Fermi National Accelerator Laboratory

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W. Koska, M. Bleadon, R. Bossert, J. Carson, S. Delchamps, S. Gourlay, R. Hanft, M. Kuchnir, M. Lamm, P. Mantsch, P. Mazur, D. Orris, J. Strait, and M. Wake

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

T. Bush, R. Coombes, A. Devred, J. DiMarco, C. Goodzeit, J. Kuzminski, T. Ogitsu, M. Puglisi, P. Radusewicz, R. Schermer, J. Tompkins, Z. Wolf, Y. Yu, and H. Zheng

SSC Laboratory
2550 Beckleymeade Ave., Dallas, Texas 75237

J. Cottingham, G. Ganetis, M. Garber, A. Ghosh, A. Greene, R. Gupta, S. Kahn, J. Herrera, E. Kelly, G. Morgan, J. Muratore, A. Prodell, M. Rehak, E. Rohrer, W. Sampson, R. Shutt, P. Thompson, P. Wanderer, and E. Willen

Brookhaven National Laboratory
Upton, New York 11973

J. Royet, R. Scanlan, and C. Taylor

Lawrence Berkeley Laboratory
1Cyclotron Road, Berkeley, CA 94720

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Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510 USA

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SSC laboratory, 2550 Beckleymeade Avenue, Dallas, TX 75237 USA

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R. Shutt, P. Thompson, P. Wanderer, E. Willen
Brookhaven National Laboratory, Upton, New York 11973 USA

J. Royet, R. Scanlan, C. Taylor,
Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720 USA

Abstract-Several 40 mm aperture, 17 m long dipoles have been built by Fermilab as developmental prototypes for the Superconducting Super Collider. These magnets differ from those manufactured at Brookhaven National Laboratory in that they have an external inner-outer coil splice design, a collet style end clamp assembly, a new, analytically designed minimum stress coil end design, and a new insulation system which does not employ shims or "shoes". In addition, the magnets were built using production-style tooling. The magnets were tested at the Fermilab Magnet Testing Facility. Quench testing and mechanical measurement results are presented and analyzed with emphasis on the new design and fabrication features of these magnets.

I. INTRODUCTION

In January of 1990 it was decided to change the aperture of the collider dipole magnet for the Superconducting Super Collider (SSC) from 40 mm to 50 mm. This was to improve the random variations in the field quality within the dynamic aperture of the magnet and to increase its thermal margin. A full discussion of the new baseline design may be found in [1]. At the time this decision was made a series of full length 40 mm aperture magnets was under construction at both Fermilab and Brookhaven National Laboratory (BNL) and it was decided to continue fabrication of these while the tooling for the 50 mm magnets was being assembled. Of the magnets being constructed at Fermilab two were successfully completed and tested. This paper describes the design and tooling features unique to the Fermilab-built magnets and presents quench results and mechanical measurements from the two complete magnets. Magnetic measurements are discussed elsewhere [2], as are results from tests of the BNL built magnets [3].

II. DESIGN FEATURES OF FERMILAB BUILT MAGNETS

The Fermilab-built 40 mm collider dipoles followed the baseline design developed at (BNL) [4] , with the following exceptions [5]:1) coil ends were wound using an ellipse on cylinder individually determined configuration [6] in which the end current blocks match those in the body, 2) inner to outer coil splices were made exterior to the magnet inside a collet style end clamp which supports the splice and provides prestress for the ends of the magnet, 3) an all Kapton ground insulation scheme was used without shims or shoes, and 4) stainless steel collars with a vertical radius 50 µm larger than the horizontal radius ("pro-ovalized") were used to insure contact between the collars and yoke under all conditions [7]. In addition to these design modifications, some unique features of the Fermilab construction of these magnets included curing the coils in a closed cavity mold of fixed size [8], key placement in the collared coils using a full length press, and welding of the stainless steel shell around the yoke blocks in a full length press using automatic welding equipment and an alignment key to reduce the amount of twist in the dipole field down the length of the magnet.

The two magnets built and tested were designated DC0304 and DC0306. These were identical in design with the exception of a slight modification to the end clamp. These magnets were instrumented with 55 voltage taps for quench localization, 28 strain gauge transducers (8 active and 6 compensating in two separate gauge packs) to measure inner and outer coil stress at the pole, and 4 strain gauge assemblies to measure end force [9].

