COLD MASS MECHANICAL DESIGN, QUENCH AND MECHANICAL TEST RESULTS FOR FULL LENGTH 50 mm APERTURE SSC MODEL DIPOLES BUILT AT BNL

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Abstract

A series of seven 50 mm aperture, 15-meter long dipole magnets was built and assembled at Brookhaven National Laboratory (BNL). Their design embodies features for evaluation for the final selection of the design for the SSC Collider dipole magnets. This paper discusses mechanical design of the cold mass and presents test results such as quench histories and mechanical parameters during construction and testing.

1 Foreword

As part of the SSC magnet development program, several collider dipole model magnets have been fabricated and assembled at both Fermilab and Brookhaven National Laboratory. This program has been carried out over the past two years under the auspices of the SSC Laboratory's Magnet Systems Division. These magnets are intended to be employed in the Accelerator Systems String Test (ASST) which is a major project milestone to be completed at the SSC site by September of 1992. All magnets built at Fermilab and Brookhaven are identical in interface requirements, magnetic design and operating parameters. However, there are some differences in the mechanical construction of the cold masses of these magnets; in particular the configurations of the yokes and collars that support the coils and the construction of the ends of the cold masses. This paper describes the mechanical construction of the cold mass for the ASST magnets built at Brookhaven and presents the significant test results relating to mechanical and quench performance.

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2 Mechanical Design

The construction features of these magnets have been previously described [1]. These include yokes that part horizontally on the mid-plane of the coils with nominal dimensions of the inside diameter of the yoke equal to the outside diameter of the collars in order to provide a line to line or zero clearance fit. The ends of the coils are confined also by collars which fit similarly in yoke modules which extend to the end of the coils. The ends of the coils are preloaded and supported by rigid end plates. Many of these design features have been extrapolated from the earlier design of the 40 mm aperture dipoles [2]. These features are shown in Figures 1 and 2.

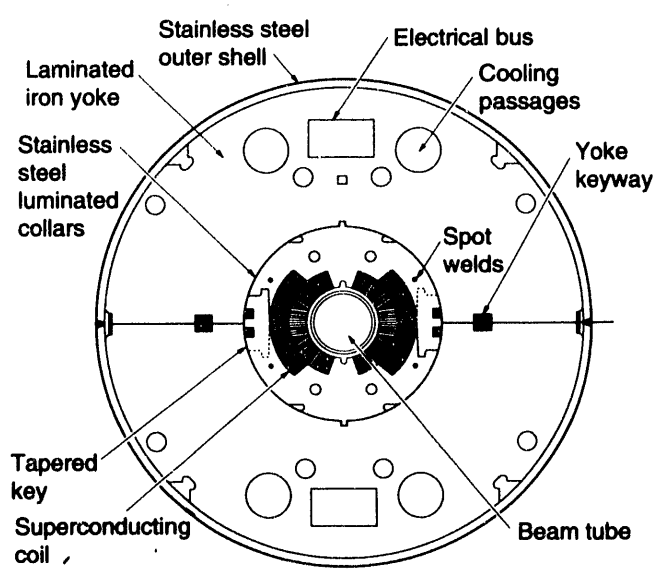

Figure 1: Cross-section of SSC model dipole

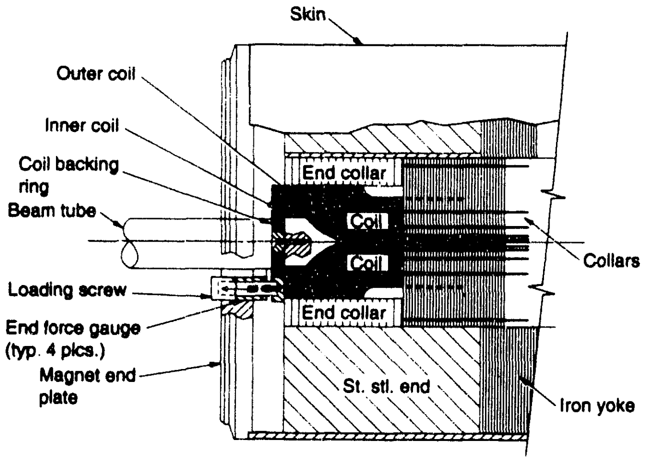

Figure 2: Section of SSC model dipole at return end

Another characteristic of the mechanical design of these magnets is an internal splice at the lead end of the magnet. The first turn of the inner coil is ramped up to the first turn of the outer coil and soldered to it. This joint is encapsulated in a G-10 piece which is clamped securely in the end collars to supply the necessary rigid support for this splice.

