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Abstract

Results are presented from tests of the third full scale development dipole magnet for the Superconducting Super Collider and from a retest of a 4.5 m model magnet of the same design mounted in an SSC cryostat. The 4.5 m magnet shows consistent quench performance between its original tests in boiling liquid helium in a vertical dewar and the current tests in forced flow helium in a horizontal cryostat. Little or no retraining is observed over several thermal cycles. The full length magnet requires 12 quenches to train to its short sample limit of 6800 A and displays a reasonably stable quench plateau following training. This represents a great improvement over the performance of the first two full length magnets. Data are presented on quench behavior as a function of current and temperature and on azimuthal and longitudinal loading of the coil by the support structure.

Introduction

In this paper we present test results from the third full scale development magnet[1],[2] for the Superconducting Super Collider (SSC)[3] and from a retest of a 4.5 meter model magnet[4] of the same design. These magnets have a "cosθ" style coil with a 4 cm aperture and a magnetic length of 16.6 m. An iron yoke outside the stainless collar laminations augments the field by about 20%. The tests were carried out at the Fermilab Magnet Test Facility. Details of the test facility, cryogenic and electrical instrumentation and magnetic measurement systems are given elsewhere[5],[6]. Test results from the first two long magnets have been previously presented[5],[7].

The quench performance of the first two full scale development magnets[5],[7] was well below specification. The peak currents obtained at 4.6 K were below the required 6500 A and the estimated short sample limit of 6700 A. Furthermore, the quench current varied erratically from quench to quench. Even after 50 quenches, no clear training toward higher current was observed. This behavior is drastically different from that of eight 4.5 m and twenty 1 m R&D magnets of similar design, previously built and tested at Brookhaven[4] and Lawrence Berkeley Lab[8]. These shorter magnets reached the short sample limit after only a few training quenches. To verify that the degraded performance of the first two long magnets did not result from the cooling method (horizontal forced flow cooling in a dedicated cryostat rather than pool boiling liquid helium in a vertical dewar) or from a fault in the test facility, one of the previously tested short magnets (SLN013) was installed in an SSC cryostat, renamed SD13, and tested.

Retest of a 4.5 Meter Magnet

Quench studies of SD13 were carried out under four different cryogenic conditions: subcooled liquid (1.5 Atm, 4.4 K), high and low pressure supercritical fluid (4.0 Atm and 2.3 Atm, 4.4 K), and low temperature, high pressure supercritical fluid (4.2 Atm, 3.4 K). Fig. 1 shows the quench history for this magnet over four thermal cycles, two at Brookhaven in a vertical dewar and two at Fermilab in a horizontal cryostat. After several training quenches in the first thermal cycle, no significant retraining occurs following subsequent cooldowns. In the horizontal tests, all quenches at ramp rates of 50 A/sec or less are in the lower outer coil. The timing of the pressure rise at the two ends of the magnet and the initial voltage rate of rise indicate that all quenches originate in the body of the magnet, not in the "dogbone" ends[9].

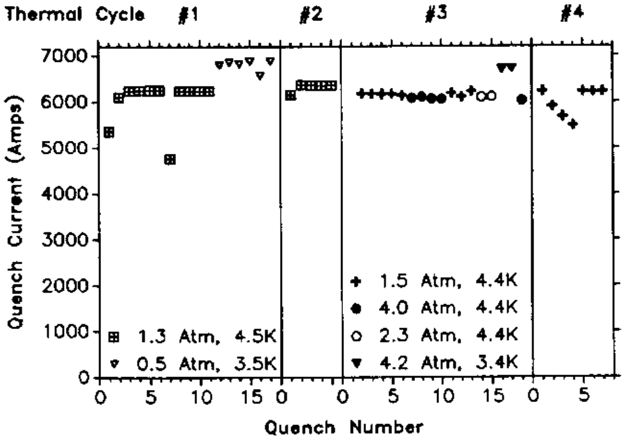

Fig. 1. Quench history of 4.5 m model magnet SD13 tested at Brookhaven and Fermilab. Quench 12 in thermal cycle 3 and quenches 2, 3, and 4 in thermal cycle 4 were done at ramp rates of 100, 200, 400, 600 A/sec respectively.