III. CONSTRUCTION DATA

The cable used in the construction of the inner coils had a critical current of 8.6 kA (DC0304), 8.9 kA (DC0306 upper coil) and 8.8 kA (DC0306 lower coil) at 4.2°K and 7 T. The copper to superconductor ratio (Cu/S) was about 1.2. The cable used in the outer coils of both magnets had a critical current of 8.5 kA at 5.6 T and 4.2°K with a Cu/S of 1.8 [10]. After a coil is wound and cured its azimuthal size is measured at a pressure of 83 MPa in 76 mm segments along the entire length of the coil. The standard deviation of these measurements for a coil is typically less than 50 µm with a maximum range of about 150 µm. This data is used to determine if additional shim is required at the pole positions to achieve the desired prestress.

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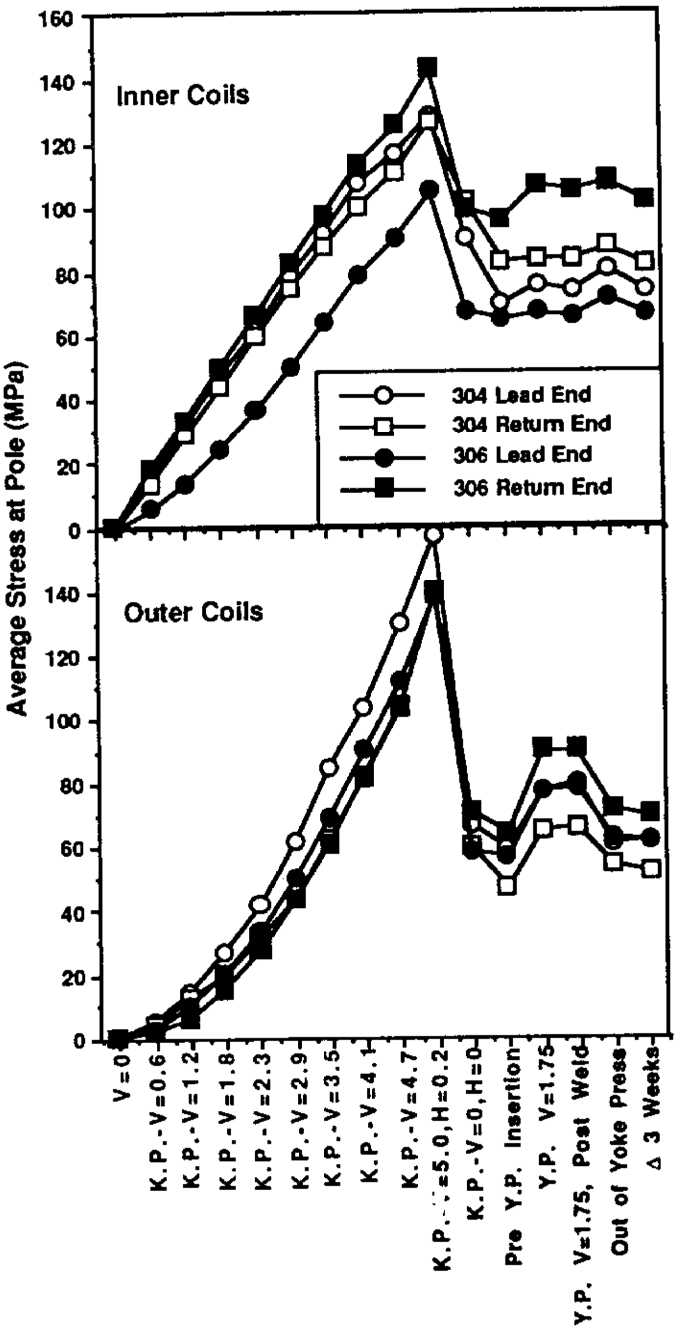

Figure 1. Prestress history of DC0304 and DC0306. The data shown is an average of the working strain gauges on the inner and outer coils. The error on these values is estimated at about 15 MPa absolute and 5 MPa relative. The values shown on the horizontal axis refer to the linear pressure in kN/mm of the keying press (K.P.) or yoke and shell welding press (Y.P.).

