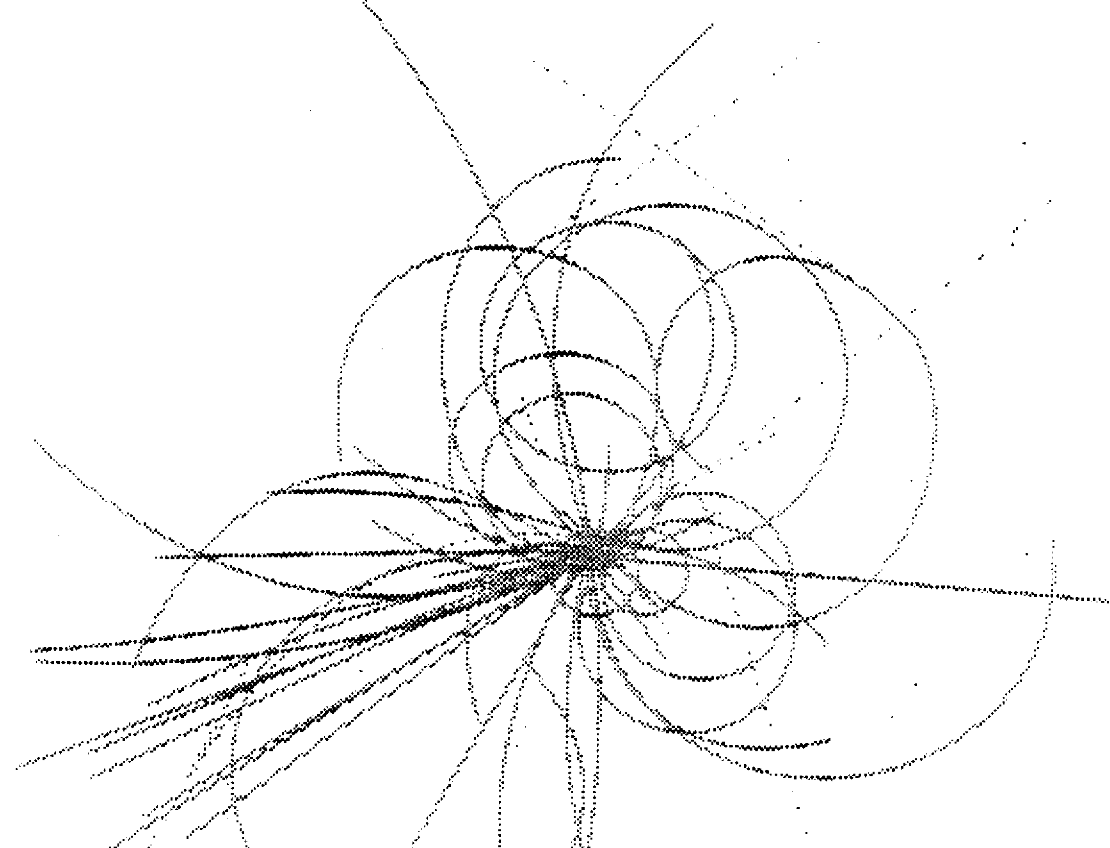
SSC-238

The Superconducting Super Collider



Mechanical Analysis of Different Yoke Configurations for the SSC Dipole

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M. S. Chapman, J. M. Cortella, and R. I. Schermer
Superconducting Super Collider Laboratory†
2550 Beckleymeade Avenue
Dallas, Texas 75237

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

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M. S. Chapman, J. M. Cortella, and R. I. Schermer
SSC Central Design Group*
Lawrence Berkeley Laboratory
MS 90/4040
One Cyclotron Road
Berkeley, California 94720

R. H. Wands
Fermi National Accelerator Laboratory*
P. O. Box 500
Batavia, Illinois 60510

ABSTRACT

Finite element methods are used to calculate the additional mechanical support offered by different configurations of the yoke and shell for the SSC dipoles. In this analysis, horizontally and vertically split yokes with different gaps between the yoke halves are evaluated in terms of collar deflections and coil stresses. The results show that the yoke offers significant additional support for the collars against the Lorentz forces. Collar deflections due to Lorentz forces can be reduced 50–75% by using the various yoke configurations studied here. Additionally, the analysis indicates that vertically split yokes are preferable to horizontally split yokes for maintaining a uniform stress state across the coil poles, and that for either horizontally or vertically split yokes, an open midplane gap between the yoke halves at 4.2 K results in a smaller coil stress loss during cooldown.

