# Construction and Results of the 50 mm Short R&D Dipole Magnets\*

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#### Abstract

The first at Brookhaven National Laboratory (BNL) of the large bore, 1.8 m SSC dipoles have been built and tested. The 2-D design of the coil, using the new, wider cables and the iron cross section are reviewed and the coil ends are described. Results from tests, including quench performance, magnetic field measurements and strain-guage data are presented.

#### I. INTRODUCTION

A primary goal of the new 50 mm SSC dipole design is that the quench margin be increased to 10% above the operating field of 6.65 T. To acheive this margin, the inner layer cable was increased from 23 strand to 30 strand and the outer layer cable was increased from 30 strand to 36 strand; in both cases, the strand size was held constant. The increased total flux necessitated an increase in the iron yoke thickness, and a new coil cross-section, collar and yoke were designed.[1] The wider cables are more difficult to wind into coils, and a series of winding experiments [2] were conducted to determine windability and endpost shape. This report describes the construction and tests of the first two, DSA207 and DSA208 of four of these 1.8 m long magnets which were built at BNL. Other than the length, these magnets contain all the features of the BNL version of the new SSC design.

## **II. MAGNET DESIGN AND CONSTRUCTION**

#### A. Cables

The superconductor in both cables is Nb,46.5 wt.% Ti. The inner cable has 0.808 mm strands with a Cu/SC ratio of 1.5, a width of 12.34 mm, mid-thickness 1.458 mm, keystone angle 1.2 degree and pitch length 86 mm. The outer cable has 0.648 mm strands with a Cu/SC ratio of 1.8, 11.68 mm width, 1.155 mm mid-thickness, 1.01 degree keystone angle and 94 mm pitch length. The performance specification minima are inner, 9990 A at 7.0 T and 4.22 K and outer, 10,152 A at 5.6 T and 4.22 K; these values of field include the self-field. Although alternative insulations are being studied [3], the present cables retain the insulation used in the 40 mm magnets: a single application of 25  $\mu$ m thick Kapton with 50% overlay plus a butt-lap layer of 100  $\mu$ m epoxy-impregnated fiberglass.

### B. Coil

A cross section of the collared coil in the yoke and helium containment vessel is shown in Figure 1. The coil cross section design [1] is termed W6733C. There are 45 turns per quadrant, arranged in blocks of 6,7,3 and 3 in the inner layer and 11 and 15 in the outer. The inner layer has an i.d. of 49.56 mm; in it, the two, pole-most wedges are symmetric and identical and the wedge nearest the midplane is symmetric by construction. There is 0.20 mm of Kapton and 0.05 mm of Teflon insulation between the two layers of coil, and the outer coil o.d. is 99.42 mm. All blocks except the midplane ones are very nearly radial.



Figure 1 Cold Mass Cross Section

In the inner layer coil ends, the first few turns are designed to be both constant perimeter and developable; successive turns assume a form determined by an insert between each turn. To lower the peak magnetic field in the pole-most turn, 6.35 mm thick, machined spacers of G-10 are put between the three turns of the pole-most block. To reduce the harmonic content of the magnetic field in the ends, there are 9.53 mm laminated spacers between the first three turns in the midplane blocks. The outer layer has 0.25 mm of G-10 between each turn to improve electrical insulation.

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Coils were cured using a single cure method in solid machined formblocks. Axial variations in coil size were small, about 18  $\mu$ m rms.

## C. Coil Assembly and Collaring

The internal splice and ramp between inner and outer coils increased in length from 152 mm in the 40 mm magnet to 243 mm, to allow for the larger bending radius of the wider cable. For the first time, the cables in the ramp are solder filled to increase mechanical and electrical stability. In the inner coil, a cable length of 152 mm next to the ramp, which is loosened to make the splice, is epoxied to the adjacent turn under pressure.

