 A/sec to 100 A/sec. The warm bore tube could potentially be a source of a large heat leak to the region near the coil. Quench results in D00001, however, were the same if the center of the warm bore was filled with room temperature nitrogen or was evacuated. Further, D00002 was tested without the warm bore and performed only marginally better than D00001.

Voltage taps allow independent monitoring of voltages in 4 quarters of the coil: upper inner, lower inner, upper outer and lower outer. All quenches have originated in the inner coil, but in both magnets quenches occur in both upper and lower coils. By measuring the time for the quench to propogate from one quarter coil to another, an estimate of the azimuthal position of the quench can be made. Most quenches begin far from the parting plane, but the inferred distance varies. Thus the quenches do not originate in one "bad spot".

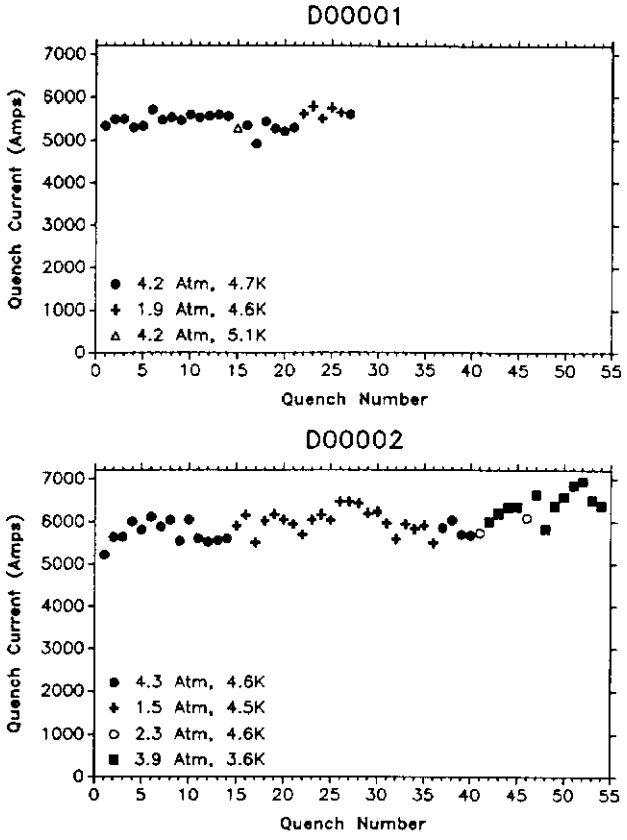

Figure 2. Quench histories of prototype SSC dipoles.

By comparing the temperatures and pressures as a function of time at the two ends of the magnet the longitudinal location of the quench origin can be estimated. While the position resolution was quite poor in the data from D00001, in both magnets there is strong evidence that quenches originate at various longitudinal locations. Improvements in the instrumentation and readout and changes in the quench protection system (delaying the firing of quench protection heaters and the opening to relief valves) result in quench position resolution of better than 30 cm for the last 25 quenches of D00002. The position scale was calibrated by inducing quenches with spot heaters located 40 cm from each end of the magnet; the leading edge of the pressure wave travels with the velocity of sound. Preliminary analysis of the data shows that 21 quenches occur at the lead end, 3 occur at the return end and 1 occurs in the middle. The end quenches appear to be a little farther from the middle than the locations of the spot heaters. This almost certainly places the quenches within the "dogbone" ends[10]. The quenches which occur in the ends have a significantly lower initial rate of resistance growth than those that occur in the body of the magnet, as is expected for quenches in a low field region.

The quench performance of the magnets has been studied as a function of the cryogenic conditions. Helium mass flow was varied from 15 gm/sec to 60 gm/sec with no observable effect. Temperature was varied up to 5.1K (D00001) and down to 3.6K (D00002). Quench current versus temperature is displayed in Fig. 3. Data from 4.5m model magnets of the same designs have a temperature dependence of the quench current of -550 A/K. The result from the one quench at elevated temperature in D00001 is compatible with either this temperature dependance or no temperature dependence. Data were taken on D00002 over a wider range of temperatures and many quenches were taken under each condition. From the 4 Atm data, the average temperature dependence measured here is -670±140 A/K, consistent with the short magnet result. The mean quench current is, however, 500 A lower and erratic behavior is observed at all temperatures. The dependence of quench current on supercritical helium pressure was explored by quenching D00002 twice at 2.3 Atm and 4.6K; no significant effect was observed.(See Fig. 2).

