To be presented at the
Third Annual 1991 International Industrial Symposium
on the Super Collider (IISCC)
Atlanta Hilton and Towers
Atlanta, Georgia
March 13-15, 1991

BNL--45719

DE91 014032

EFFECT OF PRESTRESS ON PERFORMANCE OF A 1.8 m SSC R&D

DIPOLE*

P. Wanderer, M. Anerella, G. Cottingham, G. Ganetis, M. Garber, A. Ghosh, C. Goodzeit, A. Greene, R. Gupta, J. Herrera, S. Kahn, E. Kelly, A. Meade, G. Morgan, J. Muratore, A. Prodel, M. Rehak, E. Rohrer, W. Sampson, R. Shutt, P. Thompson, E. Willen.
Brookhaven National Laboratory, Upton, New York 11973
*Superconducting Super Collider Laboratory, 2550 Beckleymeade Ave., Dallas, Texas 75237

ABSTRACT

A series of 1.8m SSC dipoles is being built and tested as part of the R&D program. One of the 40 mm - aperture magnets was tested with a standard assembly and then reassembled and retested in a special configuration which had significantly less azimuthal prestress than the initial assembly. We report quench, coil stress, end force, and harmonics data for each of the assemblies. Quench performance was not degraded for the low-prestress assembly.

INTRODUCTION

The study of short model magnets has been a cost-effective method of studying design issues for the SSC Collider Dipoles. This paper reports a study of the effects of changing the azimuthal prestress in a 1.8 m long, 40 mm aperture model. Except for length, the models are built with the same methods used for the full-size 17 m design. The magnet was heavily instrumented with voltage taps, strain gauges, and spot heaters. Tests were carried out in a vertical dewar filled with liquid helium.

A significant mechanical parameter of the coils is the retention of prestress after the collaring operation. There is a subsequent loss in stress due to creep (or relaxation), the effects of the cool down to operating temperature and the effect of the magnet excitation Lorentz forces on the stress distribution in the coils. Prior to the development of reliable methods of measuring coil stress under operating conditions, it was thought that magnet quenches were induced when the Lorentz forces exceeded the compressive force holding the prestressed coil against the pole of the collar. Thus, great effort was undertaken to ensure that the coils do not become unloaded at the pole faces under the highest possible operating current in the magnet. When one combines the above effects, a high prestress after collaring is required to overcome them and still maintain positive pressure at the pole faces at maximum current. However, as more magnet test data was produced in the R&D program, combined with accurate measurement of the coil stresses under operating conditions^[1], it became evident that the inner coil polar stress in many magnet assemblies went completely to zero at currents significantly below the maximum current attainable in the magnets

*Work supported by the U.S. Department of Energy.

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without quenching. Thus, it was demonstrated that magnets in this program went to the short sample limit and exhibited little or no training with the inner coil poles completely unloaded. This has caused a re-examination of the necessity to collar coils at extremely high prestress values in order to prevent this unloading at significant risk to the integrity of the turn-to-turn and upper-to-lower coil insulation. The experiment reported here on DSV016 serves to examine the significance of the questions relating to high and low prestress.

MAGNET DESIGN AND CONSTRUCTION

The aperture of the two-layer coil is 40 mm, with an 80 mm outer diameter (Fig. 1). The coil cross section (designated C358D) is a four-wedge non-radial block design.^[2] Parameters of the superconductor used in the magnet are given in Table I. The yoke surrounds the collared coil as shown in Fig. 1. Its inner diameter is 111 mm; its outer diameter is 267 mm. The magnet is designed to operate at 6.6 T central field in 4.35 K helium with a current of 6.5 kA. Details of the magnet design not discussed here are described elsewhere.^[3,4]

The collars were punched from Nitronic 40 stainless steel and spot-welded in pairs, with the pairs then left-right alternated to prevent twist in the collared coil. Tapered keys were used in the collaring, and the overall stress on the coil during collaring was minimized by using both vertical and horizontal force to seat the keys.

The collars used in this assembly were "anti-ovalized" such that the vertical dimension of the collars with pre-stressed coils is reduced by about .010" over that which would be achieved with the nominal geometry.

Figure 1. Cross-section of the yoke and collared coil. (Dimensions are in mm.)

Table I. Superconductor characteristics.

Coil	J_c (kA/mm ²)	Cu:SC	Filament diam. (μm)	RRR
Inner	1619	1.47	6	63
Outer	2233	1.72	4.8	72

The current density is at 4.22 K in a dipole field of 7.0 T (5.6 T) for the inner (outer) coil.