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Quench current versus magnet temperature is plotted in Fig. 2 for quenches taken near 4.4 K at ramp rates of 50 A/sec or less. The quenches taken in subcooled liquid (1.5 Atm) and in supercritical fluid (2.3 Atm and 4.0 Atm) are at the same average temperature within less than 10 mK yet the average quench current is 115±15 A higher in liquid. No significant difference is seen, however, between low and high pressure supercritical fluid.

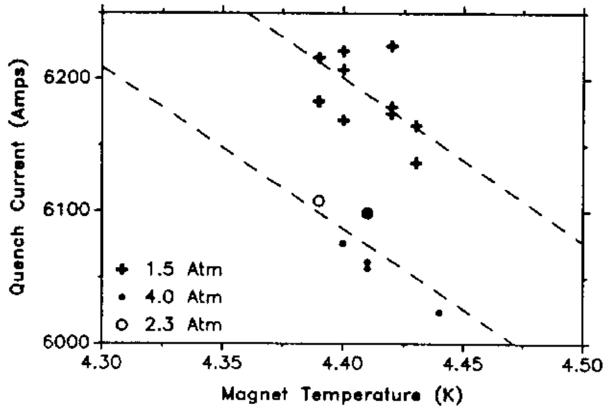

Fig. 2. SD13 quench current versus temperature for quenches taken at ramp rates ≤50 A/sec. The two straight lines indicate the expected temperature dependence of the quench current drawn through the low and high pressure data respectively.

Tests of a 17 Meter Magnet

The third long magnet tested (D0000X) differs from the first two in a number of respects: it has straight rather than "dogbone" ends and the inner conductor has a higher copper to superconductor ratio (1.4:1 versus 1.25:1), higher resistance copper (RRR of 51 versus 78), smaller filaments (5 microns versus 19 microns) and a smaller filament twist pitch (0.04/cm versus 0.5/cm)[10]. The simpler and more mechanically well defined ends[11] and the greater amount of copper are expected to improve the stability of the magnet, while the higher resistance of the copper may tend to reduce the effect of the higher copper ratio. The reduced twist pitch should make the quench current more sensitive to ramp rate[12] and may make the magnet less stable with respect to flux jumps.

Quench Measurements

Figure 3 shows the quench history of D0000X. In contrast to the behavior of the first two long magnets, a reasonably stable plateau is reached after a finite number of quenches; 8 quenches are required to reach the design current of 6500 A and the short-sample limit of 6800 A is achieved on the twelfth quench. The training quenches all originate at or near the lead end of the inner coil, although the longitudinal and azimuthal position varies somewhat. The plateau quenches occur in the body as well as near both ends of the inner coil and again the azimuthal position of the quench varies. Six quenches were taken at 3.3 K; only a small increase in current is observed. By contrast, the predicted short sample limit at 3.3 K, based on a linear temperature extrapolation, is approximately 7700 A.

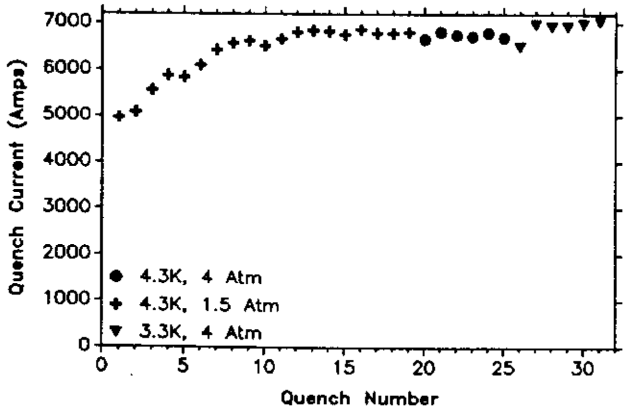

Fig. 3. Quench history of SSC development dipole magnet D0000X.

