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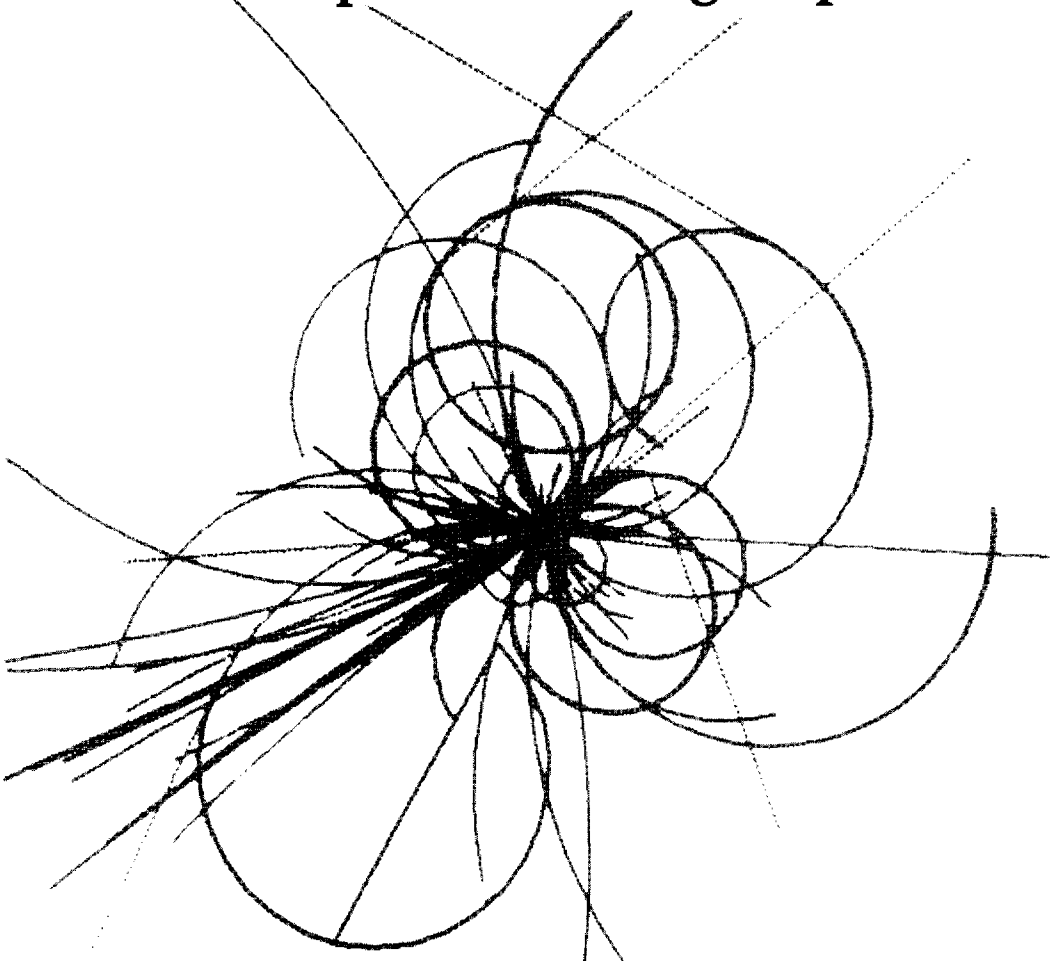

Performance of Full-Length SSC Model Dipoles: Results from 1988 Tests

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Abstract

Over the past year, magnets that meet the SSC field and quench training criteria have been developed as a result of the detailed understanding of magnet performance made possible by tests on a series of model magnets. The SSC dipole magnet design is a $\cos\theta$ style coil with a 4-cm aperture and a magnetic length of 16.6 m. The design operating field is 6.6 T at a current of 6.5 kVA. Design, fabrication, and testing of full-length model magnets has been a cooperative effort among the SSC Central Design group and three major national laboratories: BNL, FNAL, and LBL.

I. INTRODUCTION

The Super Collider will require nearly 8,000 superconducting dipole magnets to form the 83.1-m rings in which beams of protons will be circulated. The design parameters of the dipole magnets, as described in the Conceptual Design Report,[1] include an operating field strength of 6.6 T at a current of 6.5 kVA and an operating temperature of 4.35 K.

* This work is supported by the U.S. Department of Energy.

The full-scale model dipole magnets have a $\cos\theta$ style coil with a 4-cm aperture and a magnetic length of 16.6 m. The dipole inner assembly, known as the cold mass, is shown in Figure 1. The superconducting coil is restrained by stainless steel collars ,which provide both the precise alignment necessary to maintain high field quality and the primary clamping force against conductor motion. Iron yoke laminations are located outside of the collars to augment the magnetic field by roughly 20 percent. The dipole inner assembly is completed by a stainless steel skin (0.1875 inches thick) that forms the boundary of the region in which the 4.35 K helium circulates. In some of the magnets tested in 1988, the region between the iron yoke and stainless steel collars (nominally a 0.010-inch gap in older designs), was shimmed to ensure direct contact. In this manner, the collared coil assembly is restrained in its axial motion with respect to the iron yoke, and the yoke laminations and outer skin become structural elements that contribute to the effective stiffness and clamping ability of the collars. (This is discussed in more detail below.)

The design parameters were chosen to optimize cost, field strength, superconductor properties, and operational characteristics such as the machine aperture (in which the proton orbits are stable) and control and corrections schemes. The $\cos\theta$ style coil uses superconductor economically while maintaining the high field quality necessary for a storage ring. Typically, the magnetic field quality is described in terms of the strength of coefficients in a multi-pole expansion of the field.* In a perfect dipole magnet, only the lowest-order (dipole) turn would exist. Symmetry considerations dictate that certain terms should vanish. In general, the field must be uniform to a few parts in 10^4 of the central field value (with this requirement becoming more stringent for higher-order multipoles).

