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Abstract

Four full-scale SSC R&D dipole magnets, incorporating successive mechanical design improvements, have been quench tested. Three of these magnets are heavily instrumented with sensors to measure the mechanical behavior of the magnets and verify the performance of the mechanical improvements and with multiple voltage taps to locate the origin of quenches. The last two magnets of this series reach the SSC design operating field of 6.6 T in two or fewer quenches. Load cells and motion sensors show that in these two magnets the azimuthal clamping stress is higher at zero current and drops more slowly with excitation than in previous long magnets and that the axial motion of the coil upon excitation has been greatly reduced. Quenches are found to originate preferentially in several locations, suggesting other design improvements.

Introduction

In this paper we present test results from four full-scale development dipole magnets[1,2] for the Superconducting Super Collider (SSC).[3] These magnets have a "cosθ" 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 design operating field is 6.6 T at a current of 6.5 kA. The test were carried out at the Fermilab Magnet Test Facility. Details of the test facility are given elsewhere.[4,5]

The quench performance of the first full scale SSC magnets[4,6,7] was well below specifications: they required eight or more quenches to reach the design operating field. To try to understand and eliminate the causes of premature quenching, a series of dipole magnets, in which a number of crucial design parameters have been varied, has been built and tested. In addition, where shortcomings in the design have been recognized corresponding improvements in the magnets have been made. The design changes were first tested in 1.8 m model magnets at BNL.[8,9] Three of the four magnets discussed here have been heavily instrumented with voltage taps (to locate the origin of quenches and study propagation of the normal zone) and with strain gages and motion sensors (to measure stresses and deflections in the support structure under magnet excitation). The two most recent magnets of this series reached the SSC operating field in 1 and 3 quenches respectively.

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The Magnets

Mechanical Design

Premature quenching (training) of superconducting magnets is generally believed to result from frictional heating due to stick-slip motion of the conductor under the Lorentz force. Stick-slip motion can be eliminated either by clamping the coil so that no motion is possible or by ensuring that any motion is smooth and elastic. There was evidence from the first long magnets[7] that the coils were not adequately clamped azimuthally allowing the coils to become unclamped at high current. A number of improvements have been made in the collar structure to ensure higher prestress on the coils without overstressing the conductor during assembly. Collar laminations are asymmetric about the vertical mid-plane of the magnet and alternate collars are oriented in opposite directions. The stiffness of the collars against horizontal deflection can be increased substantially by spot welding collars in left-right pairs.[8] The magnets discussed in this paper are the first long magnets to incorporate spot welded collars.

The upper and lower collars are locked to each other by keys inserted in slots near the horizontal mid-plane. In earlier magnets the keys are rectangular in cross section, requiring that the key slots be slightly oversize and that the collars be slightly "over closed" in the collaring press to to allow insertion of the keys. As a consequence the coil experiences a much higher stress in the press than is ultimately required to restrain the coil and this high stress may cause insulation damage. The last magnet in this series of four is assembled with keys that have a 3 degree taper.[10] In this case the collars are closed by the press only enough to allow insertion of the narrow edge of the keys. The keys are driven into the collars from the sides providing the final closing force, while a constant vertical opening of the press is maintained. This results in a higher final prestress and a lower peak stress on the coil.

The axial component of the Lorentz force is restrained both by end plates that are connected at their outer radius to the cold mass skin, and by friction between the coil, collars, yoke and skin. To transmit the axial force more effectively from the coil to the end plate, these magnets have had their ends strengthened by either an aluminum oxide loaded epoxy applied after the coil was molded or by epoxy impregnated fiberglass cloth applied as part of the coil molding process.[9]

In earlier magnets the end plate was 19 mm thick and was split at the horizontal mid-plane allowing significant deflection at full excitation. Later magnets incorporate 38 mm thick one-piece end plates. The coil is well clamped in the collars and the yoke is tightly clamped by the cold mass skin, but in earlier magnets the frictional force at the interface between the collars and the yoke was not well defined due to a design clearance between them. In later magnets shims are placed between the collars and the yoke to increase the friction at the interface.[9] The collar-yoke shims also serve to transfer the horizontal Lorentz force from the collars to the yoke, effectively stiffening the collars. The yoke is split at the horizontal mid-plane and the collar-yoke shims are sized so that a small gap exists between the two yoke halves at room temperature. The closing of this gap, due to the greater thermal contraction of the stainless steel skin relative to the iron yoke, exerts a force on the collars increasing the net coil prestress at helium temperature.

Sensitivity to small heat impulses may be reduced by increasing the ratio of copper stabilizer in the cable.[11] The original SSC design called for a copper-to-superconductor ratio of 1.3. The magnets discussed in this paper have inner coil conductors with Cu:SC ratios varying from 1.24 to 1.6. Table I summarized the parameters of the magnets.

