FULL LENGTH SSC R&D DIPOLE MAGNET TEST RESULTS

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Abstract

Four full scale SSC development dipole magnets have been tested for mechanical and quench behavior. Two are of a design similar to previous magnets but contain a number of improvements, including more uniform coil size, higher pre-stress and a redesigned inner-outer coil splice. One exceeds the SSC operating current on the second quench but the other appears to be limited by damaged superconductor to a lower current. The other two magnets are of alternate designs. One trains erratically and fails to reach a plateau and the other reaches plateau after four quenches.

Introduction

Full scale development dipole magnets[1,2] for the Superconducting Super Collider (SSC), which incorporated improved azimuthal, radial and axial support of the coil, have shown[3] quench behavior at or near the SSC design requirements.[1] In these magnets (DD0012 and DD0014) the improved azimuthal and radial support was achieved by a combination of increased pre-stress by the stainless steel collars, due in part to improvements in the collar design, and use of the yoke to clamp the collared coil. Improved axial restraint was provided both by increased collar-to-yoke friction and by increasing the end plate stiffness. To understand better which features contribute to good quench performance, two magnets whose mechanical structure differs significantly from previous full scale models and two magnets of the standard design have been built and tested. All are heavily instrumented with voltage taps and strain gages. The tests were carried out at the Fermilab Magnet Test Facility.[4,5,6]

The Magnets

The design of two of the magnets (DD0016 and DD0017) is fundamentally the same as that of DD0012 and DD0014[3] but includes several improvements. (These changes were implemented first in 1.8 m models tested at Brookhaven.[7]) The coil size is more uniform size due to improved curing tooling. This makes the pre-stress more uniform and allows a higher average pre-stress to be achieved. The coil cross section has been modified slightly to reduce further the allowed multipoles and to improve manufacturability.[8] Yoke support of the collared coil is achieved by decreasing the yoke inner radius, eliminating the yoke-collar shims. Mechanical support of the inner-outer coil splice was determined in previous tests[3] to be inadequate; an improved design is used in DD0016 and DD0017.

Magnets DD0011 and DD0015 are significantly different from previous long magnets and from each other. DD0011 is of an alternate design originated[9] at Lawrence Berkeley Laboratory and is similar to 1 m model magnets[10] built and tested there. It has a different coil cross section, uses aluminum collars, supported by the yoke only near the horizontal mid-plane, and has 25 mm thick solid end plates. The inner-outer coil splice is made in a low field region beyond the end of the magnet, not inside the coil as in previous long magnets.

The DD0015 collared coil assembly is of the same design as DD0014 but is designed to be axially unconstrained, similar to Fermilab Tevatron magnets. Radial clearance is maintained between the yoke and collars and a brass bearing surface, impregnated with the low friction material "DU," is placed between the collar tabs and the yoke. The ends of the coils do not contact the end plates. The coil is anchored by yoke-collar shims in the center 30 cm. While the principal purpose of this experiment is to compare axially free and constrained magnets, the interpretation of the results is made less simple because the collared coil is not supported by the yoke as in constrained magnets. The lack of support may be important, particularly where the collars are weaker at the ends and at the inner-outer splice.

These magnets, similarly to other recent SSC models,[3] are extensively instrumented with voltage taps and with transducers to measure stress and strain. Multiple voltage taps (41 on DD0011, 57 on DD0015, 27 on DD0016 and 105 on DD0017) allow precise localization of quench origin and study of quench propagation.[11] Voltage taps on DD0015, DD0016 and DD0017 are present only on the inner coil in a configuration similar to previous long magnets.[3] DD0011 has voltage taps on both inner and outer layers.[10] All four magnets are equipped with strain gages to measure azimuthal coil stress, coil end force, and axial and azimuthal stresses in the cold mass skin. Linear potentiometers are used on DD0015 to measure the coil length changes.

Test Results

Inner coil stress at the pole as a function of current squared is displayed in Fig. 1 for three of these magnets[12] and for several earlier magnets.[3] The coil stress in DD0015 is as high as in earlier magnets with yoke supported collars. DD0016 and DD0017, which have more uniform coil dimensions, show even higher stress.

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The stress at full excitation ($I^2 = 42$ kA^2) is larger than at zero current in the earliest magnet shown (DD0010).

Figure 2 shows the axial Lorentz force carried by the cold mass skin and by the coil at 6.3 kA (6.4 T) in DD0015. Approximately 25% of the 7 Ton Lorentz force is transmitted to the skin at the ends presumably by a combination of friction and magnetic attraction between the ends of the coil and the yoke. Between the ends and the center the collared coil slides freely. A larger fraction of the force appears in the skin at the center because of the enhanced friction due to the yoke-collar shims. The force carried by the coil, derived from the coil extension, accounts for the balance of the Lorentz force.