INTRODUCTION

Recent SSC dipoles have included two significant mechanical changes designed to better restrain the coils against Lorentz forces developed during energization. First, the yoke and skin have been redesigned to provide additional clamping of the coils, and second, the endplates of the magnet have been strengthened against axial deflection. These magnets have demonstrated improved training behavior over their predecessors, which relied entirely on the collars to clamp the coils and employed relatively flexible endplates [1,2]. Here, finite element methods are used to calculate the additional transverse support provided by the yoke and the shell for the present yoke design and for other possible configurations.

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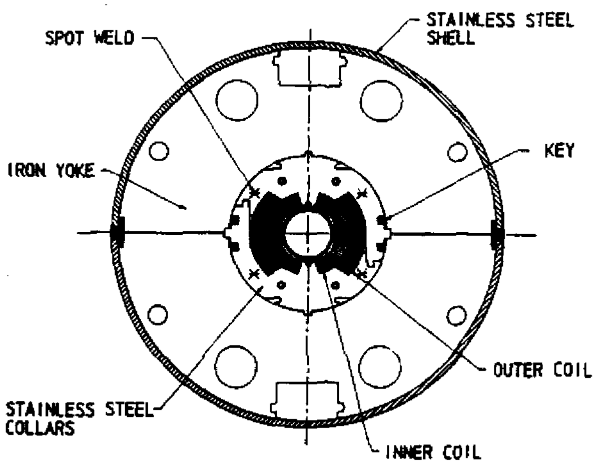

Figure 1. Cross section of the SSC Dipole

The cross section of the present design of the SSC dipole (designated C358D) is shown in Figure 1. Stainless steel, spot-welded collar laminations are tightly clamped around the coils and locked together with inserted keys. The collars azimuthally precompress the coils and support them against the Lorentz forces developed as the magnet is energized. After the coils are collared, the horizontally split carbon steel yokes and stainless steel shell are assembled around the collared coil, and the shell is welded. When the magnet is cooled down to 4.2 K, the collars and coils shrink more than the yoke and thus tend to separate from the yoke. However, yoke/collar contact along the region of the horizontal midplane is necessary in order for the yoke to be able to provide additional support to the coils during energization. To achieve this contact with the horizontally split yokes, a vertical interference fit is called for between the yoke and collar at 4.2 K such that there is a gap between the yoke halves. Tension developed in the shell due to weld shrinkage and thermal contraction tends to close the gap, and in doing so, loads the collar with a vertical force via the yoke. This force causes horizontal expansion of the collar and an inward bending of the yoke, which combine to produce yoke/collar contact along the horizontal midplane.

For the vertically split yokes, yoke/collar contact along the horizontal midplane is achieved in a more straightforward manner. As long as a sufficient horizontal interference fit is specified between the yokes and the collars, the tension developed in the shell will naturally draw the yokes in against the horizontal midplane of the collars.

It is possible to control the amount of shell tension transferred to the collars and coils by varying the yoke/collar interference fit (and thus the initial yoke midplane gap). If the specified interference is large enough so that the yoke midplane gap remains open throughout cooldown, all of the shell tension is transferred to the collars and the coils. If the yoke gap closes during cooldown, then only a portion of the developed shell tension is transferred to the collars and coils; the remainder is reacted by the closed yoke gap.

In this analysis, four yoke configurations are considered: two with horizontally split yokes and two with vertically split yokes. For each orientation of the yoke split, we consider either open or closed yoke midplane gaps at 4.2 K. In addtion to these four cases, a model with unsupported collars is considered for comparative purposes. A description of these cases is presented in Table 1. Case II, with horizontally split yokes with a closed midplane gap at 4.2 K, represents the present SSC dipole design.