In both magnets, shim sizes at the poles were nominal in the inner coil, and 0.2 mm oversize in the outer. Both magnets were collared with no electrical shorts. In magnet 207, the maximum coil pressures during collaring were 100 and 83 MPa in the inner and outer layers, respectively, and the corresponding pressures after welding of the pressure shell were 74 and 56 MPa. In magnet 208, the maximum pressures during collaring were 81 MPa, inner and outer, and the pressures after welding of the shell were 74 and 72 MPa, resp. The collar radial thickness is 17 mm, compared to 15 in the 40 mm magnets. Some collar features are 1) 100  $\mu$ m vertical o.d. compensation with respect to round 2) spot welded, in alternating left, right pairs 3) 6° tapered keys 4) 620 MPa yield strength Nitronic 40 stainless steel 5) one strain gauge collar pack to measure azimuthal coil stress. Nitronic 40 has a magnetic permeability of 1.0025; this causes slight changes in the central field, increasing it 0.08%, and introducing a sextupole deviation of 0.6x10<sup>4</sup>.

Both magnets have 41 voltage taps for quench diagnostics, all but one installed on the inner coil near the ends, especially near the ramp splice. One tap is on the outer coil near the splice.

#### D. Yoke and Shell assembly

The yoke i.d. is 135.6 mm and o.d. is 330.5 mm. The bulk of the yoke laminations are made of 16 gauge extra-low carbon steel, but the laminations over the ends, including the last 36 mm at each end of the coil straight section, are made of stainless steel. The upper and lower yoke halves are aligned by means of slots containing square keys in each leg at the midplane. The position, size and material (stainless steel) of the keys is dictated by magnetic considerations [1]. The 304LN stainless steel shell (pressure vessel) is 4.95 mm thick. The end plates are stainless steel, 38.1 mm thick to contain the axial load of 0.188 MN (19 metric tons) at the maximum quench current observed of 8.8 kA. The plates are welded directly to the shell, replacing the "bonnet" design used in the 40 mm coil i.d. magnets. Four set screws for applying axial pressure to the coil ends are distributed uniformly circumferentially in the end plate at the lead end. At the return end, these set screws are replaced with "bullet gauges", hollowed-out sct screws containing a force-measuring strain gauge. These were loaded to 2.9 kN each.

In magnet 207, after the coil was collared, a vertical o.d.

measurement showed there would be insufficient (~25  $\mu$ m) interference with the yoke; this was due to out-of-tolerance dimensions in the collar keyways. To ensure adequate contact, 76  $\mu$ m thick shims, 19 mm wide, were added in four places, one per quadrant near the vertical collar tabs, using double-sided adhesive tape. The collars of magnet 208 were within tolerance and did not require these shims. The gap between the yoke halves was 0.31 mm prior to welding of the shell in magnet 207, and 0.23 mm in magnet 208; the gaps in both magnets were zero after welding.

Channeled laminations for venting and for cross-flow cooling [4] are in place, but are now made of low-carbon iron instead of stainless steel. Cross-flow, or radial cooling is presently not planned to be used in the SSC are magnets.

## **III. TEST RESULTS**

The nominal 20 Tev operating field of 6.65 T occurs during ramp up in DSA207 and 208 at currents of 6515 and 6507 A, respectively; a detailed comparison between calculation and measurement is given elsewhere.[5]

## A. Quench Data

The performance of both of these magnets is among the best ever tested at BNL. Figure 2 shows the results for magnet 207 of the customary testing program: intial quenches at 4.35 K to obtain the plateau, then at lower temperatures in two, 0.5 degree steps, obtaining a plateau at each temperature. The ramp rate for these quenches is 16 A/sec. After a cycle to room temperature, the program is repeated, but with some variation in ramp rate. Figure 2 shows that a plateau was obtained at each temperature with little or no training, and that there was no training after the thermal cycle. At the end of the first, 4.35 K run, variations in quench current, both below and above plateau, were obtained which were due to unintentionally varying temperature. For this magnet, a 10 mK change in temperature at 4.35 K causes a 13 A change in quench current and 11 mT change in central field. Magnet 208 essentially duplicated this performance.



