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Experimental Evaluation of Vertically Versus Horizontally Split Yokes for SSC Dipole Magnets*

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EXPERIMENTAL EVALUATION OF VERTICALLY VERSUS HORIZONTALLY SPLIT YOKES FOR SSC DIPOLE MAGNETS

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ABSTRACT

The yoke in SSC dipole magnets provides mechanical support to the collared coil as well as serving as a magnetic element. The yoke and skin are used to increase the coil prestress and reduce collar deflections under excitation. Yokes split on the vertical or horizontal mid-plane offer different advantages in meeting these objectives. To evaluate the relative merits of the two configuration a 1.8 m model dipole was assembled and tested first with horizontally split and then with vertically split yoke laminations. The magnet was extensively instrumented to measure azimuthal and axial stresses in the coil and the cold mass skin resulting from cooldown and excitation. Mechanical behavior of this magnet with each configuration is compared with that of other long and short models and with calculations.

INTRODUCTION

The tests described in this paper were carried out on a 40 mm aperture dipole magnet[1] of the design originally proposed for the Super Conducting Super Collider (SSC). This magnet has a "cos θ" type coil which is clamped by interlocking stainless steel collars. A circular iron yoke of inner diameter 111 mm and outer diameter 267 mm increases the magnetic field by approximately 20%. It is surrounded by a 4.8 mm thick cylindrical stainless steel skin which clamps the yoke about the collared coil, supports the magnet between the cryostat support posts and serves as a helium containment vessel. In the original design the yoke served as a purely magnetic element and was mechanically decoupled from the collared coil except for positioning tabs at the vertical and horizontal mid-planes. Azimuthal and radial constraint to the coil was provided entirely by the collars and axial restraint was provided by end plates and the ill-defined friction between the collar positioning tabs and the yoke. Full length dipoles of this design exhibited excessive quench training.[2,3,4] In more recent magnets the yoke and collars are closely coupled mechanically. The yoke, when clamped by the skin, serves not only to enhance the magnetic field but also to provide additional preload to the coil, to decrease collar deflection under excitation and to transfer the axial component of the Lorentz force to the skin via coil-collar-yoke-skin friction.

Dipoles of this design have showed dramatically reduced training, typically reaching plateau in three or fewer quenches.[4,5,6]

For assembly reasons the yoke must be split along a diameter. If the yoke is mechanically decoupled from the collars, the direction of this split is unimportant. However, with the yoke acting as a mechanical element, the yoke split direction may effect the magnet behavior. Most SSC magnets have used horizontally split yokes. Prototype magnets[7] for the proposed Large Hadron Collider (LHC) at CERN, which also use the yoke to provide additional mechanical support to the collars, use a vertically split yoke.

Because the Lorentz force is mainly horizontal in the body of the magnet, collar deflections are minimized if the yoke supports the collars near the horizontal mid-plane. The ability to provide this support depends on the relative thermal contractions of the yoke and collar materials, the choice of yoke split direction and the details of the relative shapes of the collar outer surface and the yoke inner surface. Two different steel alloys have been used for the collars in SSC model magnets: Armco Nitronic 40 with an integrated thermal contraction to 4 K of -2.9×10^{-3} and a Kawasaki high-manganese alloy with an integrated thermal contraction of -1.7×10^{-3}. For comparison, the integrated thermal contraction of the low-carbon steel used for the yoke is -2.1×10^{-3}.

The details of the collar's design and its interaction with the yoke depend on the thermal contraction of the collar material. Figure 1 shows the yoke-collar configurations for a horizontally split yoke with both collar materials and for a vertically split yoke with Nitronic 40 collars. To be inserted easily into the yoke at room temperature the collar diameter in the direction of the yoke split must be no larger than the yoke inner diameter. Nitronic 40 collars shrink away from the yoke during cooldown and may lose contact with the yoke along the split direction. If Nitronic 40 is used with a horizontally split yoke, the collared coil is designed to be sufficiently vertically oversized that when clamped in the yoke it deflects horizontally to contact the yoke. (See Figure 1a.) High-manganese collars (Figure 1b) are designed so that after deflection due to the coil prestress the collared coil is circular with a diameter equal to the inner diameter of the yoke. With cooldown the collars shrink less than the yoke and firm 360° contact is achieved.

Each of these collar materials has its own advantages and disadvantages. The lower thermal contraction material allows a simpler design to achieve close yoke-collar contact and results in better horizontal support against the Lorentz force. However, the low thermal contraction coeficient results in a larger prestress loss with cooldown. The larger contraction material requires a less simple design to achieve horizontal yoke-collar contact at operating temperature, but suffers less cooldown prestress loss.

Both horizontally split yoke designs are sensitive to the magnet-to-magnet variation in collared coil vertical diameter due to prestress variation. The measured rate of deflection is about 4 μm/MPa resulting in an expected range of 100-150 μm in vertical diameter for a preload range of ±20 MPa. Thus there is the possibility that the yoke mid-plane gap will not close under all conditions for higher prestress coils. This is particularly likely for the Nitronic 40 collars in which vertical contact with the yoke is required by the design. Finite element calculations[8] indicate that if there is sufficient vertical interference between the yoke and collars to ensure horizontal contact for the lowest preload coils, the mid-plane will be open by 50-100 μm at liquid helium temperature for the highest preload coils. At room temperature a mid-plane gap is likely to exist for all coils. With Kawasaki steel collars the mid-plane gap is likely to be closed at room temperature but will tend to be open for the higher prestress coils at 4 K.