The inner radius of the yoke laminations was chosen to achieve line-to-line contact with unstressed collars at room temperature. To assure correct relative positioning, the two yoke halves were keyed together at the midplane with iron keys. The stainless steel half-shells were then welded together around the yoke. Then the end plate, a single piece of 38.1 mm -thick stainless steel, was installed.

COIL STRESS AND END FORCE EFFECTS FROM STRAIN GAUGE DATA

After an initial test of this magnet with then-standard collars, two assemblies of the coils were made with the "anti-ovalized" collars. The results are reported here. The two assemblies of the magnet were characterized by a high coil prestress (HP) for the first assembly and an intentionally low prestress (LP) for the second one. The average coil stresses for these cases and the resulting collar deflections are given in Table II. It is noted that the anti-ovalizing effect has limited the vertical deflection of the HP case to about 7 mils while that of the LP case did not have sufficient prestress to deflect the coil to even the nominal inner diameter of the yoke.

The behavior of the inner coils during the two tests will be shown for two cases. The mechanical parameters for the outer coils are not considered to be as significant as those for the inner coils primarily because the inner coils see higher fields than the outer coils and thus, the Lorentz forces are more pronounced and produce more of a mechanical effect. Short sample limited quenches are predominantly in the polar turn of the inner coil. Therefore, we will limit the analysis of the mechanical effects for these two assemblies to those of the inner coils. Table III summarizes the inner coil stress condition at significant points during the test procedure.

For the case of the high prestress (HP) assembly there was an increase in inner coil stress of about 2000 psi as a result of the welding of the shell around the collared coil and the yoke. This is thought to be associated with the increased vertical diameter of the collared coil which causes an interference fit with the yoke. Thus, the force of the weld shrinkage is transmitted by the yoke to the collared coil and causes an apparent increase in coil stress as the yoke midplane gap is closed. For the case of the low prestress (LP) assembly, the collars apparently had a clearance with the yoke in the vertical dimension, there was little or no increase in coil stress when the shell was

Table II. Collar deflections produced with prestress.
(Average coil stress shown, psi)

	High Prestress Assembly	Low Prestress Assembly
Inner coil stress (psi)	12225	3821
Outer coil stress (psi)	9319	3281
Vertical Deflection (inches)	.0066	- .0020
Horizontal Deflections (inches)	.0008	- .0044

welded. The stress loss from cool down is also somewhat higher for the HP case than for the LP assembly. This is related to two effects. One is the decrease in the vertical force exerted on the collared coil by the yoke from the shell welding as the collars shrink away from the yoke and the mid-plane gap closes. Also, the elastic modulus of the coils is higher at higher stress levels so that a unit change in thermal strain produces more of a stress change for the HP case. It is also seen that the coil relaxation is more pronounced during the course of the entire testing period for the high prestress case, which further illustrates the higher relaxation rate at the elevated stress level. Table III also shows a comparison of the effects of the Lorentz forces, indicating that at 7000A the polar stress dropped by about 4200 psi for the HP case; however, the inner coils for the LP assembly unloaded completely at about 4000A. This is illustrated better in Figure 2. The HP case still maintains more than 2000 psi compressive stress at the pole at 7000A, while the LP case showed complete unloading at 4000A. Note there is continued operation to the limit of the test (about 7400A) without inducing a quench.

The other significant mechanical measurements made during the assembly and testing of the magnets in the R&D program is that of the end forces that support the ends of the coils through the end plate to the shell. A summary of the measurements of the end forces for the two assemblies during the course of the tests is shown in Table IV. It is seen that for both cases the end force disappears after the magnet is cooled to operating temperature in the test dewar. The explanation of this effect is not clearly understood at this time and hopefully will be resolved in the completion of the R&D on the magnets. One possible explanation is that the longitudinal shrinkage of the shell is governed by the iron yoke, in which case the coil may actually shrink longitudinally a little more than the shell thus relieving the end force. However, when the magnet is energized, the end forces tend to make the coils push against the end plate and this is seen in the measurement of coil end force vs. current in Figure 3. It is seen that there is no apparent increase in end force until the magnet current exceeds 6000A for the HP case and 4000A for the LP one. A possible interpretation is that there is an initial gap between the coil and its end support as a result of the cool down effect. This gap appears to close earlier for the LP assembly since the coil is not clamped as rigidly in the collars because of the lower friction associated with the low prestress in the coils. Thus, the length of coil which moves axially due to the Lorentz force is longer and hence is not as stiff longitudinally. This point should be resolved during the completion of the magnet R&D.