The cable used in magnet 207 was 8.4% better than spec, resulting in an actual quench current at 4.35 K of 7500 A, about 0.8% above the calculated value. At this current, the central field is 7.52 T and the peak field in the windings is 7.89 T. The highest current obtained in magnet 207 was 8712 A at 3.35 K, corresponding to an estimated central field of 8.56 T and peak field of 8.99 T. Figure 3 shows the variation of quench current in magnet 207 with ramp rate. Below 100 A/sec, the quenches occurred in the inner coil in the turn nearest the pole, just beyond the G10 box enclosing the splice between the inner and outer layers. At higher ramp rates all quenches were inside the splice box.



In magnet 208 the plateau quench current at 4.35 K is 100 A higher than in 207; since the cable was from the same spool, the difference is believed due to a difference in the thermometers in the two dewars. These quenchs occurred in the pole turn near the splice box, the same location as in magnet 207. At 3.85 K and 3.35 K, the quenches were 125 mm farther away from the splice box. The highest quench current obtained was 8.82 kA at 3.35 K, corresponding to an estimated central field of 8.65 T and peak field of 9.09 T.

#### **B.** Stress Measurements

Figure 4 shows the coil stress measured at the polemost turn in the four quadrants of the inner layer of magnet 208; the data for magnet 207 were essentially identical. There is a decrease of about 40 MPa from the warm value on cooldown. This run was made at 3.85 K; the maximum current at which measurements were made was 8.2 kA; quench occurred at 8.219 kA. The flattened parts of the curves above  $48 \times 10^6 \text{ A}^2$  (6.9 kA) suggests that the actual stress is zero, i.e., the coil is completely unloaded.

A plot (not shown) of the forces measured by the bullet gauges at the return end of magnet 208 is essentially linear with the square of the current, running from an average of 0.9 kN at zero current (there is a decrease in preload from 2.9 kN when warm) to 7.8 kN at  $6.72 \times 10^6 \text{ A}^2$ .

#### C. Field Measurements

Table 1 gives the harmonics at 2 kA in the two mag-

nets; the b's are normal and the a's are skew harmonics, all in units of  $10^4$  of  $B_0$  at 10 mm radius. The SSC allowed systematic and random tolerances are given for comparison.

#### Table 1 Field Harmonics

pole 20				
1 1	"  -	208	Sys.	Ran.
b <sub>2</sub> 1.	67 1	1.96	0.80	1.15
b₄ 0.	36 (	).42	0.08	0.22
b <sub>6</sub> -0.	02 -0	).01	0.013	0.02
$ b_8  = 0.$	04 (	).04	0.02	0.007
b <sub>10</sub> 0.	01 (	).01	0.00	0.00
$b_{12} = 0.$	00 0	0.00	0.00	0.00
$b_1 = 0.$	04 (	).09	0.040	0.50
b <sub>3</sub> -0.	01 -(	).027	0.026	0.16
b <sub>5</sub> 0.	01 (	).00	0.016	0.02
b <sub>7</sub> 0.	00 0	0.00	0.010	0.01
<b>a</b> <sub>1</sub> -1.	34 -1	1.22	0.040	1.25
a <sub>2</sub> -0.	13 -(	).17	0.032	0.35
a <sub>3</sub> -0.	.02 -0	).08	0.026	0.32
a₄ 0.	.01 -(	).01	0.020	0.05
$a_5 0.$	.02 (	).00	0.016	0.05

Shims between the yoke and collar were present only in magnet 207; the resulting deformation of the collar and coil could account for the difference in b<sub>2</sub> between 207 and 208. Allowed harmonics higher than b<sub>4</sub> are in good agreement with calculation. Size mismatch between top and bottom coils in both magnets due to experimentation with coil curing pressure is responsible for the rather large skew har-



## **IV. REFERENCES**

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