Plateau quenches were taken in both subcooled liquid (1.4 Atm, 4.3 K) and supercritical fluid (4 Atm, 4.3 K). Fig. 4 is a plot of quench current versus magnet temperature for the plateau quenches. About 2/3 of the quenches lie in a band about 25 A wide 50 A below the predicted short-sample limit (well within the estimated uncertainty of the calculation), while the remaining quenches are spread up to 150 A below this band. The lower current quenches have systematically lower quench propogation velocities, indicating that they are indeed not short-sample quenches. They do not, however, occur preferentially in any one location and include quenches both in the body and in or near the ends. In contrast to the behaviour of SD13 (see Fig. 2) there is no difference between low and high pressure cooling modes.

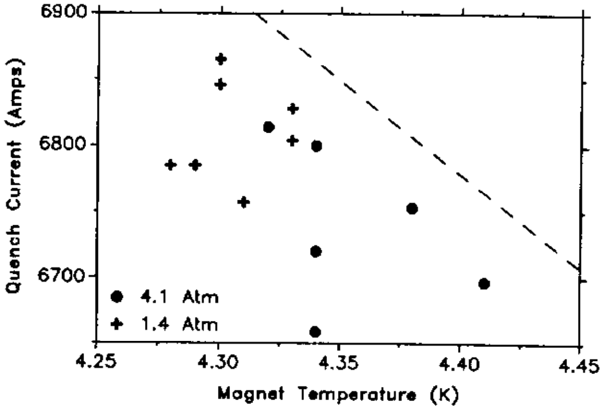

Fig. 4. D0000X quench current versus temperature for quenches on plateau. The straight line is the estimated short sample limit for the conductor.

For all previous tests of long SSC magnets, an active quench protection scheme has been used in which heater strips mounted along the outer surface of the outer coil are energized when a quench is detected. This serves to limit the total energy deposited at the point of quench origin and, by making the resistance more uniformly distributed throughout the coil, to limit the peak voltage to ground. To test the necessity of active quench protection, the protection heaters were disabled for the spontaneous quenches at 4.3 K, 4 Atm and for a series of spot heater[13] quenches induced at currents from 3000 A to 6650 A. (When a quench is detected, the power supply is turned off and its terminals shorted. This is roughly equivalent to protecting each magnet in a string with a diode across its terminals.) Figure 5 shows that the time integral of I^2, conventionally called "MIITs", is highest between 3000 A and 4000 A and drops below 7 kA^2 sec at the highest current. The magnet is instrumented with voltage taps at the joints between the 4 coil quarters and at the leads, allowing the measurement of voltage to ground at these points. The peak voltage to ground observed at any voltage tap is plotted versus quench current in Fig. 6. A relatively modest maximum of less than 400 V is observed at the highest current.

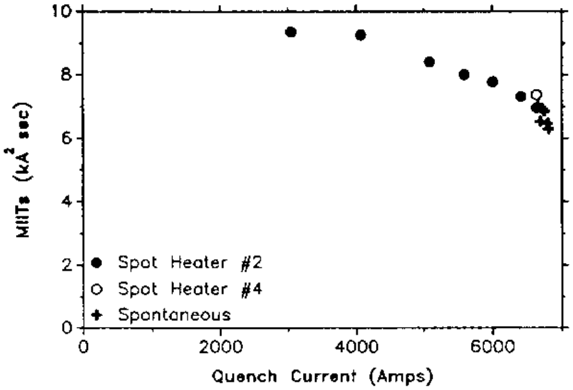

Fig. 5. Time integral of I^2 (MIITs) versus quench current for spot heater induced and spontaneous quenches with no active quench protection. Spot heaters 2 and 4 are located near the lead and return ends respectively.

