TEST OF TWO 1.8 M SSC MODEL MAGNETS WITH ITERATED DESIGN*

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Abstract

We report results from two 1.8 m-long dipoles built as part of the Superconducting Super Collider (SSC) R&D program. These magnets contain design changes made on both the 1.8 m and the full-length 17 m dipoles to improve quench performance, magnetic field uniformity, and manufacturability. The magnets reach 8 T with little training.

Introduction

The good quench performance of two recent 17 m model dipoles [1] established the principles needed for producing magnets capable of reaching the conductor current-carrying limit with little training. Design changes have been made to implement these principles and other improvements in a more production-oriented way. Except for length, the 1.8 m magnet series [2,3] has the features of the SSC design, which is based on a two-layer cosine theta coil with 4 cm aperture. As compared to the 17 m design length SSC dipoles, these 1.8 m magnets are a faster and more economical way of testing design changes. To check magnet performance, these dipoles have been heavily instrumented with voltage taps, strain gauges and spot heaters. Existing tooling sets the magnet length at 1.8 m. The magnets are tested in liquid helium in a vertical dewar.

The design changes incorporated in these magnets are briefly summarized here. The coils were wound with a revised cross section which included asymmetric copper wedges and were molded in a single-cure procedure. In both magnets, the collars which compress the coils were locked with tapered keys. When one of the magnets was assembled, however, no pressure was applied to push the keys into the collars. The yoke inner diameter was reduced to obtain a line-to-line (zero clearance) fit to the collars. The yoke laminations were assembled to produce a monolithic yoke structure. The two yoke halves were keyed with respect to each other at the midplane.

Magnet Design and Construction

The coil aperture is 4 cm and the coil outer diameter is 8 cm. The yoke inner diameter is 11.1 cm; its outer diameter is 26.7 cm. The magnet is designed to operate at 6.6 T central field in 4.35 K helium with a current of 6.5 kA. Features of the magnet design which are not discussed in detail here are as described in the SSC Conceptual Design Report (CDR). [4]

Cable

The cable used in the inner (outer) quarter coils of both magnets came from a single reel. It had a critical current density of 2.77 (2.43) kA/mm^2 at 5 T, 4.22 K, a copper-to-superconductor ratio of 1.47 (1.74), a filament size of 6 (5)μm, and a relative resistance ratio between room temperature and 10 K of 63 (123).

Coil

A cross section of the collared coil in the yoke and helium vessel is shown in Fig. 1. The coil cross section (designated C358D) is a four-wedge non-radial block design. [5] The design differs only slightly from the previous design (C358A). The change was made to further reduce allowed multipoles.

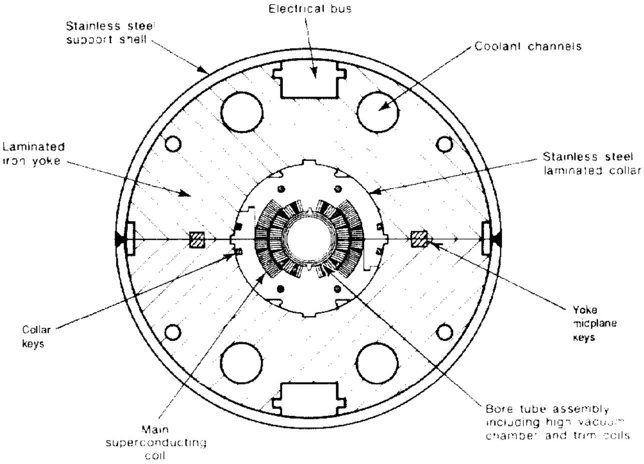

Fig. 1 Collared coil and yoke.

To eliminate the abrasion of wedge insulation during coil molding, the outer radius of the wedges was made with the same curvature as the coil. The result, in this non-radial design, was an "asymmetric" wedge.

To improve coil molding time, a "single size of the shim used in the curing fixture was determined from a size measurement made in the same fixture when the B-stage epoxy had become just warm enough to liquify. Also, further changes were made to the coil ends to make them stronger and more uniform in size.