Table I. Magnet Parameters

Magnet	D0000Z	DD0010	DD0012	DD0014
Cu:SC	1.6	1.4	1.6	1.24
Filament dia. (μm)	5	6	20	5
J_c (A/mm^2) (5T, 4.2K)	2462	2643	2399	2611
I_c (A)	6470	6710	6410	6850
T_{test} (K)	4.4	4.45	4.4	4.4
Key Shape	Rect.	Rect.	Rect.	Taper
Yoke-Collar Shims?	No	No	Yes	Yes
Coil Ends	Filled after molding	Filled after molding	Filled after molding	Molded in curing press
End Plate	19 mm Split	19 mm Split	38 mm Solid	38mm Solid

Instrumentation

To gain a better understanding of the behavior of these magnets, the three most recent magnets (DD0010, DD0012 and DD0014) have been extensively instrumented with voltage taps and with transducers to measure stresses and strains in the magnet structure. All four magnets are equipped with strain gage based load cells for measuring the azimuthal pressure of the inner and outer coils on the collars at one point along the magnet length. In the first of these four (D0000Z), the load cell absolute calibration is not considered reliable, so only qualitative results are obtained. The load cells in the other three magnets are of an improved design[12] than allows reliable quantitative measurements to be made. Magnets DD0010, DD0012 and DD0014 are also equipped with transducers to measure the force between the end of the coil and the end plate at the return end, to measure the deflection of end plates at both ends, to measure the absolute length change of the magnet on cooldown and under excitation and to measure the axial force transmitted to the cold mass skin from the coil.[13] In addition to the five voltage taps at the boundaries between quarter coils (inner and outer, upper and lower) included on earlier magnets, DD0010 and DD0012 are equipped with 4 voltage taps per turn on the inner coil. These taps are located approximately 0.4 m from each end of the magnet, dividing each turn into two end sections and two straight sections, approximately 15.8 m long. DD0014 is equipped with 48 "extra" voltage taps in a similar configuration except that only the turns near the mid-plane and near the pole are instrumented. The voltage taps allow the location of quenches to be precisely determined.

Test Results

Mechanical Measurements

Magnets DD0010 and D0000Z are similar to each other in mechanical design; DD0012 and DD0014 are also similar to each other, except that DD0014 has tapered key collars. The major mechanical differences between the two pairs of magnets are that the latter two contain shims between the collars and yoke and have much stiffer end plates.

Inner coil stress at the pole is displayed as a function of current squared in Fig. 1. The coil stress at

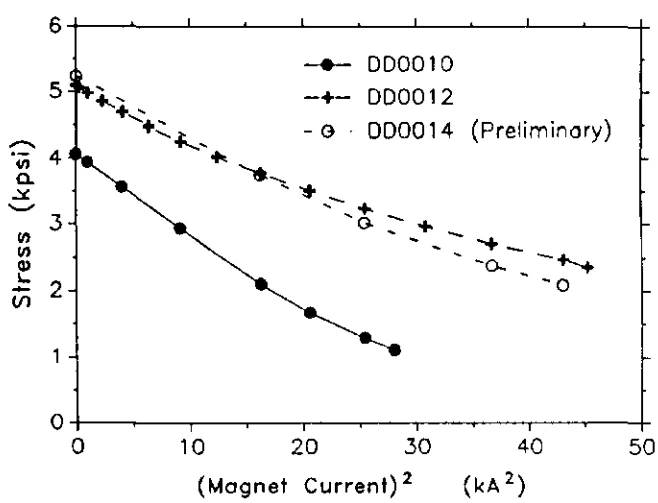

Figure 1. Inner coil stress versus magnet current squared. The data displayed are an average of four stresses measured on the left and right sides of the upper and lower coil at one location along the magnet.

zero current is larger and decreases more slowly with current in DD0012 and DD0014 than in DD0010 because the collars, supported by the yoke, deflect less. However, even for DD0010, the coil stress is still significantly greater than zero above 5 kA, a current at which previous long magnets, without spot-welded collars, showed evidence of unloading[7].

Figure 2 shows the change in axial force on the cold mass skin from zero current to 5.05 kA and 6.56 kA in DD0010 and DD0012 respectively. The dashed lines show the expected force on the skin if the coil and skin are "locked" together by friction and share the load with equal strain. Near the ends of the magnet most of the load is carried by the coil, while towards the center the load is taken dominantly by the skin. The length of the transition region is determined by the frictional force per unit length, which is much larger in DD0012 due to collar-yoke shims. Consistent with expectation the transition region is significantly shorter on DD0012.