DC0304 and DC0306 were built with 0.43 mm and 0.25 mm of Kapton shim, respectively, on their inner poles and 0.25 mm on their outer poles. Two specially built collar packs which house the strain gauges are positioned at the points where the sum of the azimuthal size of the four inner coil quadrants is a maximum and a minimum. This positioning is specified in order to bracket the maximum and minimum prestress on the inner coils. Fig. 1 shows the prestress history of magnets DC0304 and DC0306 from their keying until they were shipped to the test facility. The maximum stress during the keying operation was about 120 ±20 MPa for the inner coils and 140 ±20 MPa for the outer coils. The final stress after keying was about 40 (80) MPa lower than the peak in the inner (outer) coil. The peak stress is higher than the desired maximum of 120 MPa. These high stresses were the result of the high vertical press pressures required to open the key slots enough to drive the keys into the collars. Even with a horizontal force of 175 N/mm driving the keys in DC0306 they still extended about 1.75 mm out of the slot and were finally driven into place with rubber mallets. The large forces required to key the 40 mm magnets have been traced to inadequate stiffness in the press platten which became distorted and damaged during the 40 mm program requiring over-compression of the coil in some places in order to close the collars enough to insert the keys elsewhere in the magnet. This has been rectified in the 50 mm program.

The inner and outer coils both gain between 5 and 10 MPa from welding the stainless steel shell. They also appear to lose about the same amount in the three weeks required to

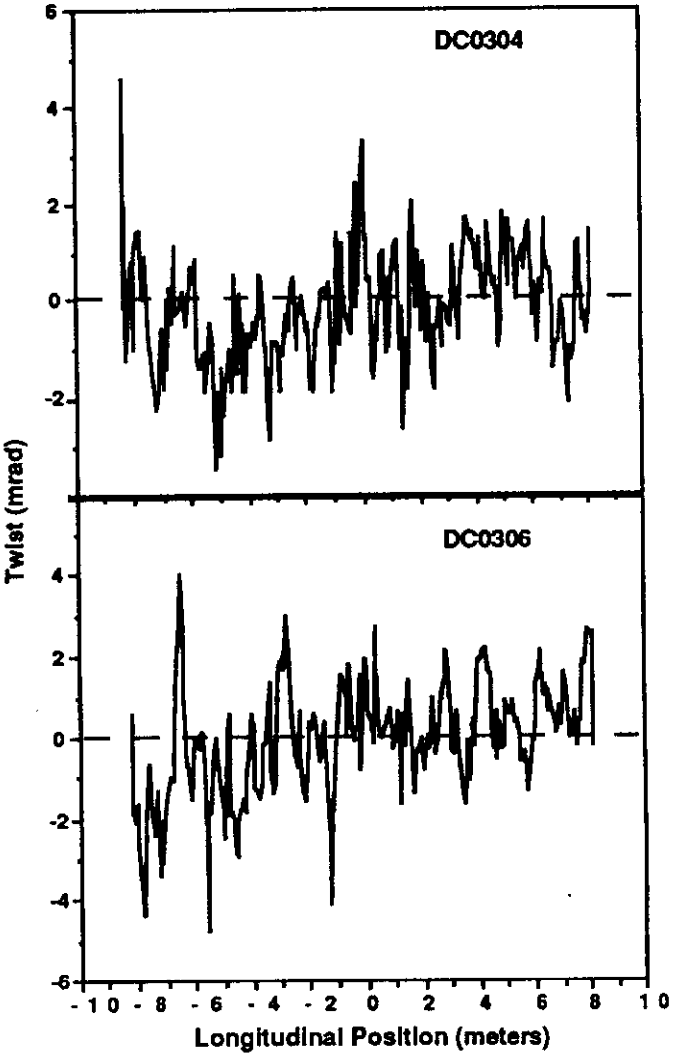

Figure 2. Vertical field angle measurements of the cryostated magnets DC0304 and DC0306 shifted to put the average rotation at 0 mrad.

cryostat the cold mass. The final prestress of the inner and outer coils lies within the desired range of 55-85 MPa and 40-70 MPa respectively to within the resolution of our instrumentation, however it appears that the inner coils of DC0306 may lie on the high side of this window.

The standard end clamp, as discussed in [1], was used on these magnets except that the G-10CR insulators used on DC0306 were built with their glass fibers oriented in the transverse direction to reduce prestress loss on cooldown [11]. After the end clamps were installed the collared coil was placed within the yoke and shell. A full length alignment key was used to hold the assembly in a nominally twist free state while the magnet shells were welded together. Fig. 2 shows the orientation of the dipole field angle as a function of longitudinal position along magnets DC0304 and DC0306. Since the average field angle is a function of the overall rotation of the cold mass within the cryostat it has been subtracted from the data to yield the point to point variations, or twist. The maximum integrated twist is 3.7 mrad-m and 5.1 mrad-m for DC0304 and DC0306, respectively. This easily satisfies the SSC requirement of less than 10 mrad-m integrated twist.