Table 1. Yoke Configurations Analyzed

Case	Type of yoke	Yoke gap at 4.2 K
I	none	n/a
II	Horizontal	closed
III	Horizontal	open
IV	Vertical	closed
V	Vertical	open

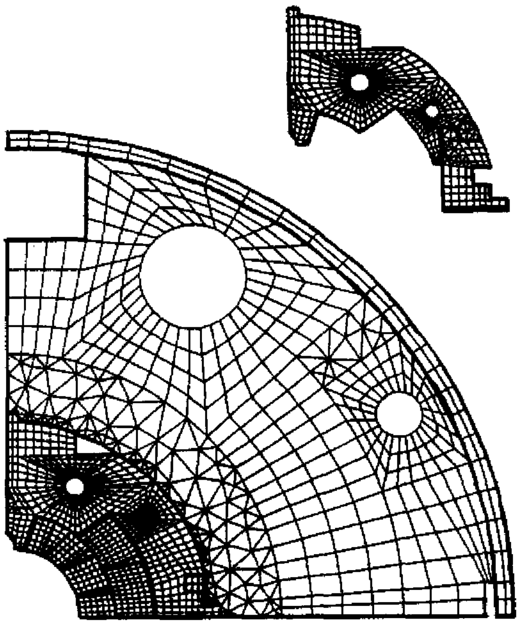

Figure 2. Finite element model of SSC dipole. Portions of collar shown separately for clarity.

THE MODEL

The ANSYS finite element code by Swanson Analysis Systems is used for this analysis. The 2–D finite element model of the magnet cross section is shown in Figure 2. The model includes the inner and outer coils surrounded by the collars, which are in turn surrounded by the yoke and shell. The collars are modeled in three separated pieces representing two laminations in depth, and constraint equations are used on the collar midplanes to enforce rotational symmetry. Additional constraints for the collars are provided by the inserted keys and spot-welds between successive pairs of laminations. Compression-only "gap" elements are used along interfaces that are permitted to separate. Horizontally split yokes are modeled with a symmetry boundary condition along the vertical midplane and a gapped boundary condition along the horizontal midplane that permits separation. For the vertically split yoke, these boundary conditions are reversed. Different initial yoke midplane gaps are specified using the gap elements along the appropriate midplane. The size of the initial gap is chosen so that after cooldown, the gap will be either open or closed. For the unsupported collars, the yoke and shell are not included in the model.

The models are loaded with sequential load steps representing coil prestress assembly, welding of the shell, cooldown to 4.2 K, and energization to 6.6 T. The coil prestress loading is modeled with positive vertical displacements of the coil midplanes to produce average azimuthal compressive coil stresses of 8000 psi at the inner coil midplane and 6000 psi at the outer coil midplane. The welding of the shell, which produces azimuthal tension due to weld shrinkage, is represented by a negative displacement of the horizontal midplane of the shell sufficient to produce 30 kpsi in the shell. At present, it is difficult to determine the amount of tension developed in the shell during welding because the welds are performed manually, and yoke halves are only loosely clamped around the collars before welding. With improved tooling that incorporates automatic welding machines and a hydraulic press to compress the yoke halves together, it is hoped that the shell stresses can be more uniformly controlled. Cooldown to 4.2 K is modeled in one step using the integrated coefficients of thermal contractions for the various materials in the cross section.

Table 2. Material Properties

	Young's Modulus E (psi)	$\Delta l/l$ (293→4.2 K)
coils	1.5×10^6	–0.0040
collars	30×10^6	–0.0031
yokes	30×10^6	–0.0020
shell	30×10^6	–0.0031

These coefficients, along with the Young's moduli, are listed in Table 2. The Lorentz forces, which have been calculated using a magnetic version of this model as reported in [3], are applied as nodal forces on the coils for currents of 2000, 3000, 4000, 5000, 6000, 6400, and 7000 amps. The operating current of the dipole at 6.6 T is 6400 amps.