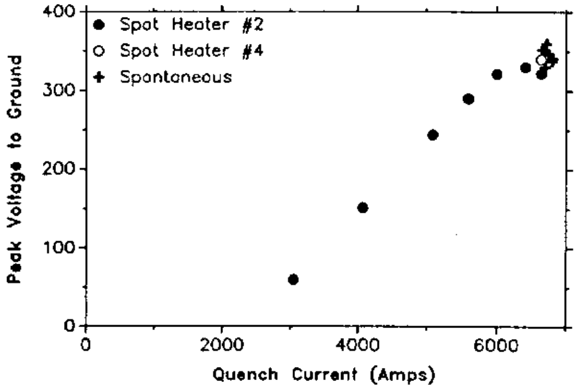

Fig. 6. Peak voltage to ground observed at any of the five voltage taps located at the boundaries of the four quarter coils.

The maximum MIITs and voltage to ground are well below the safety limits. In particular, it is calculated that no conductor damage due to heating will occur for MIITs ≤13 kA^2 sec and that in 4 Atm helium, the insulation will hold ≥2000 V to ground. Thus the magnet appears to be comfortably self-protecting. When comparison is made, however, between quenches in the second long magnet D00002 and those quenches in D0000X for which the protection heaters were used, it is found that the MIITs are systematically higher by about 2 kA^2 sec in D00002 and the peak voltages observed are more than 150 V higher. While the quench propagation velocity is essentially the same for the first 10 to 20 msec, after that quenches develop significantly faster in D0000X. At 6400 A, for instance, it takes almost 25% longer for the full length of the coil to go normal in D00002 than in D0000X. This increase in apparent quench velocity may be related to the low twist of the conductor strand in D0000X, making it sensitive to the large rate of change of current during a quench. While there is significant safety margin in both MIITs and voltage in D0000X, it is clear that further magnets must be tested with the protection heaters disabled to verify that they, too, are self-protecting.

Coil Loading

This magnet is instrumented with strain gages which allow measurement of the azimuthal loading of the coils at one longitudinal location (approximately 210 cm from the lead end) and of the longitudinal loading at the non-lead end. While the absolute calibration of these load cells at 4 K is not well understood, significant information may be obtained from the qualitative features of the change in load as a function of current. Fig. 7(a) shows the azimuthal loading of the inner coil, measured independently at the top and bottom, as a function of current. Both load cells show that the stress decreases roughly

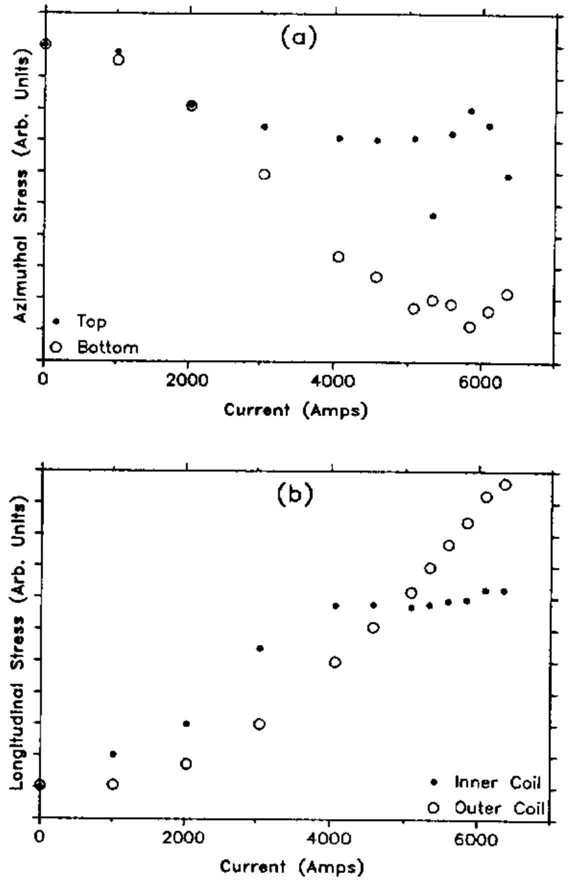

Fig. 7. Azimuthal (a) and longitudinal (b) stress of the magnet coil on the support structure as a function of current.