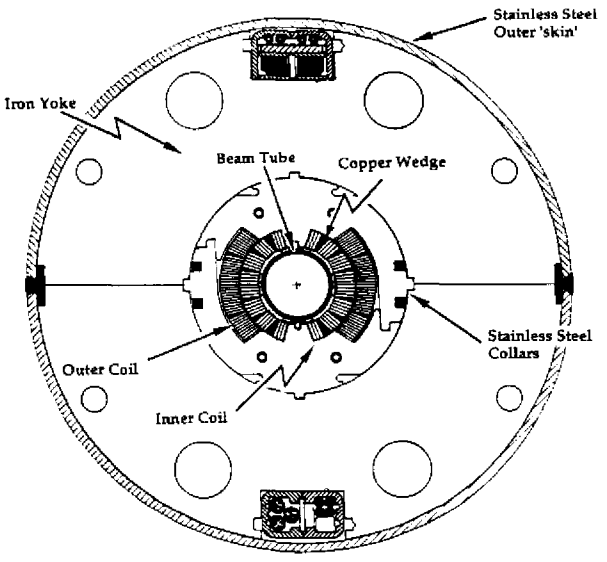

Figure 1. Cross sectional view of a model SSC dipole cold mass with prominent features labelled.

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*The multi-pole expansion used is:

$$B_x + iB_y = B_0 \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n,$$

where x & y are the usual space coordinates, and B_0 is the dipole field strength. The b_ns represent the normal multipole components, while the a_ns are the skew components.

Evidence for the success of the present design in meeting the desired field quality limits[2] can be seen in measurements of short (1.8 -m) SSC model dipole magnets. The field is measured in the uniform, two-dimensional cross section to determine the geometric multipoles, which depend on coil design and conductor placement. Data from several short magnets are shown for both normal and skew multipole components up to $n = 8$ (18-pole in our nomenclature) in Figure 2. The upper and lower limits acceptable for each term are shown as bars on the figure. The data clearly fall well within the specified tolerances.

The goal of the magnet R&D program is to develop a design suitable for industrial production of full-length model dipole magnets that meet all system requirements. The first long magnets tested (late in 1986 and early in 1987) did not achieve this goal; they did not routinely reach the operating current and they exhibited excessive training.[3] While these early model dipoles did not fully realize the goals of the R&D program, they provided sufficient data to identify for us which features of the design needed improvement and to establish the need for expanded and refined diagnostic instrumentation.

The primary focus of the magnet R&D program in 1988 was to solve the training problem. Improvements in magnet design, along with specific design variations, were incorporated into the series of magnets to be tested. The diagnostic instrumentation was also greatly expanded to provide more detailed information on quench origins and a more reliable and complete picture of mechanical behavior. Specific mechanical issues included improvement in the design of the stainless steel collars and in the treatment of the coil ends, as well as variations of the design of the interface between the collared coil assembly and iron yokes. The instrumentation expansion included a large increase in the number of voltage taps used for quench localization and major improvements in the design of mechanical sensors (strain gauge assemblies) used to measure the stress/strain state of magnet components.

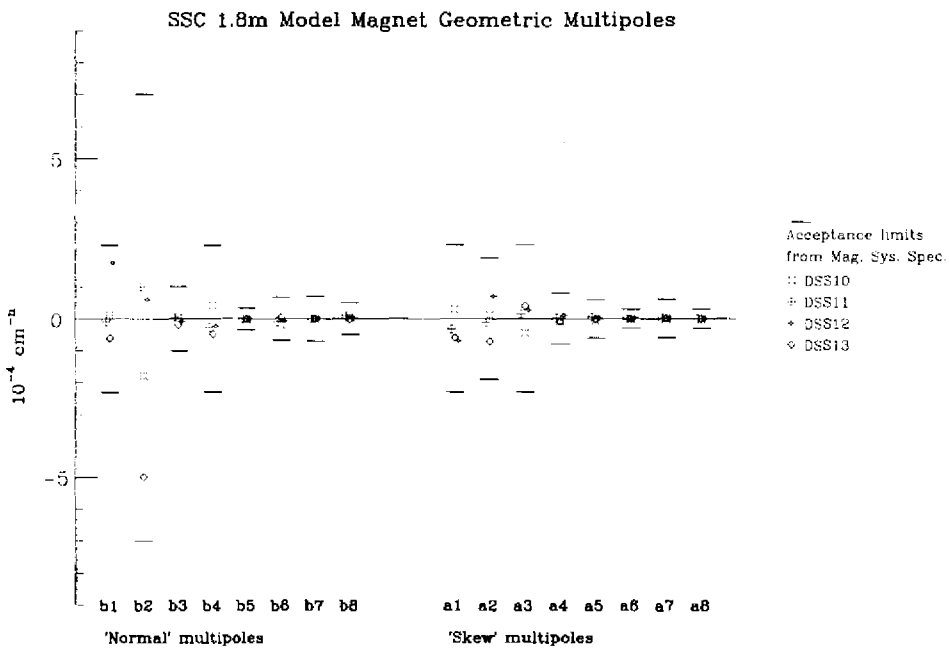

Figure 2. Geometric multipoles measured in 1.8-m model dipoles; horizontal bars indicate SSC acceptance limits.

II. ASPECTS OF MECHANICAL DESIGN

The stainless steel collared long magnets (BNL design) represent the main thrust of the magnet R&D program. An alternative design, based on aluminum collars (LBL design), had been developed only in short (1-m) models prior to 1988, when the first full-length magnet was tested. Thus the long magnet test program reflects the development of the stainless steel collar design, and most of this discussion addresses only that design. In this section three aspects of the magnet mechanical design are examined. These discussions, although in general applicable to both magnet designs, are specific to the stainless steel collar models and are based on results from tests of early models.

A. Coil Clamping–The Collars

Increasing the initial (zero current) clamping force and maintaining it during magnet excitation had become a design focus in 1987. Collars come in left-right pairs and mesh together in top and bottom sets. The left-right pairs, originally held together by pins, were spot-welded together to provide greater rigidity. (See Figure 1.) The increased strength of the spot-welded collars provides better mechanical restraint against the forces on the coils during excitation. Spot-welded collars were first used in a long magnet in mid-1987 and are now incorporated into all magnets.