All of the other construction details for the seven cold masses for the magnets in this series were identical except for the cable manufacture and method of cable insulation. Some of the magnet parameters and cable insulation information is listed in Table 1. The all-Kapton cable insulation system used for DCA212 and DCA213 required a rather high temperature in the curing press to make the bond, 225°C, compared to the 135°C required for the fiber glass-epoxy cable wrap.

Table 1: ASST Dipole Cold Mass Parameters.

Operating field at 4.35K	6.65 T	
Current at operating field	6550 A	
Magnetic length	15.815 m	
Superconductor:	Inner coil	Outer coil
Strand diameter (mm)	.808	.648
Number of strands	30	36
Cu:SC	1.3/1.5	1.8
Number of turns	19	26
Cable width, bare (mm)	12.19	11.68
Cable mid-thick, bare(mm)	1.58	1.166
Keystone angle (deg.)	1.20	1.05
Cable I_c, @ 4.22K and 7 T	9660	9780 @ 5.6 T
Operating margin to load line	11%	12%
Cable Insulation wrap[1]	48% overlap, 25 micron Kapton H-film covered with a butt wrap of 100 micron Hexcel F185 epoxy impregnated fiberglass tape.	
Cable Insulation wrap[2]	48% overlap, 30 micron (120CI-1) amorphous Kapton with XMPI adhesive on outer surface, covered with a 48% overlap of 35.5 micron (140RCI) reinforced Kapton with XMPI adhesive on both sides.	
Dimensions:		
Inner coil aperture (mm)	50	
Collar outer diameter (mm)	135.62	
Yoke outer diameter (mm)	327.3	
Shell outer diameter (mm)	340	

1. For magnets DCA207, DCA208, DCA209, DCA210 and DCA211.
2. For magnets DCA212 and DCA213.

3 Mechanical Measurements, Assembly

3.1 *Overview*

The significant mechanical measurements that are made during the assembly of the magnets are:

- Azimuthal size of the coils under stress prior to collaring to verify that proper prestress will be obtained after collaring.
- Azimuthal coil stress (inner and outer) measured at the pole during collaring and subsequent magnet assembly operations.
- Vertical and horizontal deflections of the collared coil assembly to determine the characteristics of the fit of the collared coil into the yoke.
- The coil end force transducers which support the ends of the coil are set to a predetermined load after completion of the cold mass assembly.

The coil stresses are measured with beam type strain gauge transducers which have now become a standard part of the instrumentation requirements for the model magnets in the SSC program [3]. These gauges are placed in a special collar pack which is usually located at the minimum coil size location.

The coil stresses are recorded from the collaring operation and subsequently through all phases of the assembly operation for the model magnets to verify the following significant measurements:

- Peak stress in the collaring press. Too high a pressure on the coils during collaring can degrade the conductor insulation. The present guideline is not to exceed 16,000 psi (112 MPa).
- Coil stress after collaring to verify adequate prestress to prevent polar turns of the inner coil from unloading at operating current.
- Subsequent stress history of the coils to show the effect of welding the shell on the coil stress and other effects such as relaxation of the coil stress with time.

3.2 *Coil Stress History*

An example of the stress histories of the inner and outer coils for one of these magnets (DCA212) is shown graphically in Figure 3. All of the other magnets behaved in a similar manner. The average of the coil stress at