RESULTS

The calculated collar deflections due to the Lorentz forces acting on the coils at 6.6 T are shown in Figure 3. For all the yoke configurations studied, the additional support offered by the yoke reduces collar deflections significantly. Note that the yoke is effectively more stiff against collar motion when the yoke gap (horizontal or vertical) is closed during energization. This is because when the yoke gap is closed, the yoke has the same stiffness of an equivalent solid ring, whereas when the yoke gap is open, it has the lesser stiffness of an

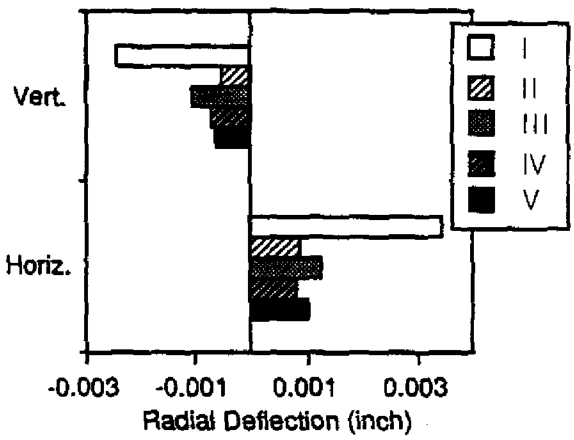

Figure 3. Radial collar deflections due to Lorentz forces only

equivalent split ring. It is surprising at first glance that the deflections of Case V, which has a vertically split yoke with an open gap, are so small. One might think that with the yoke gap open along the vertical midplane, the yoke would be unable to provide support against horizontal collar deflections. However, the yoke is preloaded in bending during the welding and cooldown steps such that it contacts the collars along the top in addition to along the side. As the magnet is energized, the preloaded contact along the top of the collars partially unloads and contributes considerably to the effective stiffness of the yoke.

In Figure 4, the average azimuthal compressive stress at the inner coil pole is plotted for the

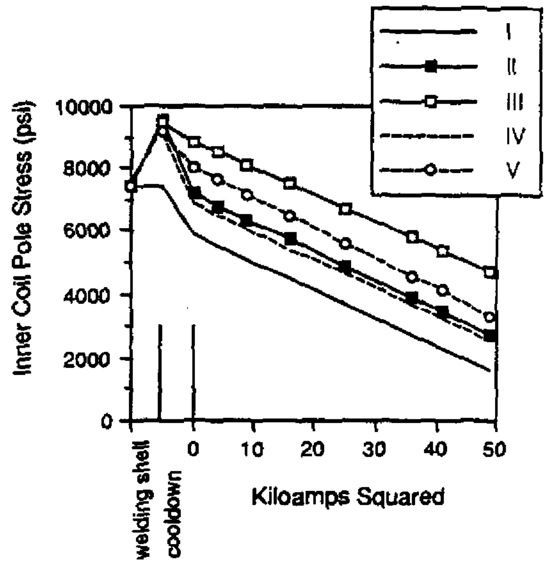

Figure 4. Average azimuthal stress (compressive) across inner coil pole face for welding of shell, cooldown, and energization.

different loadings. During welding, the yoke midplane gaps remain open for all cases, and the tension developed in the shell due to weld shrinkage is completely transferred into the coils and collars. This results in an increase of azimuthal stress in the inner coil of about 2000 psi. The different increase between the vertically split yokes and the horizontally split yokes can be attributed to the different load sharing between the collars and coils in the horizontal and vertical directions. For Case I, in which the yoke is not included in the model, the welding step is not included. The cooldown step produces different changes in coil stress depending on the particular yoke configuration. For the free-standing collars in Case I, the coil stress drops 1600 psi during cooldown because the coil shrinks more than the collars. For Cases III and V, the yoke midplane gap remains open during cooldown, and the drop in coil stress is minimized because of the increase in shell tension during this step. In cases II and IV, the yoke gap closes during cooldown and a portion of the shell stress is transferred into the now-closed yoke midplane gap. After the yoke gap closes, the collar/yoke contact begins to reduce due to greater thermal contraction of the collars and coils. However, at the end of cooldown, there is still significant contact between the yoke and collar, so the inner coil stress remains larger than the free-standing collar value. During energization to 6.6 T, the rate of inner coil stress loss versus current squared is linear and does not vary significantly from model to model.