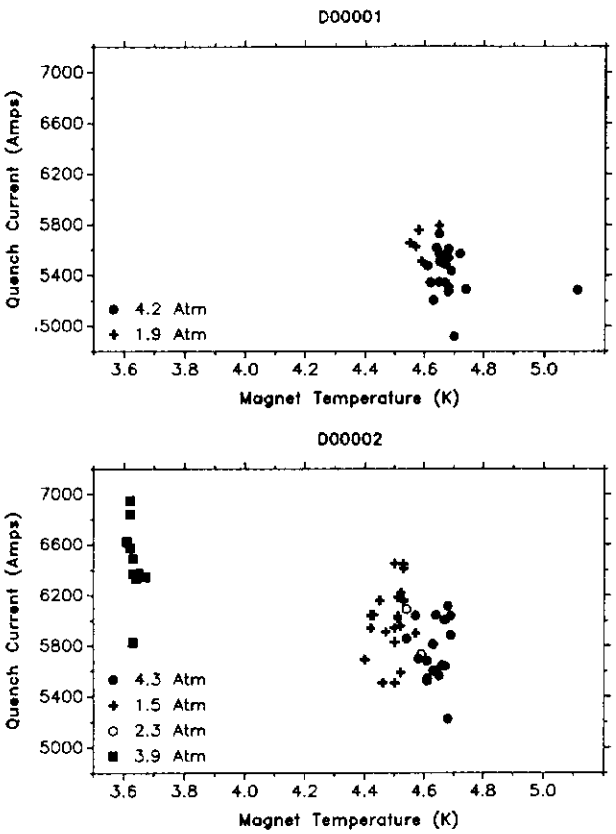

Figure 3. Quench current versus temperature.

Both magnets were run in subcooled liquid (1.9 Atm, 4.6K in D00001 and 1.5 Atm, 4.5K in D00002). In each case the mean quench current in liquid, corrected for temperature, is higher than that in supercritical fluid; the average difference is 180±50 A. Again, however, the quench currents are erratic and are well below the short sample limit.

Conclusions

Quench data from these two magnets strongly suggest that the low and erratic quench currents do not result from the cryogenic system or from a single "bad spot" in the magnet. Most of the quenches occur in the dogbone ends and may be related to loss of prestress at high current. The fact remains, however, that 15 R&D magnets of the same design, made with the same tooling and similar cable, performed well.[10] One of these magnets is currently being installed in an SSC cryostat and will be tested at Fermilab in the near future. This will allow a direct check of the effects on quench behavior of the cryostat, cooling method and interaction with the test facility. All future long magnets will have straight ends and incorporate improved collar laminations. In addition one magnet is being manufactured with cable with a higher copper to superconductor ratio (1.6:1 rather than 1.3:1) which may be more stable against small perturbations.

Acknowlegements

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References

1. J. Strait, et al., "Full Length Prototype SSC Dipole Test Results", Proc. of the Applied Superconductivity Conference, Baltimore, MD (1986), J. Schooley (Ed.).

2. P. Dahl, et al., "Construction of Cold Mass Assembly for Full Length Dipoles for the SSC Accelerator", Proc. of the Applied Superconductivity Conference, Baltimore, MD (1986), J. Schooley (Ed.).

3. R.C. Niemann, et al., "Design, Construction and Test of a Full Scale SSC Dipole Magnet Cryostat Thermal Model", Proc. of the Applied Superconductivity Conference, Baltimore, MD (1986), J. Schooley (Ed.).

4. "Conceptual Design of the Superconducting Super Collider", SSC Central Design Group, Lawrence Berkeley Laboratory, One Cyclotron Road, Berkeley, CA 94720.

5. K. McGuire, et al., "Cryogenic Instrumentation of an SSC Magnet Test Stand", to be presented at the Cryogenic Engineering Conf., St. Charles, IL (June, 1987).

6. P. Wanderer, et al., "Production Techniques for Measuring SSC Accelerator Magnets", Proc. of the ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory (1986), P. Dahl (Ed.).

7. M. Kuchnir and J. A. Carson, "Vertical Tilt Measurements in Magnet SD-13", SSC note SSC-N-309.

8. The warm bore heat leak is estimated to be at least 20 W. The SSC design calls for a total heat leak, dominated by synchrotron radiation, of 2 W.

9. A. W. Chao, "Magnet Field Quality Requirements for the SSC", Proc. of the ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory (1986), P. Dahl (Ed.).

10. These two magnets, as well as 13 of the 15 short model magnets built and tested at Brookhaven have flared ends called "dogbones". Subsequent magnets will have straight, unflared ends.