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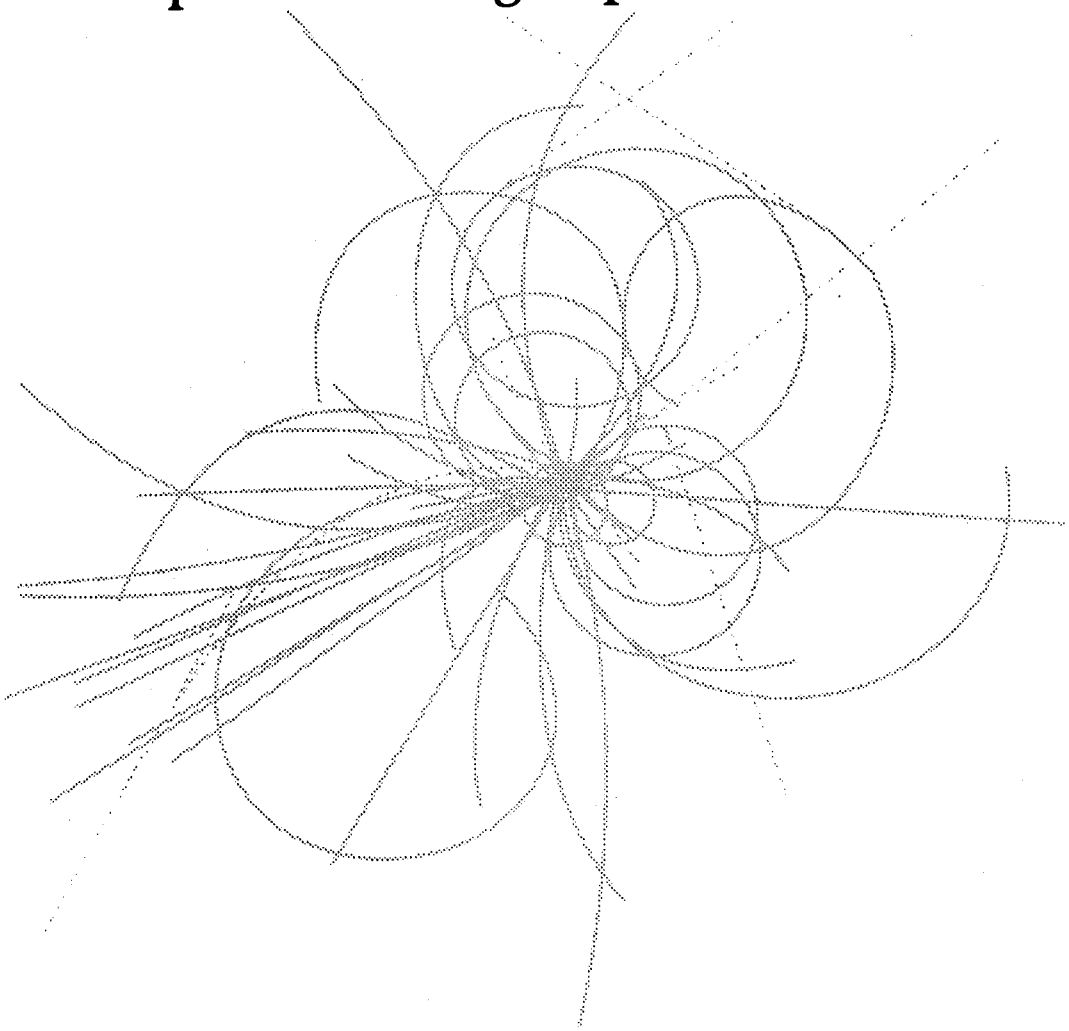

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Test Results of BNL Built 40-mm Aperture, 17-m-Long SSC Collider Dipole Magnets

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Abstract. **Eleven 17 m long, 40 mm aperture SSC R&D superconducting collider dipole magnets, built at BNL, have been extensively tested at BNL and Fermilab during 1990-91. Quench performance of these magnets and details of their mechanical behavior are presented.**