The initial clamping pressure is determined during the collaring process by the azimuthal thickness of the coils and by the thickness of shims placed between the collar pole faces and the coil. (Maximum pressure limits are set to maintain the integrity of the insulation.) The upper and lower collar pack assemblies are pushed together by collar presses until slots (keyways) on both sides are aligned and a metal bar (called a key) can be inserted. In collars used in long magnets prior to mid-1988, the keys and keyways were square in cross section (called straight keys). By the third long magnet of 1988, following developments in shorter model magnets,[4] the collar design was modified to incorporate tapered keys and keyways.[5]

The assembly procedure followed with tapered keys differs from that with straight keys and obtains a given collared coil pressure with less overpressure during collaring, lessening the possibility of damage to the coil insulation. In the collaring procedure for square keys, the collaring force is vertical, and significant overpressure must be applied to allow alignment of the keyways and insertion of the keys. The clamping force obtained is significantly lower than the maximum collaring force. For tapered keys the procedure is quite different: a vertical force sufficient to get the keyways nearly aligned is applied, and then the keys are driven into the keyways by a horizontal force, the taper forcing the keys and keyways into alignment. In this manner, it is possible to obtain a desired clamping pressure with a minimum of overpressure.

Intimately coupled to the design issue of coil clamping is the consideration of coil size variation. Variation in the azimuthmal size (arc length in the collars) of the coil translates into variations in the clamping pressure. Shim sizes are determined by the requirement of bringing the low point to a minimally acceptable level.[6] This consideration directly interacts with the collaring: shimming to the low point must not overpressure the high point.

The variation in coil size in the magnets tested in 1988 was typically ±0.004 inches, nearly a factor of two greater than design requirements. The variation in coil size was determined to be caused by the coil molding tooling. However, until recently, funds were not available to improve the tooling. Coils made for long magnets to be tested this year have greatly improved uniformity. Further improvements are under way at BNL and entirely new, more robust coil fabrication tooling is being developed at FNAL.[7]

B. Coil End Treatment

The treatment of the coil ends, where the cable must bend up and over the beam pipe to return along the opposite side, was also enhanced. Analyses of 1987 test results determined that quench origins were predominantly in or near the end regions of the coil.* (During excitation, the Lorentz force exerts several thousand pounds of force on the coil ends.) A weak coil end structure, coupled with relatively weak end plates holding the coils, was thought to contribute to end quenching.

The first attempt to strengthen the end region was to use an alumina-loaded epoxy to fill in the the spaces between coil windings, after the molding process, to form a hardened unit. Subsequent revisions to the design used epoxy-laden inserts between coil turns and fiberglass layers on the inner and outer surfaces, added as part of the molding process. The result is a smooth coil end of uniform radial thickness. Short (1.8-m) magnets tested with hardened ends showed improved quench performance[8] and this procedure was incorporated into the fabrication of long magnets. The ends of magnets DD0010 and DD0012 were filled with epoxy, while the later magnets, DD0014 and DD0015, were constructed with the revised end treatment.

The older design, including DD0010, had "thin" (0.75-inch) stainless steel end plates, split at the middle. These thin end plates deflect when the coil is excited, allowing some coil motion. To further constrain the coil ends, magnets after DD0012 were constructed with thicker (1.5-inch stainless steel), solid end plates. The thick end plates show very little deflection during excitation and prevent motion of the coil end. The added stiffness of the end plate, however, results in a greater buildup of force between the coil end and the plate during excitation.

C. Collared Coil–Yoke Lamination Interface

A third, and perhaps the most important, design issue to be examined in the 1988 magnet test series was the treatment of the collared coil-iron yoke lamination interface. In the original design, there was a 0.010-inch clearance between the collared coil assembly and the yokes. This clearance was to facilitate centering of the coil within the iron to obtain optimal field characteristics. The clearance, however, led to a somewhat poorly defined mechanical interface, which could result in erratic motion between the two components: the coil could both slip and stick as it was elongated by the Lorentz force during excitations. Motion of the collared coil assembly within the yoke could cause premature quenching; it could push the end of the coil against the end plate or generate heat along its length.

In addition to the evidence for quenching near the ends, the 1987 test progam showed evidence of inelastic "stick-slip" motion of the collared coil assembly within the yoke blocks. The first magnet tested in 1988, DD0010, was of the older design and clearly exhibited the same mechanical behavior, dubbed "ratcheting," during its test history. Following each quench to successively higher currents, it was observed that the coil moved outward during excitation but did not return completely to its initial position. This ratcheting was detected as a buildup of the quiescent force on the end plates and by direct measurement of the change in the quiescent position of the coil ends.

The other stainless steel collar magnets designed for 1988 addressed this design issue in two ways: two magnets (DD0012 and DD0014) were constructed with shims placed between the collars and the yoke to prevent motion, while one magnet (DD0015) was built with a "slide plane" to allow free, elastic motion of the coil within the yokes.

*The analysis, based on the pressure transducer data, could only localize the quench origin to roughly ± 1 m along the axis of the magnet; the actual extent of the coil end region is less than 20 cm.

The effectiveness of the shimming technique was first tested in short magnets, and improved quench performance was observed.[4] Magnets constrained in axial motion of the collared coil assembly by the shimming technique had increased stiffness in the radial direction. The shims directly coupled the collared coil assembly to the iron yokes and thereby to the outer stainless steel skin. This tightly coupled package of collars-yoke-skin results in a stronger clamping of the coil against the Lorentz force: during excitation, the coils are more tightly held and hence the restraint against quench-inducing motion is increased.

The design of the current (1989) R&D magnets follows the axially constrained coil assembly line of development: the new magnets have no clearance between the collars and yoke (a so-called "line fit"). An additional clamping force is obtained when the outer stainless steel skin is welded around the assembly and weld shrinkage applies additional compression.

III. IMPROVEMENTS IN INSTRUMENTATION

The results from magnet tests in 1987 illuminated certain design features for study and improvement. The 1987 test results also clearly demonstrated the need for improved instrumentation to determine where quenches originated and to understand what aspects of magnet mechanics caused quenching below the cable short sample limit. Quench origins can be localized by detecting the resistive voltage associated with the presence of a normal zone: an elaborate system of voltage taps was inserted in the coils to trace quench evolution. The mechanical state of the magnet assembly was determined with an improved and expanded set of strain gauge transducers. These topics are discussed in greater detail elsewhere in these proceedings;[9,10] we present only a brief overview below.