quadratically with current as the magnetic force tends to compact the coil towards the mid-plane. Above about 3000 A and 5000 A, however, the stress indicated by the top and bottom load cells respectively becomes essentially independent of current. This is the behavior expected if the azimuthal load of the coil against the collars goes to zero. It is unknown why the unloading appears to take place at substantially different currents at the top and bottom. That the preload is not sufficient to keep the coil clamped up to the design current, at least at this one location, may be related to the relatively large number of training quenches. On the other hand, all of the training quenches take place at one end of the magnet, so the relation between the training behavior and low prestress in the body of the magnet is less than clear. Furthermore, magnet D00002 had a somewhat higher preload but never trained to full field at all.

The longitudinal force of the inner and outer coils against the end plate of the helium containment vessel is measured by two load cells and is displayed as a function of magnet current in Fig. 7(b). Both load cells show that the stress increases roughly quadratically with current as the magnetic force tends to lengthen the coil. The inner coil stress, however, appears to become independent of current above 4000 A. This behavior is not understood. That the force begins to grow immediately as the current increases from zero shows that at all times the coil is in contact, through an intervening support structure, with the end plate. In particular, the coil has not become longitudinally unconstrained due to differences in thermal contraction between the coil and the shell.

Conclusions

D0000X, the third full scale SSC development dipole magnet, represents a dramatic improvement over its two predecessors[5],[7]. While the number of training quenches is significantly larger than is desirable, once the magnet is trained it reliably exceeds the design field. All of the training quenches and about 2/3 of the plateau quenches occur in or near the ends of the magnet. Thus it is reasonable to expect that with improvements to the ends, most or all of the training quenches can be eliminated. Several candidate modifications to the end design are under study. Some have been incorporated in short model magnets at Lawrence Berkeley Lab[8] and Brookhaven[14] and will be included in the next full scale magnets.

Hints of instability of the quench plateau exist. Possible sources of this instability include low prestress, insufficient copper stabilizer, or the anomalously low twist of the conductor strand used in this magnet. Improvements in the collar design and in coil manufacturing techniques will allow future magnets to be built with reliably higher preloads. A series of 1.8 m and 17 m magnets with varying copper to superconductor ratios will allow a test of the relation between the quantity of copper stabilizer and quench performance.

Acknowledgements

We would like to thank the members of the technical staff of the Fermilab Magnet Test Facility without whose dedicated efforts, these tests would not have occurred.

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[8] S. Caspi, et. al., "Development of a 40 mm bore magnet cross section with high field uniformity for the 6.6 T SSC dipole," Proc. of the Applied Superconductivity Conference, Baltimore, MD (1986), J. Schooley (Ed.).

[9] This magnet as well as the first two full size magnets have flared ends called "dogbones". Subsequent magnets all have straight, unflared ends.

[10] Due to an error in the cabling process, a twist was put into the strands which almost completely cancels the original twist.

[11] Most of the quenches in the first two long magnets originated in or near the flared "dogbone" ends.

[12] A 1 m model magnet made from the same cable showed a loss in quench current of 200 A for a ramp rate of 32 A/sec and almost 3000 A for 300 A/sec.

[13] Spot heaters are located on the parting plane between the upper and lower inner coils approximately 30 cm from the ends of the magnet.

[14] P. Wanderer et al., "Test Results from 1.8 m SSC Model Magnets," Proc. of the 10th International Conference on Magnet Technology, Boston, MA (1987).