Coil Assembly and Collaring

The G10 "ramp-splice" assembly was modified to better support and prestress the cable. This piece encapsulates the inner coil cable as the cable moves to the outer coil radius; it also encapsulates the splice between the inner and outer coils.

As in earlier models [2], the collars were punched from Nitronic 40 stainless steel and spot welded in pairs, with the pairs then left-right alternated to prevent twist in the collared coil. Tapered keys were used in the collaring. For DSS013, the usual procedure for tapered key assembly was followed, whereby the overall prestress on the magnet during collaring is minimized by using both vertical and horizontal force to seat the keys. As an experiment to test differences between this procedure and assembly with rectangular keys, DSS014 was assembled with tapered keys but with no significant horizontal force.

Yoke and Shell

The inner radius of the yoke laminations was 0.63 mm smaller than on previous magnets so that there would be a line-to-line (zero clearance) fit of yoke and unstressed collars at room temperature.

For the portion of the yoke which covered the straight section of the magnet, 15 cm-long stacks of standard iron laminations were alternated with single stainless steel laminations punched to provide channels for radial helium flow during quenches. All the laminations were stacked on rods and then compressed to a predetermined length to obtain a "monolithic" axial structure. The yoke end (including the last 5.2 cm of the inner coil straight section) contained only stainless steel laminations, bonded together.

To assure correct relative positioning, the two yoke halves were keyed together at the midplane with iron keys, as shown in Fig. 1. The stainless steel half shells were then welded around the

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yoke. The welding was done by hand, by two welders. The rods used to stack the yoke were withdrawn after the welding was completed and the end plates installed. A modest preload (a few hundred pounds) was applied to the coil ends via the one-piece 38.1-cm thick end plates.

Test Results

Quench Data

The initial quench program was carried out at temperatures close to those of SSC operation, 4.35 K. The helium temperature was then lowered in two 0.5 K steps to determine the mechanical limits of magnet performance. After a cycle to room temperature, these steps were repeated. As seen in Figs. 2 and 3, both magnets reached the conductor limit at fields above 8 T with little training and the training was retained after a thermal cycle. The maximum quench current in DSS013 was 8.11 kA; in DSS014 it was 8.14 kA. The current required to reach 8.0 T is approximately 8.07 kA.

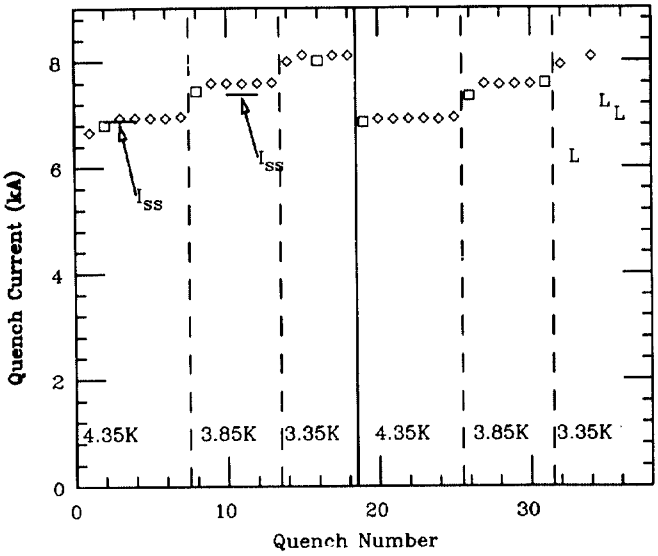

Fig. 2 Quench performance of DSS013. The solid line indicates a thermal cycle. Quenches originating in the lower (upper) inner coil are indicated by squares (diamonds). I_{SS} is the calculated quench current, based on measurements made on a short sample of the cable. Quenches designated L were due to a test stand fault.