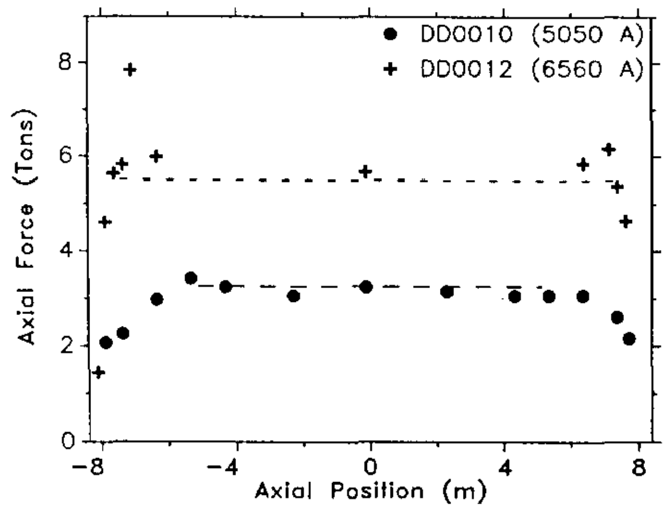

Figure 2. Axial Lorentz force transmitted to the cold mass skin as a function of position along the magnet. The left and right boundaries of the figure represent the ends of the magnet. The dashed lines show the expected force if the load is fully shared between the coil and the skin.

The deflection of the end plate as a function of current for 3 successive excitations is shown in Fig. 3. As expected, the 38 mm thick end plates on DD0012 deflect only about 5% as much as the 19 mm thicksplit end plates on DD0010. In addition, the motion of the DD0010 end plate is not reversible, with the coil "ratcheting" outwards between 15 and 20 μm per excitation cycle. Because its coil is less well axially restrained, a significant length of the coil can slip with respect to the skin. Due to the collar- yoke friction the coil does not return to its original length upon de-excitation.

Quench Performance

Quench currents for these magnets are displayed in Fig. 4. The performance of D0000Z and DD0010 is no better than previous long magnets[7], but DD0012 and DD0014 represent a dramatic improvement. DD0012 exceeds the calculated critical current at 4.4 K on the first quench and trains above the critical current at 3.2 K in three quenches. Why the magnet behaves more poorly at 2.8 K than at 3.2 K is not understood. DD0014 shows a somewhat erratic plateau that is slightly below the predicted critical current, but reliably exceeds the SSC operating current of 6.5 kA following

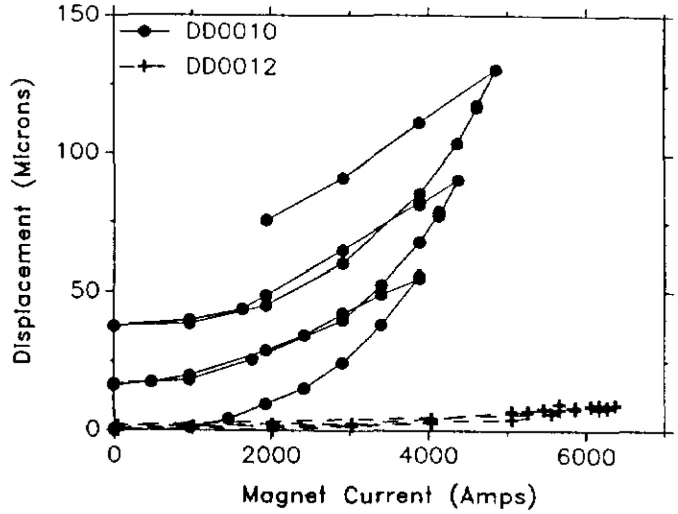

Figure 3. Deflection of the lead end plate as a function of current for three excitations of each magnet.