Deflections of the collar and coils produce bending stresses in the coils such that the stress profile across the poles is non-uniform. The bending stresses are analogous to those developed in a thick cylindrical ring subjected to a

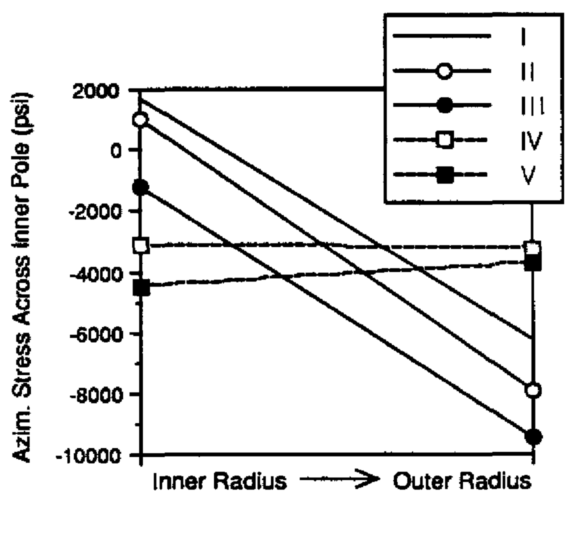

Figure 5. Linearized azimuthal stress profile across the inner coil pole at 4.2 K, 6.6 T assuming an initial coil prestress of -8000 psi. Positive stress values result from the linearization of the actual stress distribution across the pole; in the model, gap elements between the coil and the collar prevent tensile stress from developing.

transverse point load. The calculated stress profile across the inner coil pole at 6.6 T is shown in Figure 6 for the different cases. The deflection of the collar due to the Lorentz forces causes the inner radius of the coil pole to lose more stress than the outer radius. While reducing the collar deflections should, in general, reduce the stress gradient, this is not the case with the horizontally split yokes because the vertical clamping of the collar causes a significant stress gradient with the same sign as that produced during energization. The vertically split yokes, on the other hand, clamp the collars in the horizontal direction. This produces a stress gradient opposite to that produced during energization, and the two effects cancel. This cancellation produces a uniform stress profile across the coil pole, as indicated by the dashed lines in Figure 5.

Maintaining compressive stress across the poles is generally considered essential in limiting quench-causing conductor motion. It may be somewhat alarming, then, that the calculation predicts that the inner radius of the inner coil pole unloads completely at 6.6 T for both the unsupported collars and the present design. The calculation employs a relatively simple isotropic, linear, elastic model of the coil, however, so the calculated stress quantities are only qualitatively correct. Including the non-linear stress/strain behavior of the coil in the model would likely keep the pole from unloading because the coil becomes very soft at low stresses.

Although the cases with the open yoke gaps show the highest average stress at the inner pole (Figure 4), these configurations may not prove to be a practical design from a magnetic standpoint. With an open midplane gap, the final shape of the coils, and thus the magnetic field uniformity, is determined to some extent by the amount of tension in the shell. Because of the nature of the welding process, the final shell tension is hard to control, and therefore, an open midplane gap may result in significant magnet-to-magnet field variations. In addition to potentially affecting the field uniformity, an open gap at the yoke horizontal midplane reduces the magnitude of the field. The severities of these effects are not precisely known at this point and need to be better evaluated regardless of which yoke configuration is used.

CONCLUSION

From a mechanical point of view, the vertically split yoke with an open midplane gap after cooldown seems to be a promising configuration for the SSC dipole. It provides excellent support against collar deflections, minimal stress loss during cooldown, and a uniform stress profile across the inner coil pole at operating field. If an open yoke gap proves to adversely affect the magnetic field uniformity in an uncontrollable manner, then the vertically split yoke with a closed gap seems to be a good alternative.

The horizontally split yokes also provide excellent support against collar deflections and show small stress losses during cooldown. However, the bending stresses induced in the coils by the vertical clamping of the collars by the yokes produce a severe, undesirable stress gradient across the inner coil pole.

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