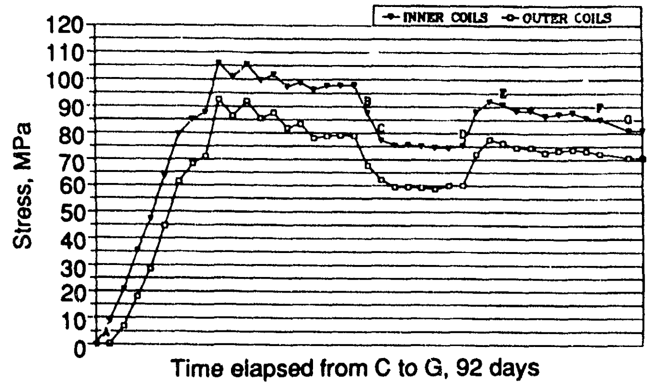

Figure 3: DCA212 overall coil stress history (average coil stresses)

the polar positions for the four quadrants of each coil is shown from the initial collaring through the completion of the cryogenic testing. The initial parts of the curves from A to B show the collaring operation. The collars have been designed to be assembled with keys having a 3° taper. The collars are first loaded by the vertical pressure of the press until they close up enough to align the key ways from the top and bottom collar segments and thus permit the tapered keys to be inserted partially into the key ways in the collars. Horizontal force is then applied to the keys by means of hydraulic cylinders and the keys are seated firmly in the key ways. This effectively pulls the collars around the coils, putting them in tension, and thus limiting the amount of coil stress loss, ("spring back loss"), when the hydraulic pressure is removed from the press. In the example shown this amounts to about 10 MPa for the inner coils which compares with about 35 MPa that would be lost if the tapered key feature were not used. There is a rather rapid loss in coil stress (relaxation) that occurs immediately following the collaring operation. This is attributed to the tendency for the cable insulation to flow out of the high stress regions at the points of the contacting surfaces between the turns. In this case, about 10 MPa has been lost from the inner coils after the first 24 hours. The rate of stress loss then decreases to a low level and from C to D, which encompasses 12 days, there is only a small effect. The coil stress rise from D to E represents the effect of welding the shell (and thus closing the midplane gap at the yoke parting plane) as a result of the tensile force built up in the shell from the weld shrinkage effect. This is seen to be typically about 15 MPa for the inner coils. In the 80 day period from E to G which included cryogenic testing and subsequent warm up of this magnet there is a gradual continuation of the relaxation of the coil stresses from the increased stress level produced from the shell welding. However, at the end of this measurement cycle, the average coil stress is still above the level that existed prior to the shell welding.

3.3 Collar-Yoke Interface Considerations

Early in the development of the dipole magnets for the SSC, it was recognized that the fit of the collared coil into the yoke was an important factor in quench performance. This was described by Peoples [4] who summarized the results of the effect of increasing the rigidity of the clamping of the collared coil in the yoke. The earliest SSC model dipoles with 40 mm aperture inner coils had relatively poor quench performance compared with later magnets in which the 250 micron gap between the collar and the yoke was eliminated.

Thus, the concept of providing rigid clamping of the collared coil in the yoke has carried through to the present design of the 50 mm aperture model magnets for the SSC. The collars have a vertical deflection or "ovality" when assembled with prestressed coils. The amount of "ovality" is optimized by a keyway location adjustment, $e = 0.05$ mm, as shown in Figure 4. The collars are forced into a circular shape by the yoke from the tensile forces induced in the helium shell during the welding process. The effect of this is to increase the coil stress as was seen in Figure 3. Thus, after assembly there is a tight fit between the collar and the yoke.