I. INTRODUCTION

Several years ago an extensive R&D program was launched to develop the prototype for industrially produced superconducting dipole magnets for the SSC. A number of magnets manufactured according to the specifications presented in the SSC Conceptual Design report [1], achieved the required field strength of 6.6 T but several magnets experienced poor training and erratic quench behavior. In January 1990, the SSC Machine Advisory Committee recommended enlarging the dipole aperture from 40 mm to 50 mm for field quality reasons. Since detailed design, tooling conversion and materials procurements for 50 mm aperture magnets would take several months, the 40 mm program was continued in order to provide a base for better understanding of magnet mechanical behavior and its influence on quench performance. During this transition period, eleven 40-mm aperture, 17-m-long SSC dipole magnets were built at Brookhaven National Laboratory [2]. More recently, Fermilab started construction of dipole magnets of similar design, two of which have just completed old test and are the subject of another report to this conference [3]. In this paper we present the quench performance results of the five DD series (DD0019, 0020, 0026, 0027, 0028) and six DC series (DC0201-206) Brookhaven built superconducting dipole magnets. Magnetic measurements [4] are the subjects of other reports to this conference.

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II. MAGNET DESIGN AND CONSTRUCTION

A. General features

All eleven magnets followed the 40 mm baseline design, with "line-to-line" fit, developed at BNL. The general features are summarized below. The magnetic field is generated by a two layer, cosθ type coil. Fig. 1 shows a cross section designated C358D, of the cold mass. The coil is held by stainless steel collars which are spot welded in pairs. The collar steel is Nitronic 40 for all magnets except DD0019 and 0026 in which Kawasaki high manganese stainless steel was used. The pairs are stacked together to form upper and lower packs which are locked together at the midplane by means of four phosphor-bronze tapered keys. Typically one collar pack per magnet is adapted to contain an assembly of 8 beam-type strain gauge transducers to measure azimuthal coil stress, usually located at a minimum of inner coil size [5]. The collared coil assembly is encased in a laminated iron yoke, composed of modules separated by a stainless steel spacer for directing helium flow (see below). Alignment of the yoke, which determines the alignment of the collared coil is provided by two keys at the yoke midplane. A full length, 4.77 mm thick stainless steel shell, is welded around the yoke laminations forming the cold mass. The coil ends are restrained by G-10 shoes and single piece, 38.1 mm thick, stainless steel end plates, which are anchored to the stainless steel shell. Each end is preloaded by a set of 4 screws; the screws at the return end are instrumented with "bullet" strain gauge assemblies to measure the force exerted by the coil against the end plate. In all magnets a "cross flow cooling" system, which directs helium flow

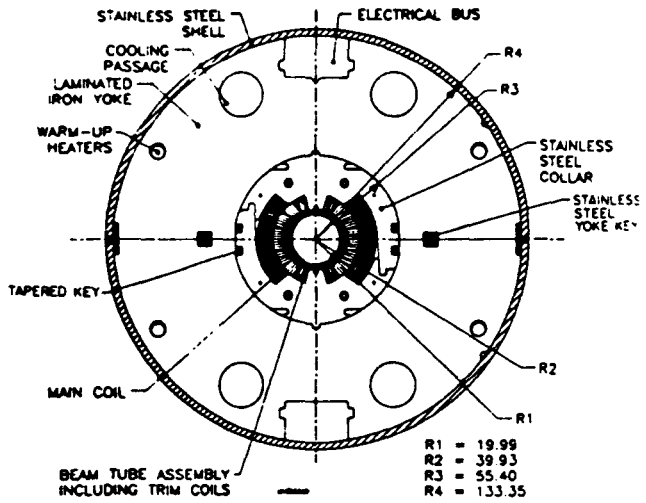

Fig. 1. C358D cold mass cross section. Note that the trim coils were implemented only in DD0020 magnet

perpendicular to the magnet axis, was implemented by using bypass hole flow restrictors and the above mentioned stainless steel lamination spacers [6]. Each magnet has ~40 voltage taps for quench diagnostics, all located on the inner layer of the coil, where quenches are most likely to occur.