IV. QUENCH HISTORY

Magnets DC0304 and DC0306 were tested at the Fermilab Magnet Testing Facility (MTF) [12]. Fig 3 shows the quench history of these magnets with the nominal operating current of 6.5 kA (6.6 Tesla) indicated. To condition the magnets, both were initially cooled to 3.5°K and ramped up at 16 A/s until quench. DC0304 was cycled to progressively higher currents during this initial conditioning to take strain gauge data. It quenched at 6591 A in or near the inner-outer splice region. The second quench with the magnet now at 4.35 °K, the nominal operating temperature of the SSC, was in the same location. The third quench was in the lower inner pole turn. The final three quenches were in the upper inner pole turn and were conductor limited at 6970 amps. There were two training quenches during the second thermal cycle of DC0304 both of which were about 100 A below the conductor limit established during the first thermal cycle. The final three quenches of this thermal cycle again appear to be conductor limited. DC0306 experienced one training quench during its conditioning cycle at 3.5°K at 6280 A originating in the upper inner pole turn close to where the inner conductor ramps up to be spliced with the outer coil. It then went to its conductor limit of about 7040 A. These quenches were in the straight section of the pole turn very near the return end. Two training quenches were required to reach the conductor limit during the second thermal cycle, about 150 and 100 A below 7040 A, respectively. The conductor limited quenches of DC0306 were all in the lower inner coil and were at a slightly higher current than those of DC0304. Both these results are as expected from the measured critical currents of the cable used in these magnets.

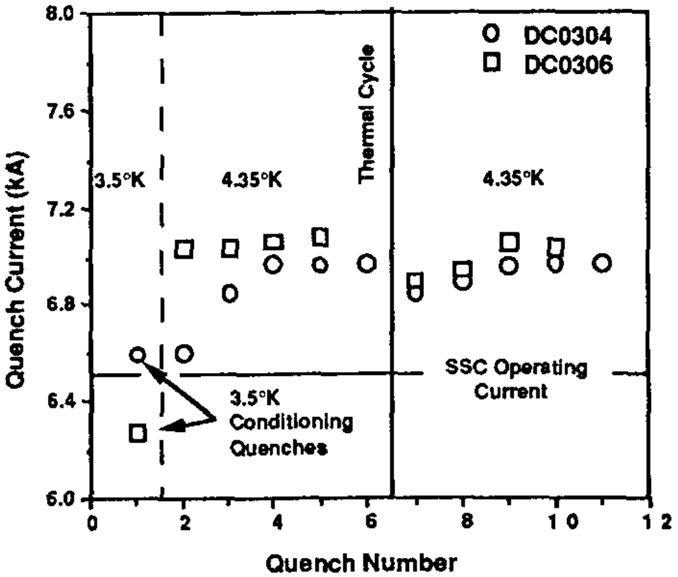

Figure 3. The quench history of magnets DC0304 and DS0306. The ramp rate for plateau quenches was 16 A/s.

V. MECHANICAL BEHAVIOR

Fig. 4 shows the stress at the poles, as measured by the the inner and outer gauges, as a function of current squared for the first data run after the quench plateau was achieved. The inner coils appear to have lost about 25 MPa of prestress on cool-down and the outers between 10 and 20 MPa. The drop in stress at the pole on excitation appears to be consistent between the sets of inner and outer gauges, respectively. The initial slope of the inner gauges is 0.95 ±0.05 MPa/kA^2. Most recent BNL built magnets have lower initial slopes [13], generally in the range 0.75±0.1 MPa/kA^2, except for DC0201 which had a slope of 1.05 MPa/kA^2. The pole stresses remain positive in both magnets to > 7 T.

Four strain gauge transducers, referred to as bullets, are used to apply and measure the axial force between the stiff end plate of the magnet and the coils. The end force is initially set to approximately 1200 N per transducer, for a total of about 4800 N, at room temperature. Fig. 5 shows the average end force per bullet for the two magnets as a function of current squared for the same runs as in Fig. 4. The apparent large difference in the end force between the two magnets can be traced to two causes. Higher than normal end force at room temperature resulted when extra welding was required between the cold mass and the bellows at MTF to completely seal all leaks. Secondly, there was a much larger than normal increase in preload during cool-down observed. However, protective mylar jackets were installed around the bullet gauges on DC0304 which probably modified the temperature profile relative to that obtained during calibrations and this could have faked the apparent large increase in force during cool-down. These jackets were not used on DC0306. The slope of the curve for DC0304 is approximately 33% steeper than that of DC0306. This probably reflects a true difference between the magnets.