A. Voltage Taps

A quench is detected by sensing the resistive voltage generated in the magnet when a region of the conductor goes out of the superconducting state. This voltage is detected by attaching sense wires to various points on the coil wires (voltage taps) to measure the voltage difference between taps. The coil in an SSC dipole magnet consists of four parts, which are wound separately and then joined: two inner (upper and lower) and two outer (upper and lower) quarter-coils. In magnets prior to DD0010, the voltage tap information was typically limited to the voltage across an entire quarter coil. Beginning with magnet DD0010, the turns of the inner coils were divided into four parts by connecting four voltage tap wires to them, separating the more complicated end regions of the coil from the body, resulting in 128 additional channels of voltage information. The quench origin is determined by finding the first segment of coil to develop voltage.

By analyzing the rate of voltage development in the initial coil segment and the time at which voltage is seen in adjacent coil segments, the quench origin can be determined to roughly ±10 cm along a given turn.[9] With this resolution, it is possible to determine a particular site or mechanical feature associated with the quench origin and thus to understand and improve magnet performance.

B. Strain Gauge Assemblies

Premature quenching (quenches below the cable short sample limit) is believed to be associated with inelastic motion of the conductor. Magnets tested in 1988 had specific design modifications to control the motion of the conductor. Using improved strain gauge assemblies, we are able to determine the mechanical response of key system components, such as the collar clamping pressure and the force of the coil on the end plates, and to correlate the measurements with magnet performance.

Specially designed collar packs incorporate strain gauges to measure the collar-coil pressure.[10,11] These gauge collar packs were mounted at the point where the inner coils were smallest in azimuthal length, corresponding to the lowest prestress. The strain gauge assemblies were carefully designed to give accurate, reproducible measurements of the average stress at the collar-coil interface.

Forces at the coil ends were measured by another type of strain gauge assembly.[11] Threaded bolts, in which pairs of strain gauges were mounted, connected the end plates to the coil end. Four of these assemblies, called "bullets" because of their shape, transmitted and measured the Lorentz force between the coil and the end plates at each end of the magnet.

IV. THE 1988 TEST PROGRAM

In 1988, five full-length model SSC dipole magnets were tested. Four of these were constructed with stainless steel collars (the BNL design), representing a progression of design improvements as well as variations in the approach to a specific design issue; the fifth magnet was the first aluminum-collared (LBL design) long magnet to be tested.

To place the magnets in perspective from both chronological and design evolution viewpoints, a genealogical chart of the long magnets is shown in Figure 3. Time and design evolve from left to right; distinct design variants are separated vertically. Only a few of the design elements, those considered most likely to affect quench performance, have been included.

The design issue of axial restraint (for the BNL design magnets) is separated into three classes of implementation: in the earlier magnets, including DD0010, the collared coil yoke interface was not well defined. Full axial constraint describes magnets (DD0012 and DD0014) in which shims were inserted between the collars and yokes to lock them together. Magnet DD0015, on the other hand, was axially free: a slide plane was introduced between collars and yokes to permit free, elastic motion. The treatment of the collars also evolved with time: from straight keys (DD0010 and DD0012) to tapered keys (DD0014 and DD0015). The details of the coil cross section and changes in the coil end treatment are also indicated on the figure.

By the end of 1988, a clearly identified mainstream design had emerged. A mature version, incorporating axially constrained coils and the various collar and end treatment improvements (as well as improvements in the coil fabrication procedure), has been employed in the next series of long magnets, DD0016–DD0018.

Table 1 presents a summary of design characteristics and other properties of these five magnets.

A. Quench Performance

The quench performance for the five magnets tested in 1988 is presented in Figure 4 where the quench currents are displayed. The dashed lines represent the short sample current, calculated using the measured I_c(4.2 K, 5 T) of the inner coil conductor, for each magnet. The variation in short sample current results from differing superconductor J_c as well as variations in the cable copper-to-superconductor ratio. Two of the magnets, DD0012 and DD0014, were "thermally cycled": the first series of tests was followed by a warmup to room temperature and then a second cooldown and test period. The thermal cycles are indicated by vertical dashed lines.