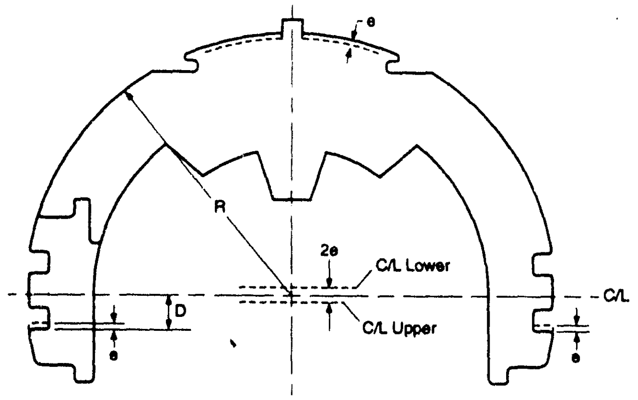

Figure 4: Method of compensating collar keyway location for vertical ovality

Therefore, as part of the normal assembly procedure for the ASST magnets, particular attention is paid to verifying the fit of the collared coil into the yoke. This is done by measuring the vertical and horizontal dimensions of the collared coil after the collaring operations at 150 mm intervals along the straight section and 25 mm intervals at the ends. Figure 5 shows a typical plot of these dimensions along the length of the magnet which indicates that about 200 microns vertical interference is obtained when assembled into the yoke. The vertical deflection is rather constant along the straight length of the magnet but the ends have different deflection characteristics. Since the ends contain a transition from the straight section and various components of the saddle windings, the mechanical complexity produces a different deflected shape of the collars. For this magnet, the fit of the collared coil in the yoke in the horizontal direction is zero to 10 microns radial interference. In this group of magnets the average vertical interference of the collared coils with the yoke was 179 microns on the diameter at the location of the collar pack that contains the strain gauge transducers for measuring coil stress. The average horizontal gap between the collared coil and yoke in the mid-plane region was 10 microns, radially.

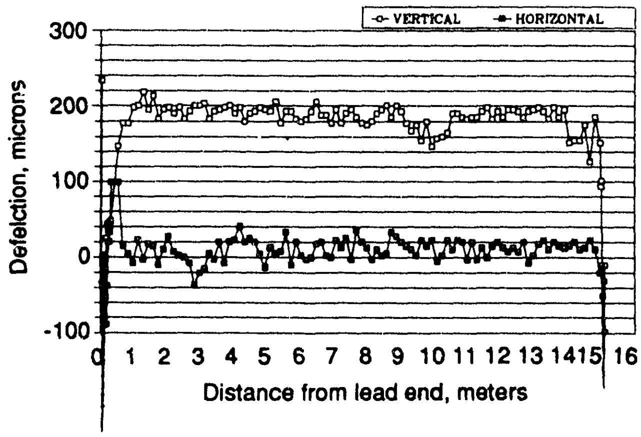

Figure 5: DCA211 collar deflections (based on 135.89 mm yoke inner diameter)

4 Magnet Quench Performance

The seven magnets described herein have been installed and tested cryogenically in supercritical helium at the cryogenic test facility at BNL. The test procedure involves quench performance testing, multipole measurements, quench propagation studies, persistent current and ramp rate dependency effects. The quench performance relates particularly to the mechanical design considerations and will be covered here. Other measurements and test results from these magnets are treated by Wanderer, et al. [5]. The quench performance test procedure uses a ramp rate of 1 A/sec at the high current levels to determine the quench current in order to minimize ramp rate effects until such time that the mechanism and effect of the ramp rate phenomenon has been understood and corrected.

In order to examine the quench performance of these magnets, it is useful to define what is meant by "training" which usually has a rather loose definition. We will define training based on these criteria:

- The establishment of a plateau or a series of typically four quenches at the short sample limit (sometimes 1% or 2% higher) with current fluctuations less than ~ 30 A (caused by temperature variation).
- Training quenches are assumed to be mechanically induced, thus quenches in the multi-turn blocks of the coils, those near the mid-plane, are verified to be eddy current induced and not training quenches by measuring the quench current vs. ramp rate.

Applying above criteria to the initial quenches at 4.35K for the seven magnets tested, we can see from Figure 6 that all of them except one, DCA211, had initial quenches well above the 20 TEV operating point. The vertical lines within each magnet's bin indicate thermal cycles to room temperature. Only one magnet, DCA208, exhibited a minor re-training quench after the thermal cycle. Table 2 lists the number of training quenches for all of the magnets tested to date in this series at the various temperature levels. The low number of training quenches at the highest current values achieved at 3.5K appear to indicate that a sound mechanical design has been achieved for the cold mass of these magnets.

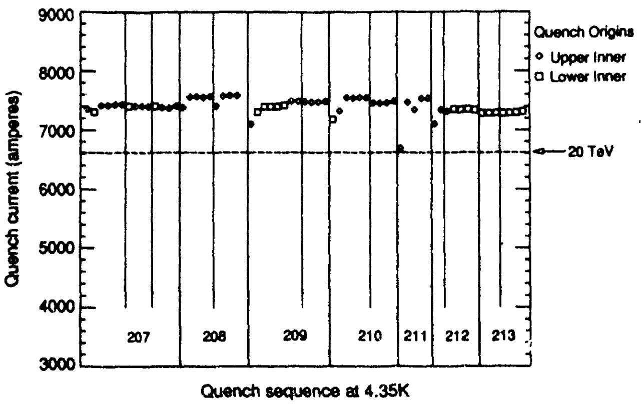

Figure 6: DCA200 series full length 50 mm aperture SSC dipoles

Table 2: Summary of Quench Performance.