Quench currents are displayed in Figs. 3 and 4. Except for the first and last quenches, all quenches in DD0011 originated in the straight section of the upper outer coil pole turn at three locations of 0.3 m, 1.8 m and 3.5 m from the inner-outer coil splice. The first quench was in the straight section of the upper inner pole turn and the last quench was at the lead end of the lower inner coil in the second turn from the pole. On the second quench at 1.8 K, a ground fault occurred terminating the testing. The magnet has been disassembled to investigate the cause of the fault. It is likely that it originated as a turn-to-turn short in a region in which there were insulation problems during assembly. (This was one of the first coils of its design to be manufactured.)

Magnet DD0015 reached a stable quench plateau at 4.4 K after four training quenches. Three were in the lower inner-outer splice and the fourth training quench and all plateau quenches were in the lower outer coil near the return end. Because there are no voltage taps on the outer coil, the quenching turn cannot be identified. Axial location is determined, with a resolution of about 1 m, by the time of the pressure rise at the two ends. The calculated critical current for this coil is about 400 A higher than the plateau. The observed temperature dependence, however, is that expected for

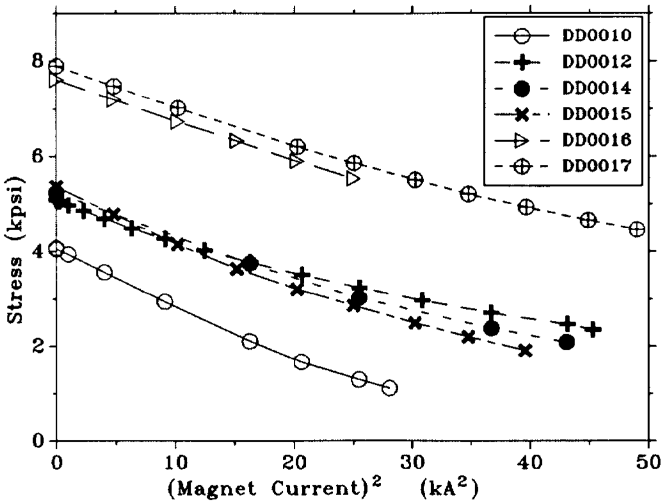

Fig. 1. Inner coil stress versus magnet current squared. Data displayed are an average of four measurements on the left and right sides of the upper and lower coils at a location where the stress is expected to be smallest.

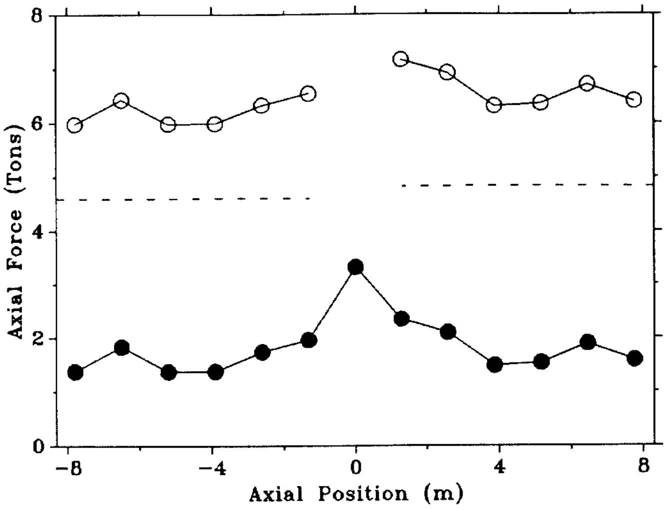

Fig. 2. Axial Lorentz force carried by the cold mass skin (closed circles) and by the coil (dashed lines) in DD0015. Open circles show the sum. Plot boundaries represent the magnet ends.

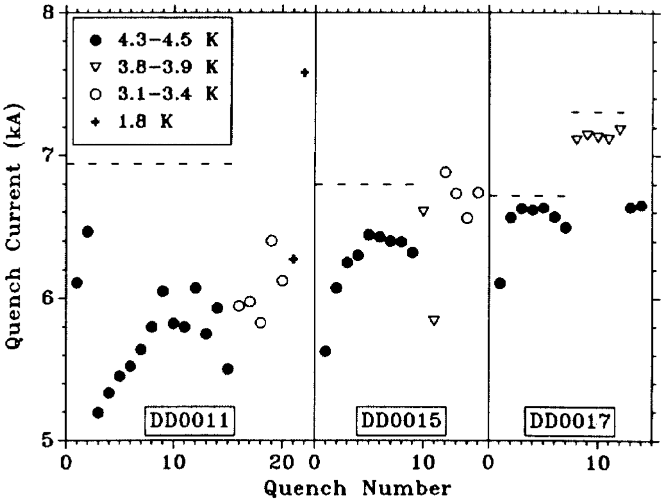

Fig. 3. Quench histories. Dashed lines show the predicted critical current at 4.4 K for each magnet and at 3.8 K for DD0017. Variation in plateau quench current in DD0015 and DD0017 is consistent with temperature variations.