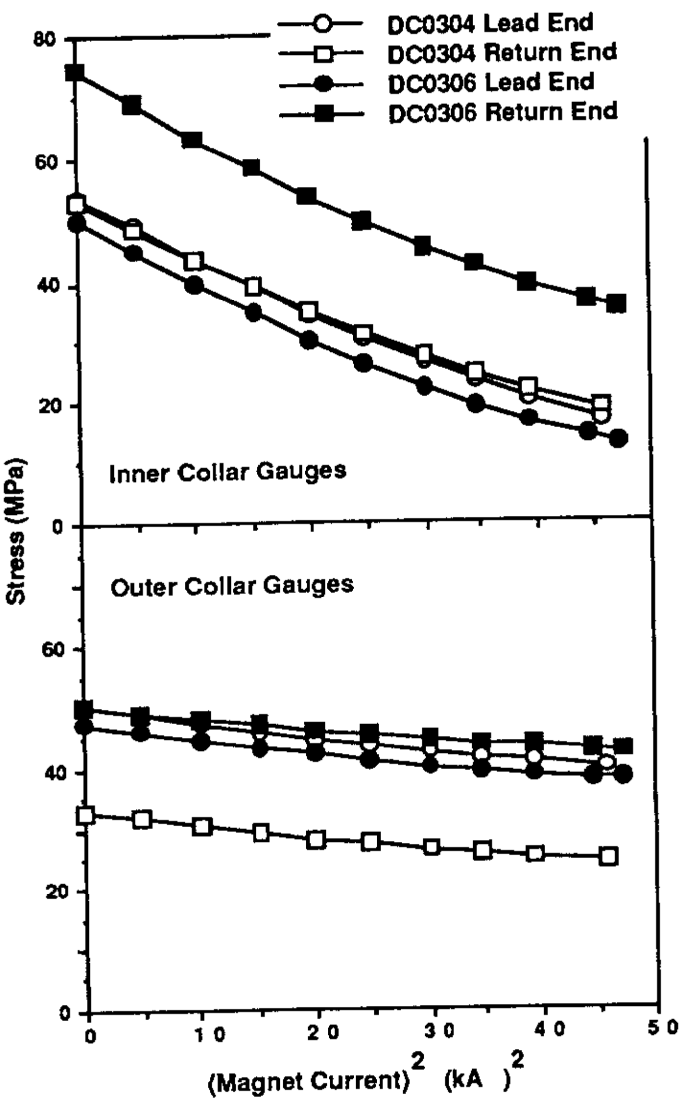

Figure 4. Inner and outer coil stress as a function of current squared after the plateau current had been achieved. The data points shown are averages of the working gauges in the magnet.

VI. SUMMARY

We have presented results of tests on two 40 mm aperture SSC collider dipole magnets which have been built and tested at Fermilab. We have also discussed some of the features unique to these magnets, both in their design and in the fabrication process, relative to those built at BNL. The performance of these magnets was very good from a quench and mechanical behavior standpoint. The magnets did not exhibit excessive training behavior and only one training quench was below the nominal operating current. The coil prestress remained positive to >7 T in both magnets and most of the quenches originated in the high field region of the pole turn.

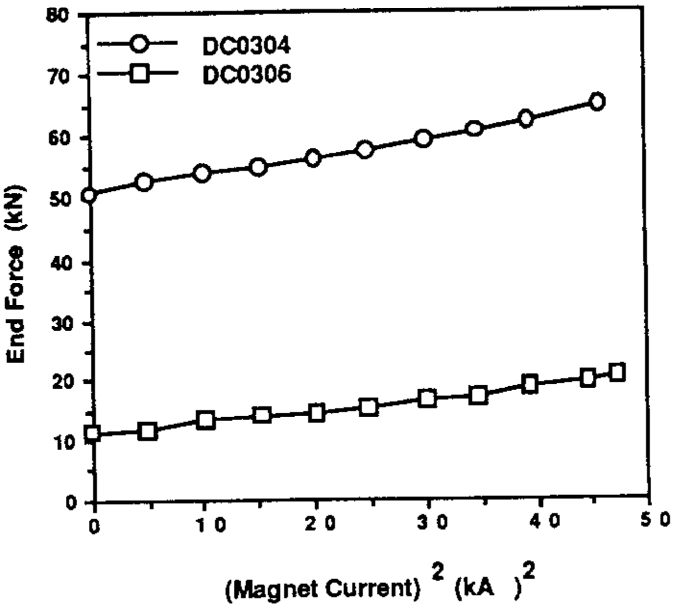

Figure 5. End force as a function of current squared.

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