Magnet	Initial (4.35K)			Thermal Cycle (4.35K)		
	T	P	A	T	P	A
DCA207	2	4	7430	0	4	7400
DCA208	1	4	7560	1	3	7582
DCA209	2	4	7490	0	4	7480
DCA210	2	4	7550	0	4	7460
DCA211	1	4	7530			
DCA212	1	1	7340	0	6	7343
DCA213	0	3	7287	0	4	7296

Magnet	Initial (3.85K)			Thermal Cycle (3.5K)		
	T	P	A	T	P	A
DCA207	0	4	8070	0	4	8420
DCA208						
DCA209	2	2	8120	1	4	8400
DCA210	1	4	8130	0	4	8550
DCA211						
DCA212	1	4	7836	0	3	8163
DCA213						

T: Training quenches
P: Plateau quenches
A: Plat. Current

5 Mechanical Measurements During Testing

The following significant mechanical measurements are usually taken during the testing program on these magnets:

- Change in inner and outer coil stress from ambient to operating temperature to verify thermal stress loss. The change in end force due to cooldown is also checked.
- Change in polar stress of inner and outer coils during magnet excitation. This gives information on the current level required to unload the polar stress on the inner coils as well as the rate of change of inner and outer coil polar stress with excitation.
- Change in end force during magnet excitation and cumulative change in end force over the span of the test.

5.1 *Coil Stresses*

The stress loss in the coils after cool down is of interest to determine if there is sufficient polar stress, particularly in the inner coils, to prevent the unloading or loss of compressive stress at the poles during excitation of the magnet to operating current. The amount of the stress loss appears to be related to the level of the initial stress. Thus, DCA213 with 86 MPa initial coil stress lost 39 MPa during cool down while DCA208 with 65 MPa initial stress lost 27 MPa. Other magnets followed this trend.

When the magnets are powered, the Lorentz forces acting on the turns of the inner coil tend to pull them away from the poles and compress them at the midplane. This effect on the polar stress can be seen, for the case of DCA209, in Figure 7. This is one of the magnets that was tested at 3.5K so that the data can be seen up to 8400 A. The stress in each of the four quadrants of the coil is plotted against magnet current and it is seen that the decrease appears to be somewhat quadratic until about 7000 A where the stress does not change with magnet excitation. At the operating current of 6500 A there is still compressive stress at the poles; however, above 7500 A the slope to these curves is zero which is interpreted as unloading of the polar turns. (Note that this unloading effect does not cause the magnet to quench.)

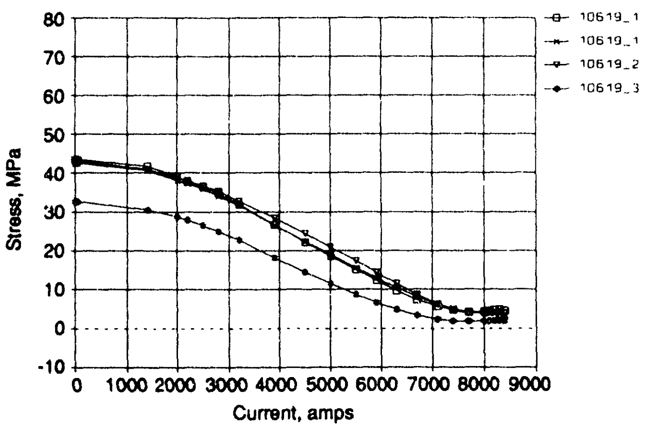

Figure 7: DCA209, testing at BNL—Inner coils @3.5 K

The effect of the Lorentz forces is much less on the outer coils than the inner coils. We have never seen outer coils unload under the effects of the Lorentz forces. However, if we examine the variation of coil stress with current squared, as shown in Figure 8, there appears to be a knee or change in the slope of the curves at about 4500 A (2e7 A^2). The plausible explanation for this is that there exists a small gap between the collars and the yoke in the midplane region after cool down which is due to the difference in thermal contraction of the collar and yoke materials. Thus, as the Lorentz forces build up with magnet excitation, and their resultant is primarily horizontal, the collars deflect outward to close this small gap. Once the collars bear against the yoke, the rate of change of polar stress with excitation decreases. This effect almost always appears at about 4500 A in all the long and short magnets of this cold mass design.