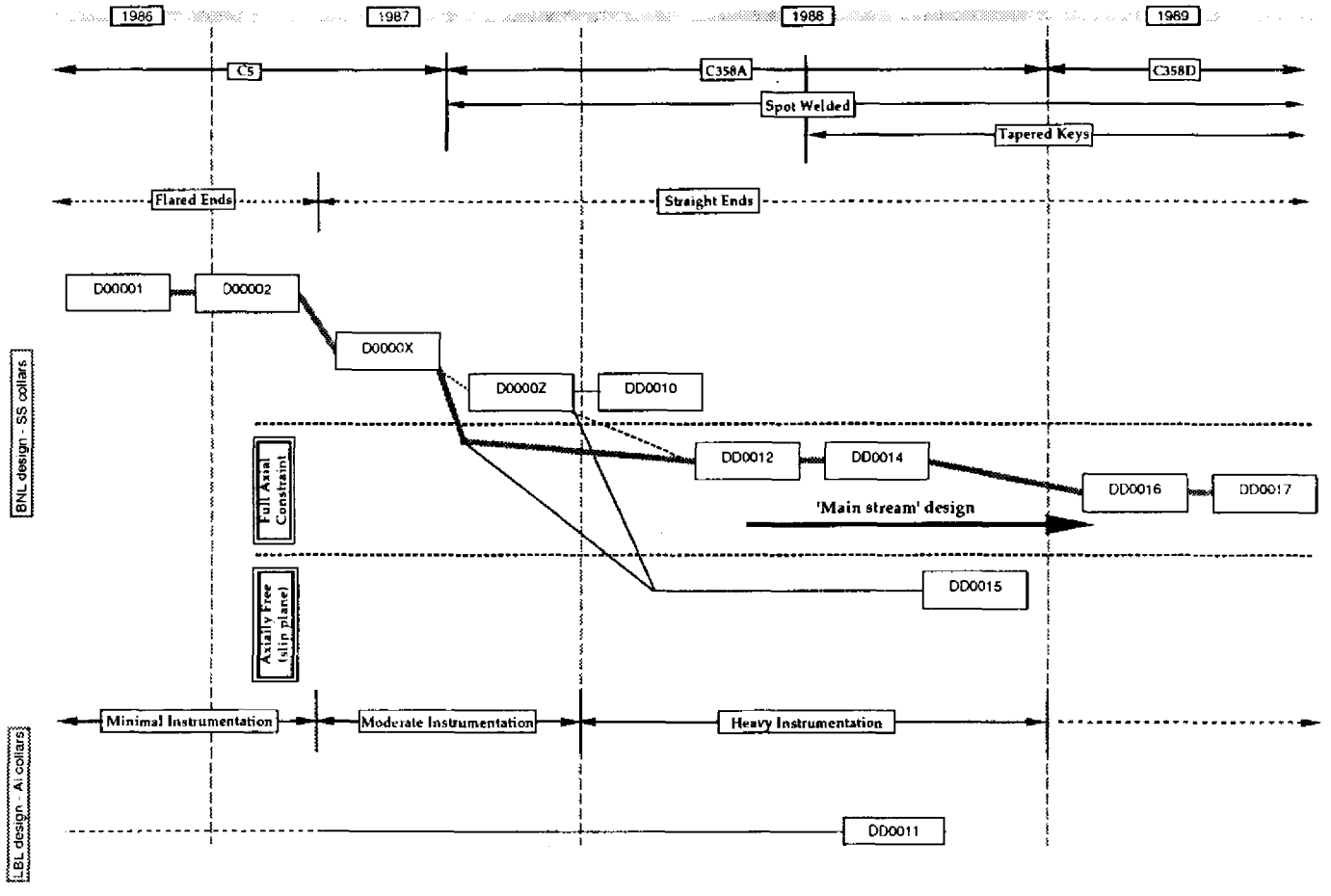

Figure 3. A 'genealogical' chart of the SSC model dipoles; the main stream design path is indicated by heavy lines.

TABLE 1. MAGNET DESIGN CHARACTERISTICS

Magnet	Collars	Collar/Yoke* Interface	Coil End Treatment	End Plates	Inner Coil Cu:Sc	Inner Coil I_{SS} (4.35K)	Inner Coil Pre-Stress (Cold)
DD0010	S.S. C358A St. keys	? Nom. 0.010" clearance	Filled w/Al. loaded epoxy	3/4" S.S. split	1.4:1	6840 amps	4050 psi
DD0012	S.S. C358A St. keys	Constrained w/shims	Filled w/Al. loaded epoxy	$1\frac{1}{2}$" S.S. solid	1.6:1	6450 amps	4990 psi
DD0014	S.S. C358A tapered keys	Constrained w/shims	Molded inserts & fiberglass 'shoes'	$1\frac{1}{2}$" S.S. solid	1.24:1	6900 amps	4830 psi
DD0015	S.S. C358A tapered keys	Free 'DU' slide	Molded inserts & fiberglass 'shoes'	N.A.**	1.24:1	6910 amps	5360 psi
DD0011	Al. NC9 tapered keys	? constrained warm	G-10 spacer with Al. clamps	1" S.S. solid***	1.25:1	7170 amps	****

*? ⇒ not well defined when cold; stick-slip motion possible and ratchetting observed.

**DD0015 end plate was backed off from, and not in contact with, coil end.

***LBL end plate design differs from that used in the other magnets in table.

****Measurements not directly comparable due gauge effects.

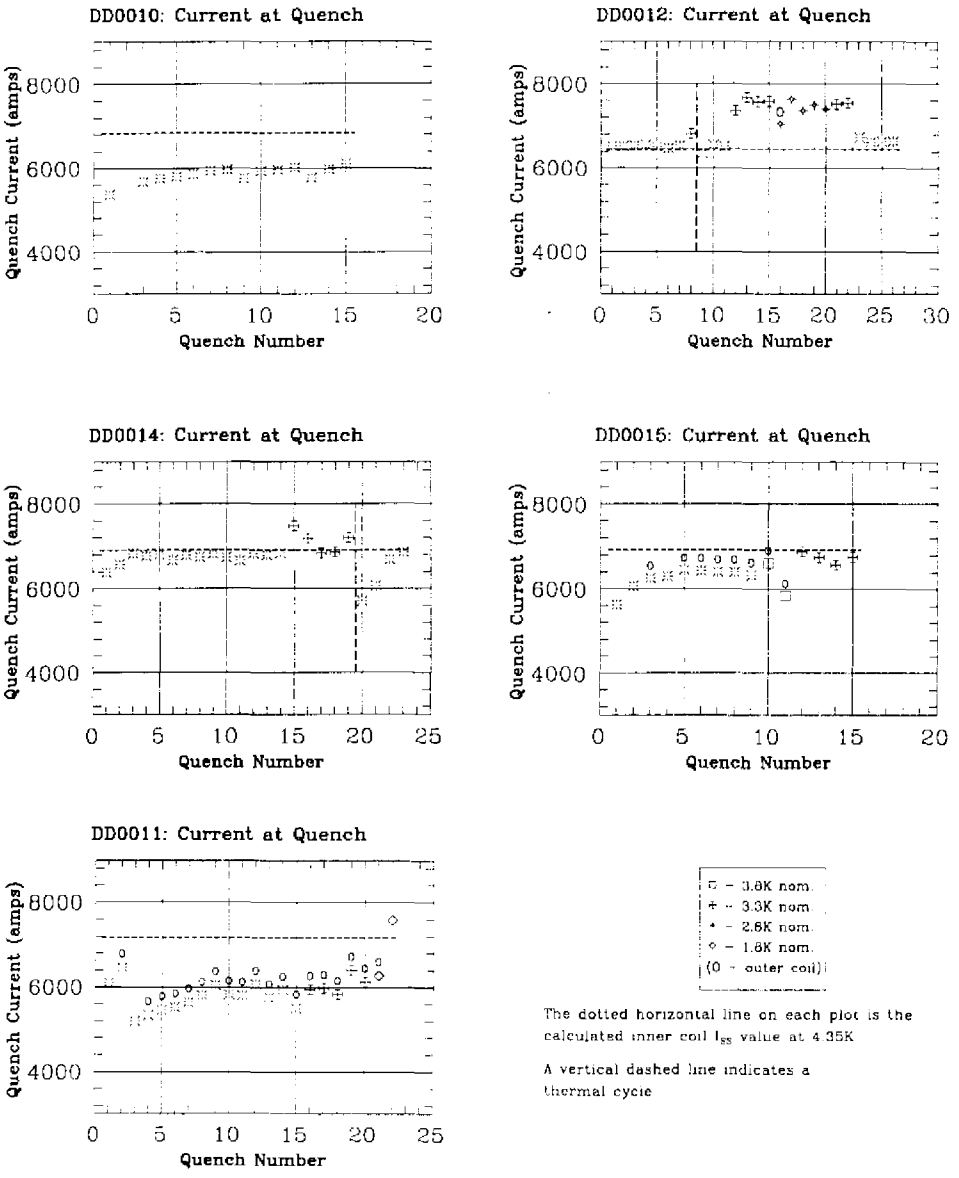

Figure 4. Summary of quench currents obtained in tests of SSC full length model dipoles during 1988. The horizontal dashed lines indicate the predicted short sample current; vertical dashed lines indicate a thermal cycle.