Table III. Comparison of significant coil stress values for DSV016 for the high and low prestress cases. (psi)
(Inner coils only, gauge 90627-1)

Condition	High Prestress	Delta	Low Prestress	Delta
Stress after collaring	12486		4800	
Stress before shell welding	11871	- 615	4503	- 297
Stress after shell welding	13936	2065	4796	293
Stress in test dewar (ambient temp.)	12978	- 958	4577	- 219
Stress in dewar (at 4.4 K)	8636	-4342	1541	-3036
Stress prior to ramp to 7 KA	6905	-1731	1301	- 240
Stress at 7 KA	2661	-4244	*	1300
Stress prior to warm up	6816	4155	1840	540
Stress at ambient temp.	11367	4551	4866	3026
Overall stress change in dewar		-1119		66

* Stress goes to zero at 4000 A.

Figure 2 - Comparison of the Effect of Lorentz Forces on Inner Coil Stress.

Figure 3 - Comparison of Coil End Force at Return End with Current

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Table IV. Summary of coil end force changes
Return end gauges (lbs.)

	Temperature (K)	High Prestress	Low Prestress
Initial setting	296.00	- 1049	- 1000
In test dewar	297.06	- 736	- 632
Before quenching	4.17	0	0
After quenching	4.17	0	0
Prior to warm up	4.14	0	0
End of test	285.49	- 352	- 357
Overall change in dewar		384	275

QUENCH TESTS

In quench tests following the first assembly, the magnet reached the limit of the conductor after two quenches at 4.35K. Subsequent quenches of this assembly (at 3.85K, 3.35K, and after a thermal cycle to room temperature and back) were all at the conductor limit. This test indicated that the coils were well-made, and were, therefore, suitable for reuse in subsequent tests of collars and prestress. (Past experience indicates that coils do not remember their training if the collars are removed.)

Quench test results from the next two assemblies, HP and LP, are shown in Fig.4. It can be seen that the quench performance of the HP assembly was good, and that the LP assembly was even better. In the HP assembly, the magnet reached the limit of the conductor after typically 1 or 2 quenches, whereas all quenches in the LP assembly (except the first) were at the limit of the conductor. (The first quench was 0.5% below the conductor limit.) Also, the HP assembly had one quench below the conductor limit after the limit had been reached, during a strain gauge run, whereas the LP assembly had no such quenches. (During a strain gauge run, the current is stepped in intervals of 100 A or 500 A and held constant while the gauges are recorded, whereas a constant ramp rate is used for a standard run.)

From voltage tap information it was determined that all quenches in the LP assembly occurred in the expected location, the two-dimensional high field region, located at the pole turn (turn #16) of the inner coil. The location data confirms that the magnet is operating at the limit of the conductor. In the HP assembly, all quenches but two also originated in the inner coil pole turn. One of the two started in the outer coil, as indicated in the quench plot. The other started in inner coil turn 13.

FIELD MEASUREMENT

It is possible to gain information about conductor position and motion from measurements of the non-dipole portion of the magnetic field. The notation for the multipole representation of the magnetic field is defined by the following equation:

$$B_y + iB_x = B_0 \sum_{n=0}^{\infty} (b_n + ia_n) (x + iy)^n$$

where B_0 is the dipole field, and x and y are the horizontal and vertical coordinates measured from the magnet center. It is convenient to define a multipole "unit" as 10^{-4} of the dipole field, with the multipole evaluated at a radius of 1 cm.

The even- n b_n coefficients are determined by the symmetric (top and bottom, left and right) position of the conductor in the iron. The change in these coefficients

is listed in Table V. Also given in the Table is the change calculated from a rigid cavity, no friction model which assumes that the only result of the change in the shim thickness is a change in the average thickness of each turn. The calculated changes are about 1/3 larger than the measured changes, indicating that effects such as the change in collar shape with prestress are important.

The coil motion caused by the electromagnetic force and indicated by varying prestress also changes the allowed multipoles. This change is in addition to multipole changes due to magnetization currents (at low field) and iron saturation (at high field). In comparing different magnets, it is difficult to separate the three effects. In a single-magnet comparison the magnetization and saturation effects will be identical, and differences can be attributed to differences in coil motion. The lowest-order harmonics are the most sensitive to conductor position, so the best multipole coefficient to study as a function of current is the sextupole, b_2 (Fig. 5). It can be seen that shapes of the curves are nearly identical over the full range of excitation. As the current is varied the difference between the curves is constant within 0.1 unit.

Table V. Difference of multipoles for HP and LP assemblies.

Multipole	$b_n(HP) - b_n(LP), 10^{-4}$ Units	
	Calculated	Measured
Sextupole (b_2)	8.18	6.21
Decapole (b_4)	- 1.01	- 0.64
14-Pole (b_6)	0.21	0.12
18-Pole (b_8)	- 0.05	- 0.03

Figure 5. Variation of normal sextupole (b_2) with current for the high prestress (lower points) and low prestress assemblies (upper points).

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