B. Design Variants

Superconducting Cables

The superconducting cable in all tested magnets is made from Nb (46.5 wt.%) Ti conductor stabilized with low resistivity copper. The copper-to-superconductor ratio (Cu:SC) of cables for inner coils is nominal 1.5:1 for the magnet of the DD series and for DC0201, 0202, and 0203. For the magnets DC0204-206, the Cu:SC ratio was chosen to be nominal 1.3:1. For the outer coil the Cu:SC ratio was nominal 1.8:1. Filament diameter in both coils is 6 μm. The 1.6° keystone angle cable of the inner coils is wound from 23-strand wire, 0.808 mm in diameter and the 1.8° keystone angle cable of the outer coil is wound from 30-strand wire, 0.648 mm in diameter. The cable insulation consists of a double layer of 24.5 μm kapton, helically wrapped with 55% overlap, followed by one layer of 0.10 mm thick fiberglass tape impregnated with epoxy, wrapped with 50.8 μm gap between turns.

Collar Shape and Collar-Yoke Interference

Magnets of the DD series used round collars that are designed to match the inner boundary of the yoke at room temperature. It was found however in the later tests, that the vertical distortion of the coil assembly after collaring assembly was probably excessive and could create gaps between upper and lower yoke halves. Therefore, in the DC series, "anti-ovalized" collars were implemented. In anti-ovalized collars the location of keyways has been modified in such a way that centers of the top and bottom collars are shifted by 254 μm, resulting in a collar vertical diameter reduction to compensate for the collar distortion. Since reduction of collared coil size could potentially lead to loss of contact to yoke, in the cold state, brass shims of 76.2 μm thickness were added at the bottom and top of the collared coil assembly for all magnets of the DC series, after DC0201.

Ramp Splice Region

In order to provide electrical connections between four quarter coils, a ramp splice is used between inner and outer coil layers. The conductor is ramped up and spliced over a length of 76.2 mm using 96% Sn-4% Ag solder. Since the ramp splice is located in the high field region, it is supported by a specially designed G-10 box. It was found in magnets of the DD series that a number of quenches originated in this area and therefore, in the DC series, inner layer conductor length from the pole turn was epoxied to the adjacent turn.

III. EXPERIMENTAL PROCEDURE

The magnets are cold tested at a nominal temperature of 4.35 K. The mass flow of supercritical helium at 4 atm. is typically 40 g/s at the Fermilab Magnet Test Facility and ~100 g/s at BNL. Magnets cold tested at Fermilab were: DD0019, 0026, 0027, and 0028; the other magnets were tested at BNL. The generic test sequence calls for restricted cool down and generally includes two test cycles, separated by warm-up to room temperature. Restricted cool down limits the temperature difference between helium inlet and outlet of the magnet to 125 K. Initial test cycle starts with conditioning, during which the magnet is cooled to at 3.5 K and attempts are made to ramp the magnet to 6800 A. One reason behind conditioning is that by lowering temperature, magnet can be operated in regime farther away from the conductor critical surface. Following the conditioning procedure, the magnet is warmed up to 4.35 K and quench tested. The second test cycle is performed without conditioning. The test quench at 4.35 K is usually followed by testing at lower temperatures (i. e. 3.85 K and 3.5 K). Cold magnetic measurements are performed during both test cycles, with warm magnetic measurements between the subsequent cycles. Additional test cycles were performed for a number of magnets, e. g. DD0019, 0026, and 0028. In the case of magnets DD0019, and 0028, "unrestricted cool down" was tried both with and without subsequent conditioning. Testing of magnet DD0020 was interrupted after the fifth quench because of failure of the quench protection heaters (heater ground fault).