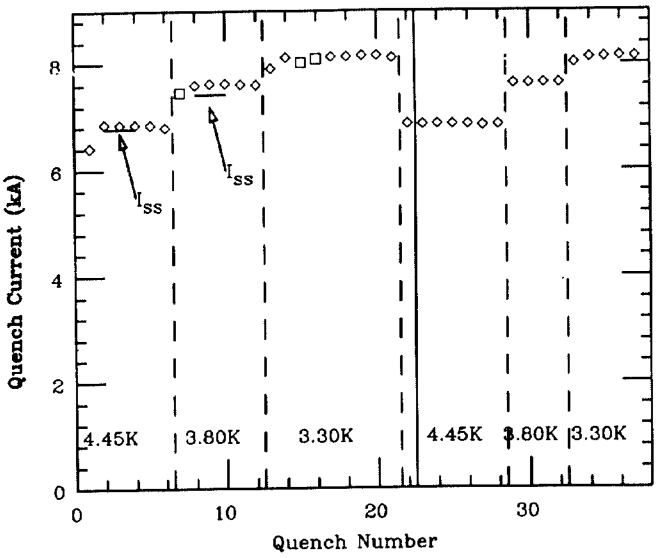

Fig. 3 Quench performance of DSS014. (Notation is the same as in the previous figure.)

Each magnet had more than 100 voltage taps, nearly all in the inner coils. Quenches which occurred when the magnet reached the current-carrying capacity of the conductor ("plateau" quenches) originated in the expected place, the pole turns of the inner coils. At 4.35 K, plateau quenches were at 6.93 kA, reproducible within about 0.01 kA.

Taking the locations of the non-plateau quenches of the two magnets as a group, the most common origin was the section of inner coil cable 5–10 cm beyond the G10 ramp-splice assembly. Other quenches also originated in the pole turn, in and near the non-lead end, and in the turn next to the largest wedge.

The longitudinal quench velocities generally agree with those in 17 m SSC dipoles. [6] These velocities are substantially higher than those measured in 4.5 m SSC dipoles [7] and in 1 m SSC models built at LBL [8]. These velocities are also faster than would be calculated in the adiabatic approximation. [6] The reason for this discrepancy is not understood at this time. Azimuthal quench velocities are about the same for all these magnets.

Stress Measurements

Each of the magnets was instrumented with two "beam-type" strain gauge packs. [9] One pack was located in the straight section, near the lead end. The other was the last pack in the straight section at the non-lead end. Each pack had four gauges for each coil, plus temperature compensating gauges. Average data from the gauge pack in the straight section of DSS013 are presented in Fig. 4. Gauge-to-gauge variations in stress make the average stress somewhat uncertain; however, the linear variation with I^2 does indicate that the coils do not become unloaded at the highest current measured, 7.5 kA.

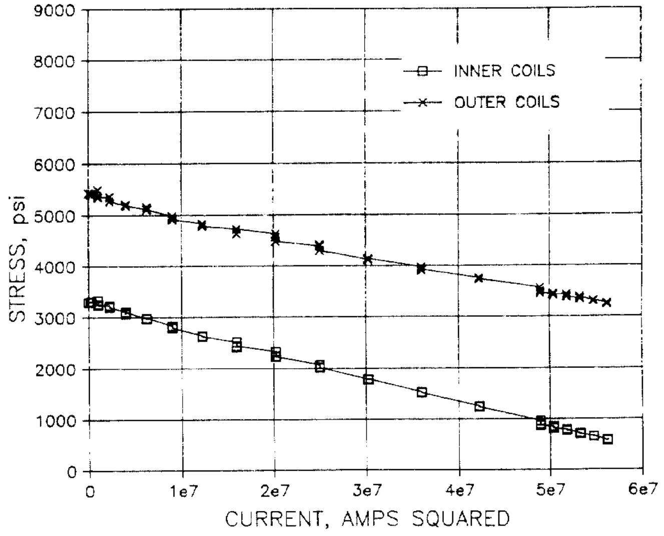

Fig. 4 Average inner coil stress vs. I^2, for strain gauge pack in DSS013 straight section.