The axially constrained magnets, DD0012 and DD0014, exhibit quench performance that is clearly superior both to the other magnets and to previous long magnets. In the initial tests at 4.35 K, DD0012 exceeded the SSC operating current of 6500 A without a training quench, while DD0014 has only one quench below that value. Both perform near or above their predicted short sample limits. Magnet DD0010 displayed slow training at currents significantly below its short sample limit, as was characteristic of its predecessor, DD000Z,[12] and other magnets of the old design. Magnet DD0015 appeared to plateau at currents well below its short sample prediction.

Finally, magnet DD0011—the first long dipole magnet with aluminum collars—showed erratic training behavior at relatively low currents. The quench performance of each magnet is examined in more detail below.

DD0010

Magnet DD0010 was both the last long magnet of the "old" design (in which the collar-yoke interface was not well defined) and the first long magnet to have expanded diagnostic instrumentation. During the final stages of assembly at FNAL, the cold mass was heated during the application of strain gauges to the stainless steel outer skin. Subsequent measurements indicated an apparent drop in inner coil prestress of about 1000 psi. Fifteen spontaneous quenches were recorded during its first test cycle.*

The voltage tap data were used to determine quench origins. In DD0010, all quenches occurred on turn 13 (counting from the midplane) of the inner coils, both upper and lower. The axial location of the quenches was distributed along the length of the magnet, with two clusters at locations roughly 350 and 440 inches from the feed end. Subsequent disassembly revealed that the copper wedge between turns 13 and 14 (refer to Figure 1) was not bonded to the adjacent cable. The combination of diagnostic measurements—prestress monitoring and quench origin determination—and observations during disassembly presented a reasonably complete explanation for the magnet performance.

DD0012

Magnet DD0012 was the first axially constrained long magnet having shims between the collared coil and yoke assemblies to prevent relative motion. It also was the first long magnet to have thick (1.5-inch stainless steel) end plates to further constrain the coil ends. DD0012 went directly to its short sample limit on its first quench and displayed very good quench behavior at 4.35 K. At 3.2 K, DD0012 exhibited some training before reaching currents near the calculated short sample value of about 7500 A. Lowering the temperature further did not increase the quench current obtained: a mechanical limit had been reached.

The 4.35 K quenches, although very close in current, fell into two classes depending upon whether they exhibited short sample behavior. Short sample behavior is distinguished by several characteristics: the current reached, the location and repeatability of the quench origin, and strong correlation with temperatures are among the most important criteria used. The voltage tap data indicated that the short sample quenches of DD0012 occurred on turn 16 (the high field turn) near the warmer return end of the magnet in essentially identical patterns of voltage development. The correlation of quench current with temperature is shown in Figure 5. The slope dI_q/dT is in good agreement with an expected value of about 1070 A/K.

* Following a second cooldown, a short was detected between the quench-protection heaters and the lower outer coil to ground, and further testing was cancelled. The magnet was returned to BNL, disassembled, inspected, and repaired. Modifications were made to the quench-protection heater design.

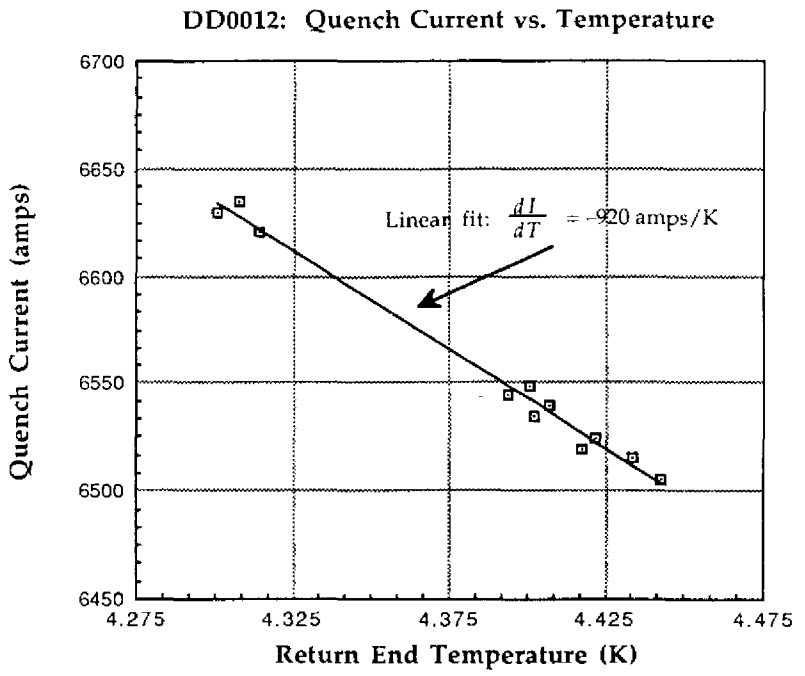

Figure 5. A plot of DD0012 quench currents versus return end temperature for quenches identified as short sample quenches. The line is the result of a linear fit to the data which yields $\frac{dI}{dt} = -920$ amps/K.

The non-short sample quenches were dominantly in a region of the coil called the ramp splice. In both halves of the magnet, the inner and outer coils are joined on the innermost (pole turns) at the feed end. This joint occurs in the straight section of the magnet just before the end. Turn 16 of the inner coil is bent radially outward to the outer coil radius while turn 20 of the outer coil is brought around the end to the azimuthal position of inner turn 16. The solder joint and ramp of the inner cable to the outer radius are held inside a G-10 box. The collars in this region must have a notch cut out to hold the splice assembly and thus are weaker than the regular collars. The voltage tap data provided the resolution necessary to identify this relatively short 10-inch length of conductor as the source of quenches. The ramp splice subsequently has been improved, and a revised ramp splice assembly has been included in recent R&D magnets (DD0016 and after.)