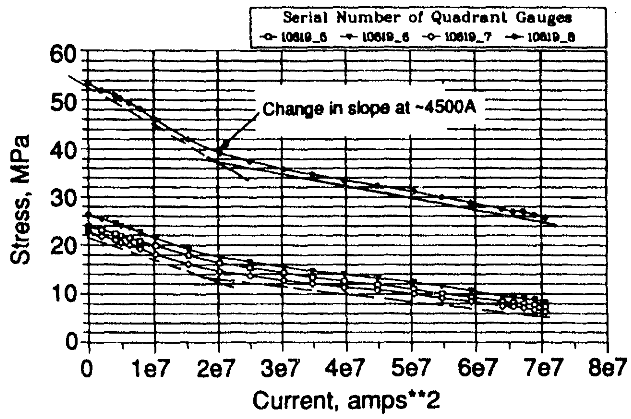

Figure 8: DCA209, testing at BNL—Outer coils

5.2 *End Forces*

The behavior of the end forces during the course of assembly and testing of these magnets was quite similar for both the lead and return ends. The end forces had the following characteristics:

- The end force always increased significantly from the initial setting to the value achieved after mounting the magnets in the test stand. Most of this increase occurred as a result of the welding of the cold mass extension tube to the end plate of the magnet in which the end force transducers were mounted. This effect, which was believed to be caused by warpage of the end plate was verified in magnets DCA207 and DCA208 and thus the level of the initial setting of the end forces was reduced from a nominal value of about 36 KN to about 10 KN in subsequent magnets. Nevertheless, the forces were quite high after the end plate welding, typically increasing to 45 KN.

- The end force change during cool down was not consistent, either at the lead or return end. Usually there was an increase but also there were magnets which showed a decrease.

- The end forces at both ends always increased from the initial warm value in the test stand to the warm value at the end of testing. This was associated with a retention of a portion of the axial Lorentz force developed during the excitation of the magnets during each cycle. This effect is sometimes referred to as "ratcheting." The highest level of retained force was in those magnets that were excited to the highest levels ($\sim$ 8500 A), DCA207, DCA209 and DCA210. The mechanism of this force retention is not fully understood at this time but appears to be associated with a frictional slippage at one of the interfaces that can move; i.e., between the collars and yoke or between the yoke end modules and the shell.

The final end force measurement of interest is the variation with magnet excitation. These forces, in all cases, increased linearly with current squared. For the seven magnets tested, the average increase in end force from zero to 7200 A was 30.2 ± 4.1 KN at both the lead and return ends. This is about 24% of the 127 KN calculated value of the increase in end force to this level of magnet excitation.

6 Conclusions

The data from the mechanical assembly and the test results of these magnets have indicated that a sound mechanical design has been achieved for the cold masses of the BNL (and Westinghouse assembled) ASST magnets. The quench performance has been shown to meet the operating requirements for the accelerator in that there were no more than two (mechanically induced) training quenches at any temperature level and that initial quenches, except for one, were well above the operating point of the machine. We have verified that the collar-yoke interface has been designed such that there is a contact between the collar and yoke in the horizontal region at magnet currents in excess of about 4500 A in all cases. The magnets retain sufficient polar coil stress to resist unloading at operating current. In those magnets that have been tested up to 8500 A, it is seen that the magnets pass through the region of zero polar stress without quenching which indicates that the mechanical design provides rigid clamping at these high excitation levels. There is some concern, however, about the increase in retained end force when these magnets have been cycled to operating current and above. The mechanical design features such as the horizontally split yoke and collars at the ends of the coils with an internal ramp splice have been retained in the prototype magnet being undertaken by General Dynamics for the CDM development and thus, there should be more data forthcoming on the mechanical measurements and performance of this basic cold mass design.

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