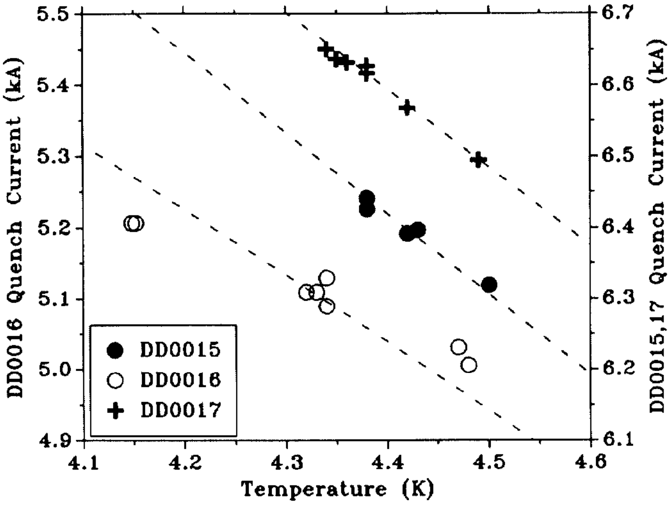

Fig. 4. Plateau quench current versus temperature. Dashed lines represent the calculated critical current for each magnet scaled to the average current at the average temperature.

conductor limited quenches. (See Fig. 4.) The cause of the low quench current is not understood. The temperature was lowered to 3.8 K and 3.4 K, yielding little increase in quench current. Both quenches at 3.8 K were in the lower outer coil, one in the body and one near the return end. All quenches at 3.4 K were in the inner-outer splice. The cause of the anomalously low quench at 3.8 K is not understood.

All DD0016 quenches were far below the expected 6.7 kA at 4.4 K. The quench current varies linearly with temperature (Fig. 4), suggesting that the limit is the superconductor. It is not understood why the measured temperature slope does not match the calculation. All eight quenches originated in the lower inner coil. Detailed voltage tap information, available for the last five quenches, gives the same origin for each quench: the pole turn about 70 cm from the return end. The time development of resistance suggests that the damaged section is probably 1 - 2 m long. The magnet is now being disassembled for inspection and test of the damaged region.

Magnet DD0017 exceeded the SSC operating current of 6.5 kA (6.6 T) on the second quench and reached a plateau 2.5% below the calculated critical current on the third quench. The temperature dependence (Fig. 4) indicates that the magnet is conductor limited. The first training quench was in the lower inner coil pole turn 20 - 30 cm from the lead end and the second was in the same turn <10 cm from the return end. All plateau quenches were in the upper inner pole turn <10 cm from the entrance to the "ramp-splice" assembly. In the ramp-splice, the inner conductor moves to the radius of the outer coil and is spliced to the outer conductor. The magnet had one training quench at 3.9 K before reaching a plateau, again 2.5% below the calculated current. The training quench was in the upper inner coil in the turn just below the first wedge. The plateau quenches were in the same location as those at 4.4 K.

Conclusions

One of the magnets of the standard design performed well, exceeding the SSC operating field on the second quench. The second magnet appears to contain damaged superconductor. Both have substantially higher coil pre-stress than earlier models. The success of DD0017 indicates that the magnet design is mechanically sound. There is evidence, however, that the inner-outer coil splice design may need further improvement.

One of the two magnets of alternate design (DD0015) performed moderately well, requiring four training quenches to reach plateau. All training quenches were in locations where the lack of yoke support to the collared coil is particularly important. Three are in the inner-outer coil splice, which is of an earlier inadequate[3] design. The quench performance of DD0015 is dramatically better than previous long magnets without yoke supported collars, presumably because the coil pre-stress is higher. Using the yoke to support the collared coil increases the mechanical margin and may be required at the ends and at the inner-outer splice, where the collars are weaker than in the body. DD0015 does not provide evidence that axial restraint is required for good performance.

Acknowledgments

This work was supported by the United States Department of Energy. We would like to thank the staff of the Fermilab Magnet Test Facility, whose skill and hard work made these tests possible.

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