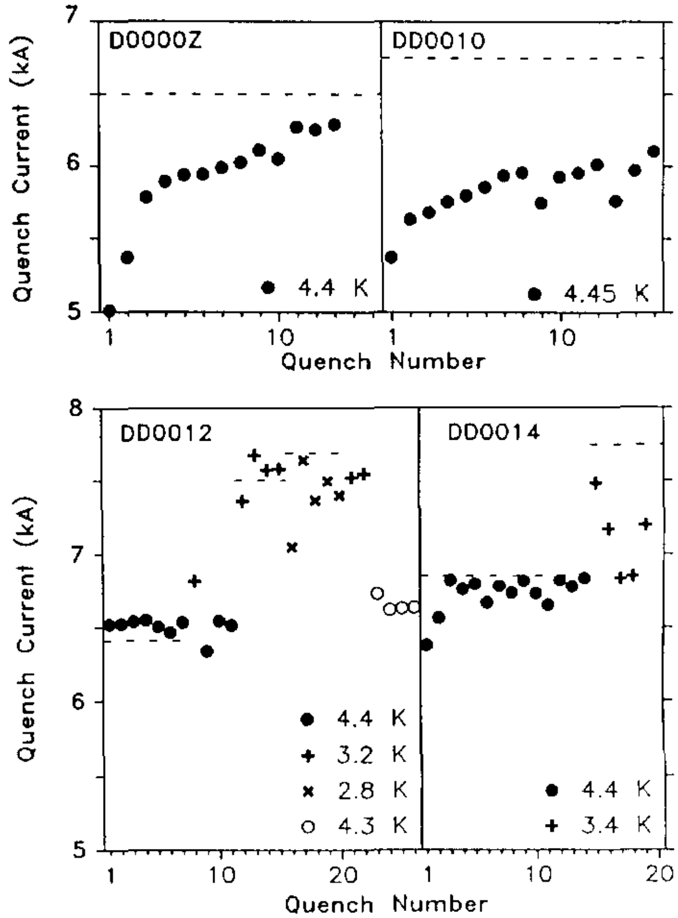

Figure 4. Quench histories. The dashed lines show the predicted critical current at each operating temperature. The variation in "plateau" quench current at 4.4 K in DD0012 is consistent with quench- to-quench temperature variation, while the spread in quench current at 4.4 K in DD0014 and at 3.4 K in DD0012 is not.

the second quench. At 3.2 K, the the quench current is erratic and no clear plateau is established.

Since there were no extra voltage taps on D0000Z, the precise origin of the quenches cannot be determined.

All the DD0010 quenches were found to originate in turn 13 (counting from the mid-plane) of one of the inner coils. The quenches originated in both the upper and lower coils, on both the left and right sides and at various locations along the length of the magnet. Turn 13 is located just below the wedge nearest the pole. This behavior is similar to some of the 1.8 m model magnets tested at BNL.[9]

DD0012 was quenched seven times at 4.4 K and once at 3.2 K. It was then warmed to room temperature, re- cooled, and operated at 4.4 K, 3.2 K, 2.8 K and 4.3 K. In the first test, the magnet exceeded the critical current on the first quench, while the first quench after the thermal cycle is just below the critical current. All the quenches except the second training quench at 3.2 K occur in the pole turn. This one quench occurs in turn 13 in the body of the magnet. The first quench after the thermal cycle occurs in the body of the magnet in the pole turn; all other quenches occur at one end or the other. Ten of the 12 quenches taken at $T < 4$ K and 7 of the 14 higher temperature quenches occur in the region of the splice between the inner and outer coil at the lead end.

All of the DD0014 quenches originate in the pole turn. At 4.4 K, 5 quenches occur at the non-lead end and the remaining quenches, including all those at 3.4 K, occur at a single spot in or near the inner-outer coil splice.

Conclusions

Four full scale SSC R&D dipole magnets, containing successive mechanical improvements, have been quench tested. Two of these magnets, which incorporate features to constrain the conductor more firmly azimuthally, radially and axially, perform much better than any previous long SSC magnet. The crucial features of their design appear to be 1)the use of the iron yoke to support the collared coil assembly, increasing the coil prestress and reducing the stress loss with increasing excitation and 2)the increased collar-yoke friction and the strengthened end plates, which essentially eliminate inelastic lengthening of the coil with successive excitations. Further experiments with upcoming magnets should help determine the relative importance of these two effects.

Magnet DD0012, however, shows a much more stable quench plateau at 4.4 K than does DD0014 and at lower temperatures goes consistently to higher current than does DD0014 despite having a lower critical current. This difference may reflect subtle mechanical differences between the two magnets, for example at the inner-outer coil splice, or may result from greater stability of the higher Cu:SC cable[11] used in DD0012. Again, only further experiments with magnets of similar mechanical design but differing cable or the demonstration of stable performance in a magnet with low Cu:SC ratio will be able to resolve this question.

Voltage tap data showing the location of the quenches reveal several problem areas in the magnet. If the magnet is inadequately clamped, (e.g. DD0010) turns adjacent to the wedges seem prone to quenching. This problem is most directly addressed by increasing the prestress, but small changes in the wedge design may also be necessary.

Many quenches in both DD0012 and DD0014, especially at higher currents at lower temperatures, occur in the region of the inner-outer coil splice. At this point, the inner conductor ramps to the radius of the outer coil and is soldered to the outer conductor, which is then brought around the end to the azimuth of the outer coil pole turn on the other side. Particularly in the region of the ramp and splice, mechanical support is difficult to guarantee. An improved design of this region will be incorporated in subsequent magnets. Most of the remaining quenches in these two magnets occur within a meter of the return end.

Acknowledgements

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