DD0014

In addition to having its coil axially constrained with shims in the same manner as DD0012, magnet DD0014 was the first long magnet with tapered-key collars and coil ends strengthened during the molding process. It exceeded the SSC operating current on its second quench and then reached a plateau near its short sample value. The plateau shows considerably more variation than DD0012, and close inspection of the data reveals that 9 of the 14 quenches at 4.35 K are in the ramp splice regions. The first quench, a training quench, occurred on turn 16 of the upper inner coil in the return end region. The remaining quenches were near the return end of turn 16 of the upper inner coil.

The temperature was lowered to 3.3 K and further quench tests were performed. The first quench occurred at 7478 A, but subsequent quenches were lower in current. All of the 3.3 K quenches were in the upper inner coil ramp splice region.

A thermal cycle was followed by rapidly cooling the magnet to 4.35 K; the usual limitation placed on the temperature differential across the magnet of <125 K* was removed. This took less than 13 hours; a normal cooldown typically takes about 36 hours. It then took two training quenches (at currents lower than previously observed) before DD0014 was back to its pre-thermal cycle level. All quenches in the second test cycle were in the lower inner coil; the first quench was on turn 16 in the body of the magnet; the remainder were in the ramp splice segment.

DD0015

DD0015 was the last of the BNL design, stainless steel collared magnets to be tested in 1988. Unlike DD0012 and DD0014, DD0015 was an axially free magnet in which the collared coil assembly was free to move with respect to the yoke laminations. The end plates were not in contact with the coil ends. Due to lack of cable while DD0015 was being fabricated, the lower outer coil was re-used from a previously tested magnet, DD000Z.[12] Other design characteristics included tapered-key collars and coil ends strengthened in the molding procedure.

Three of the first four quenches at 4.3 K were in the lower inner coil ramp splice segment; the remainder were in the lower outer coil, which did not have voltage taps, so precise quench location was not available. Following the fourth quench, the quench current reached a plateau at about 6400 A. The expected short sample limit for the inner coils was about 6910 A (upper inner); for the lower outer coils, the value expected was essentially the same.

A plot of the lower outer coil quench currents versus temperature, shown in Figure 6, reveals a strong correlation at nearly the expected slope. This is highly suggestive of conductor- (as opposed to mechanically) dominated behavior. A crude longitudinal position analysis using pressure transducer data indicated that all but one of the lower outer coil quenches occurred in a localized region near the return end. It was also noted that magnet DD000Z, the source of the lower outer coil, had failed with a short to ground in the upper inner coil *near the return end.*[12] The observed behavior is consistent with a loss of J_c for the lower outer coil conductor. (However, the highest current reached in DD000Z testing was about 6300 A, below the DD0015 plateau value.)

The temperature was lowered to 3.8 K, and two additional lower outer coil quenches occurred. The first quench was at 6600 A; the second quench was at 5840 A. The temperature was then lowered to 3.3 K, and four quenches were recorded. These last quenches all occurred in the lower inner coil ramp splice region.

The quench behavior of DD0015, when looked at in detail, is encouraging: quenching was associated with either the ramp splice (as in other magnets) or the outer coil. There were no other inner coil quenches. Freedom of the collared coil assembly to move during excitation and removal of the constraining end plate do not appear to have resulted in inner coil end quenching.

DD0011

Magnet DD0011 was the first long magnet with aluminum collars (LBL design) to be tested. The coil cross section (NC9) differs slightly from that of the stainless steel (C358A) design, as do other aspects of the mechanical assembly. Specifically, both the coil winding

* The temperature is monitored in interconnect regions where the magnet is attached to the test stand. Temperature sensors mounted in the interconnect regions measure the helium temperature before it enters the magnet (feed end) and after it has traversed the length of the magnet (return end).

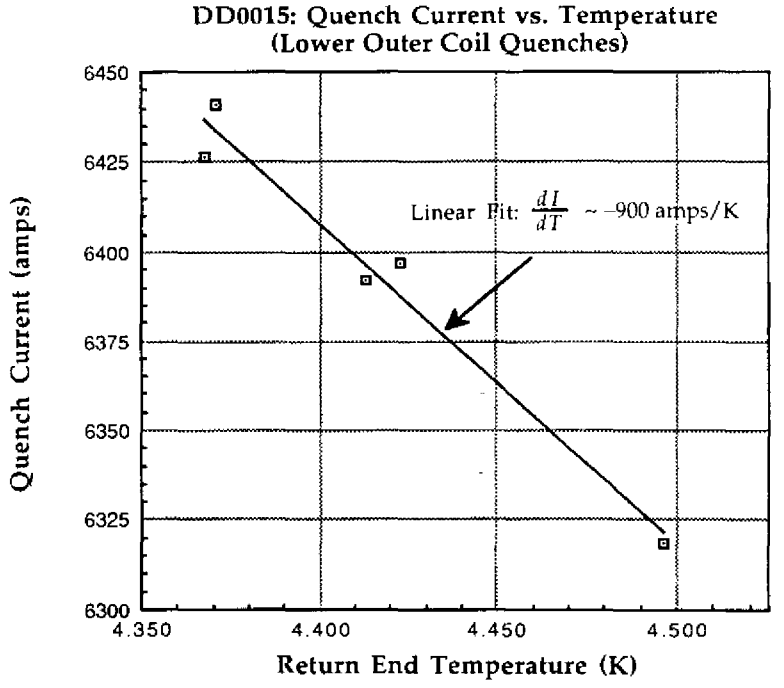

Figure 6. A plot of lower outer coil plateau quench currents in DD0015 versus return end temperature; a linear fit yields $\frac{dI}{dt} = \sim -900$ amps/K.

and mechanical assembly procedures for the end regions differ from the BNL design. Not unexpectedly, the first NC9 long coil winding and fabrication encountered some difficulties, and several shorts had to be repaired.