IV. MAGNET TEST RESULTS AND DISCUSSION

A. Quench performance

Figure 2a and 2b show two sets of the results of quench performance measurements. Only quenches during

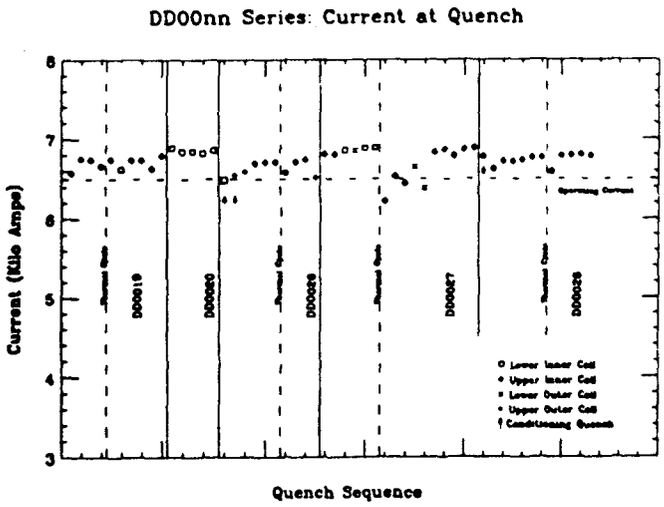

Fig. 2a Quench performance of the magnets of DD series.

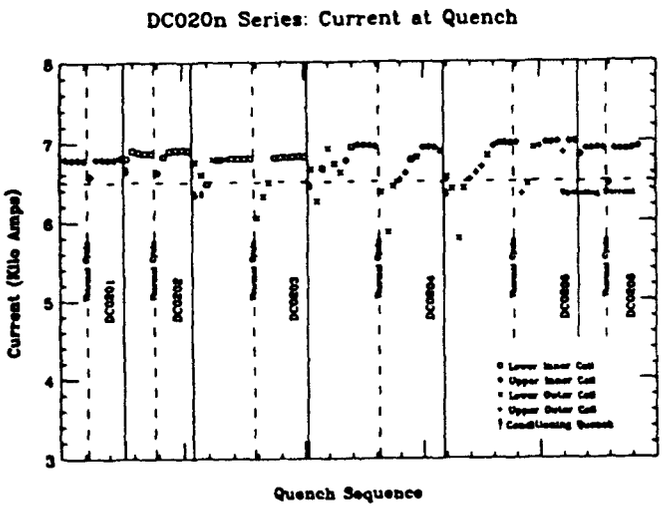

Fig. 2b Quench performance of the magnets of DC series.

during conditioning and spontaneous quenches occurring at nominal 4.35 K, with the beam tube sealed and evacuated, of the first and second TC are included The horizontal line corresponds to a nominal value of 6500 A. Although there are a number of quenches occurring below design operating current, the majority of magnets achieved designed current without training quenches. Table 2 summarizes quench performance of tested magnets: conditioning, first spontaneous quench, number of training quenches and plateau current at 4.35 K nominal.

TABLE 2
DD AND DC MODEL MAGNETS QUENCH PERFORMANCE DURING 1st TC

Magnet	Conditioning *	Nr of Training Quenches	First quench (A)	Plateau (A)
DD0019**	OK	1	6581	6750
DD0020	OK	0	6887	6853
DD0026**	Q	3	6493	6706
DD0027	OK	2	6817	6890
DD0028	Q	2	6624	6750
DC0201	OK	0	6790	6785
DC0202	Q	1	6804	6885
DC0203	Q	4	6754	6800
DC0204	Q	7	6656	6960
DC0205	Q	8	6554	6985
DC0206	OK	1	6841	6920

* Q means that magnet quenched during conditioning
** Kawasaki high-manganese steiness steel collars

Among the magnets of the DD series, the worst performing magnet was DD0027, which, at the begining of the 2nd TC, exhibited a total of five retraining quenches, three of these were below operating current. These quenches originated in the end sections of the magnet and were later attributed to the lack of the axial preloading, in the cold state. Among the DC magnets the majority of the training quenches originated in the outer coils. This behavior, under current investigation, is thought to be related to subtle changes of collar-yoke interference. The best performing magnets are those with highest axial preloading in cold state e. g. 26 kN in DC0201, 11 kN in DC0202 and 16 kN in the DC0206.