Field Strength and Multipoles

The notation for multipoles is defined by the following equation:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

where B_0 is the dipole field, x and y are the horizontal and vertical coordinates measured from the magnet center. It is convenient to define a multipole "unit" as 10^{-4} of the dipole field, with the multipole evaluated at a radius of 1 cm.

Magnetic field measurements from the central section of the magnets are reported in Table I. The variation of the sextupole with current is shown in Fig. 5. The multipoles were measured with a

76-cm long rotating coil centered axially in the magnet. Measurements have been analyzed to remove feeddown and magnetization *effects.* [2]

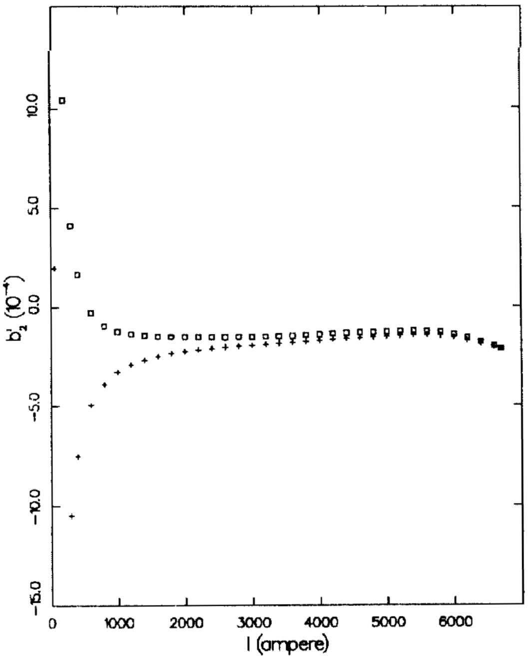

Fig. 5 Variation of sextupole with current in DSS014. The crosses are up-ramp data; the squares, down-ramp data.

Insofar as can be determined from two 1.8 m magnets, the higher order terms meet the SSC two-dimensional tolerances. [10] The low order terms deserve further comment. The quadrupole terms can be affected by the hand-welding involved in welding the shell around the yoke. Use of an automatic welding machine, to be introduced in the future, may reduce these terms. Allowed multipoles can be affected by changes in production procedures, such as the implementation of the line-to-line yoke-collar fit. It should be possible to compensate for these effects by making further small changes in the coil cross section.

Table I
Multipole Coefficients (1 "unit" = 10^{-4} B_0, r = 1 cm)

	Measured		SSC Tolerances (body)	
Coefficient	*DSS013*	*DSS014*	*Random (rms)*	*Systematic*
a_1	−.55	−2.53	0.7	0.2
a_2	−.65	−.01	0.6	0.1
a_3	.43	−.12	0.7	0.2
a_4	−.12	−.01	0.2	0.2
a_5	−.02	−.03	0.2	—
a_6	−.02	.01	0.1	—
a_7	−.01	−.01	0.2	—
a_8	.00	.00	0.1	—
b_1	−.55	.42	0.7	0.2
b_2	−2.80	−1.86	2.0	1.0
b_3	−.19	.01	0.3	0.1
b_4	−.59	−.82	0.7	0.2
b_5	.00	−.01	0.1	0.04
b_6	.02	.04	0.2	0.07
b_7	−.01	.01	0.2	0.1
b_8	.05	.03	0.1	0.2

The field strength was measured with an NMR probe at 1.8 T. The measured transfer functions were 1.0460 T/kA for DSS013 and *1.0463 T/kA for DSS014*. The calculated value is 1.0459 T/kA, with design shims.

References

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[8] W. V. Hassenzahl, "Heater Induced Quenches in SSC Model Dipoles," ibid., pp. 934-937.

[9] C. L Goodzeit et al., "Measurement of Internal Forces in Superconducting Accelerator Magnets with Strain Gauge Transducers," presented at the Applied Superconductivity Conference, San Francisco, CA., Aug. 21-25, 1988.

[10] SSC Specification Number SSC-MAG-D-1010 (December 1988).