The quench performance of DD0011 was erratic, reminiscent of the first long stainless steel collared dipole, DD0001.[3] Its first quench was at 6107 A in the upper inner coil; the second was at 6464 A, in the upper outer coil. The second quench was followed by a quench at 5192 A (a precipitous drop in current) in the upper outer coil, and subsequent quenches remained in the upper outer coil showing slow, erratic training. A total of 15 quenches were recorded at 4.35 K. Lowering the temperature to 3.3 K did not appreciably improve quench behavior.

At this time in the test program, the ability to operate in helium II became available on the DD0011 test stand. Tests of 1-m magnets at LBL had shown promising improvements of quench behavior at 4.35 K by conditioning magnets at lower temperatures.[14] DD0011 was run at 1.8 K, and its initial quench was in the upper outer coil at 6273 A. The next quench was in the lower inner coil at 7579 A. Post-quench tests revealed that a ground fault had developed. Opening and disassembly revealed that the short occurred at the feed end of the magnet, in the vicinity of one of the shorts that had been repaired during assembly.

B. Prestress Comparison

An important variable in magnet performance is the clamping pressure exerted by the collars on the coil. Two aspects of the clamping are of significance: the quiescent (zero current) value of the pressure or prestress and the rate at which this pressure decreases as a function of magnet current. The combination of these two factors determines the clamping force at high currents, an important factor in determining quench performance.

Figure 7 displays the average inner coil stress versus I^2 for the four magnets with stainless steel collars tested in 1988. (Note: the operating current of 6.5 kA corresponds to a value of 42 on the I^2 scale.) The correlation of stress values with performance is quite clear:

- DD0010, which performed well below specifications, had low prestress and fell rapidly to low values with I^2.
- DD0012 and DD0014, which performed quite well, started with acceptable prestress values and maintained reasonable clamping pressure at the operating current.
- DD0015, whose performance was dominated by outer coil limitations, had sufficiently high prestress to maintain an acceptable level at the operating current.

The shimmed magnets, DD0012 and DD0014, show a slower decrease in pressure with I^2 than either DD0010 (older-style collar-yoke interface) or DD0015 (axially free). The rate of stress change with I^2 reflects the greater effective stiffness of the shimmed magnets in which the yoke and stainless steel skin of the cold mass are contributors. The fact that DD0015 performed reasonably well, given the limitations discussed above, indicates that the value of stress obtained at the operating current is among the most important variables.

C. Ramp-Splice Quenches

The voltage tap data permitted identification of the ramp splice region, a length of cable less than 30 cm long, as the source of a large number of quenches. As noted above, the collars in this region are weakened by a notch cut out to accommodate the ramp splice.

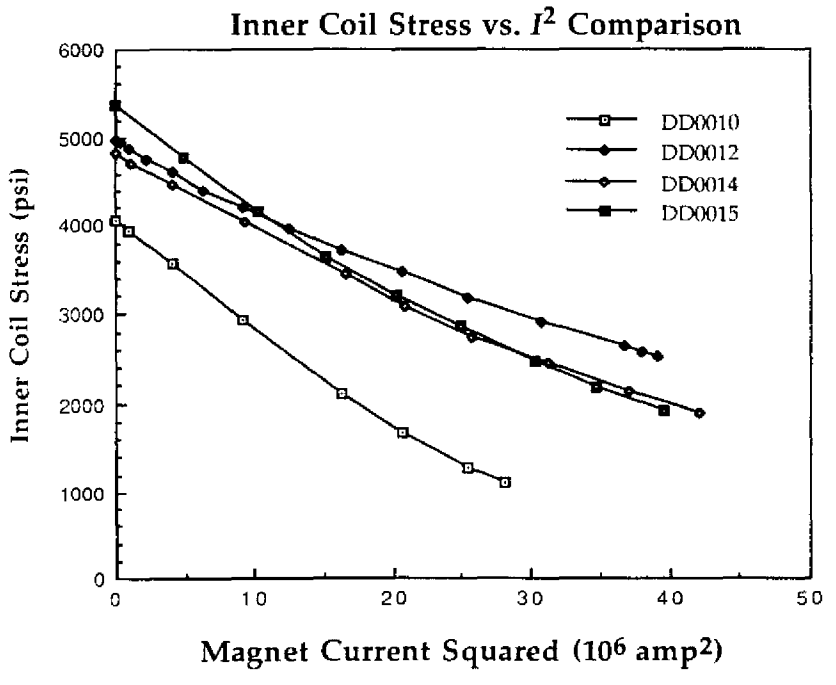

Figure 7. Average inner coil azimuthal stress versus I^2 for the four full length SSC model dipoles with stainless steel collars tested in 1988.

In the axially constrained magnets, shims provide additional support in this region, and quenching does not occur until relatively high currents; in unshimmed magnets, ramp splice quenches can occur at lower currents. The fact that quenches at the ends of older magnets were largely correlated with the feed end is strongly suggestive of a ramp splice origin.

The support of the ramp splice by the collars in this region has been revised. New magnets will incorporate design changes to the ramp splice assembly to prevent motion and better constrain the cable.

VIII. SUMMARY

The SSC magnet R&D program made significant advances in 1988. A clearly defined set of mainstream magnet design parameters has been determined. The magnetic field quality of the present design falls well within the limits set for accelerator operation. The problem of training in the long magnet is rapidly being solved. The two magnets representative of the mainstream design, DD0012 and DD0014, reached operating current with one or zero training quenches.

Advances in instrumentation have resulted in greatly improved diagnostic information. Quench origins have been determined to within 10 cm. The ramp splice region has been clearly identified as a source of quenches at higher currents and is being revised. The end regions of the coils have been strengthened and are associated with only a few quenches. Quenching in the body of the magnet—the region of uniform two-dimensional cross section—has largely been eliminated by controlling the collar clamping force.

Great improvements have been made in the system of strain gauge sensors that measure the mechanical state of the magnet. Repeatable, reliable coil stress and end force measurements are now available. The coil stress measurements correlate well with magnet performance.

The next series of long magnets—DD0016, DD0017, and DD0018—incorporate the features of the mainstream design which evolved in 1988:

- an axially constrained collared coil assembly,
- revised ramp splice,
- strengthened ends, and
- modifications to the coil cross section (wedge shape),

and are made using improved coil molding fixtures that make more uniform coils. We expect in the near future, with some further minor tuning, to have resolved most of the major issues affecting magnet quench performance.

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