B. Mechanical behavior.

Azimuthal inner coil stress, averaged over the four layer quadrants, as a function of I^2, is shown in Figure 3a for magnets of the DD series and on Figure 3b. for the DC series. For the DD series, the average stress loss between 0 and 6500 A is about 20 MPa. and there is no indication of inner coil unloading in this range. On the other hand, most of the magnets of the DC series exhibit inner coil unloading at currents of the order of 6500 A. This unloading occurs probably as a result of a combination of lower initial prestress and greater loss of prestress during excitation. A lower level of initial prestress results from a lower level of prestress during assembly, while a greater rate of prestress loss can be related to reduced collar-yoke interference [7].

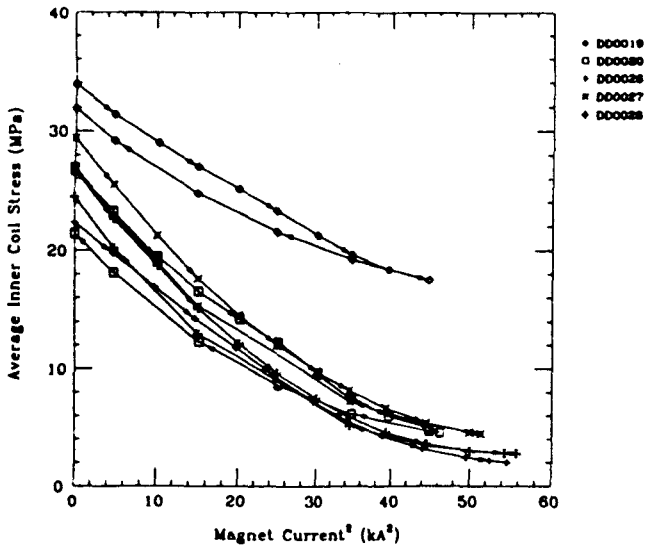

Fig. 3a Azimuthal coil stress as a function of excitation current in magnets of the DD series.

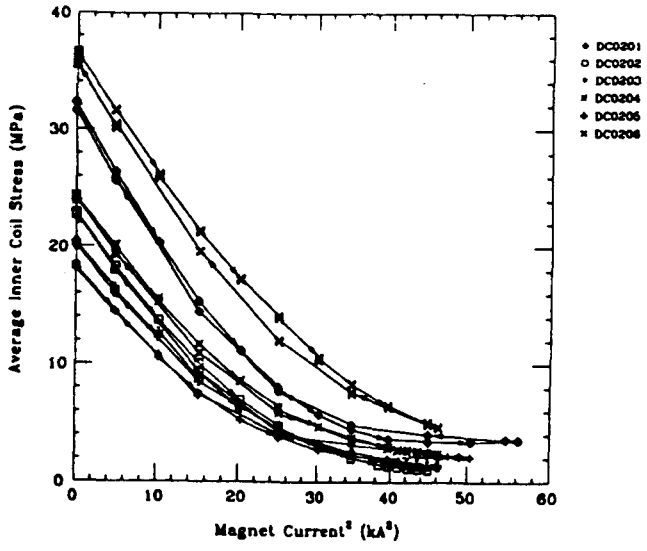

Fig. 3b Azimuthal coil stress as a function of excitation current in magnets of the DC series.

C. Training and Conditioning.

There is some evidence with limited statistics, that while conditioning does not eliminate the training; it helps to reduce the number of steps to reach plateau. Although these magnets reached plateau during the first test cycle, they also exhibit retraining at the beginning of the subsequent test cycle. This lack of "memory" would seem to indicate that most of the training is related to thermal effects induced during cool down.

V. SUMMARY AND CONCLUSIONS

Eleven full size, 40 mm aperture SSC R&D magnets have been built at BNL, following base line design and cold tested to determine their quench performance. Although the quench performance of the most recent magnets shows slightly more quenches than expected, we now have better understanding of the mechanical behavior of these magnets. The baseline design, embodied in the DD series of magnets, leads to reasonable quench performance. The quench performance of the DC series of magnets, however, seems to indicate a strong sensitivity to subtle changes in design parameters - key among them being the collar-yoke interface. Several issues, such as a more realistic cool down scenario, remain to be resolved and will be addressed in the upcoming 50 mm program.

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