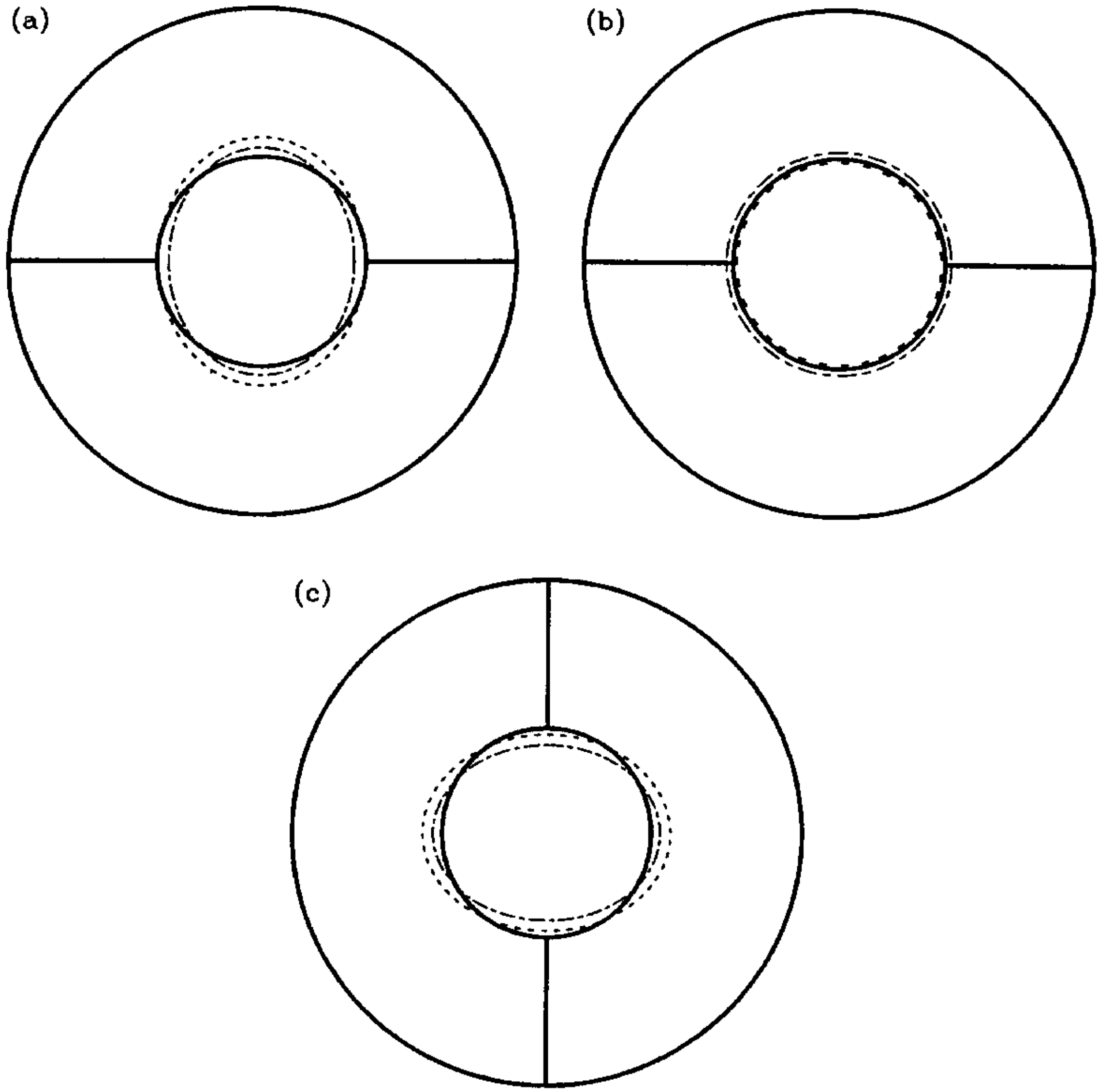

Fig. 1. Horizontally split (a and b) and vertically split (c) yoke configurations with high (a and c) and low (b) thermal contraction collars. The solid lines represent the yoke laminations, the dotted lines represent the free collared coil at T=300 K and the dot-dashed lines represent the free collared coil at T=4 K. (The collared coil distortions relative to the yoke are greatly exaggerated.)

In contrast, the collared coil horizontal diameter is relatively insensitive to coil prestress. (The vertical force from the coil prestress is applied at a smaller radius than the opposing force for the keys. This couple causes an inward bending of the sides of the collars that almost perfectly cancels the outward deflection due to the internal pressure of the coils.)[9] The rate of horizontal deflection is less than 20% of that in the vertical direction; horizontal diameter varies by < 30 μm for the full range of expected coil preloads. If a vertically split yoke design is adopted it is relatively easy to ensure both good horizontal support to the collared coil and a closed mid-plane gap independent of the coil preload. This can be achieved with the larger thermal contraction collar material by appropriately choosing the horizontal and vertical diameters of the collars. In this case (Figure 1c) the collared coil is oversize in the horizontal direction and undersize in the vertical direction to allow easy insertion into the yoke for even the highest preload coils. Under cooldown the collars move away from the yoke at the vertical radius but positive contact is maintained at the horizontal radius, guaranteeing both horizontal support and transfer of the axial force to the skin. At zero field, the skin tension is balanced primarily by a pressure between the mating surfaces of the yoke halves. As the field increases, the mid-plane progressively unloads as the horizontal Lorentz force is transferred to the yoke. As long as the skin tension exceeds the Lorentz force, the mid-plane gap remains closed and the yoke behaves as a rigid solid structure. The mechanics of this design are described in more detail in Reference 7.

TEST MAGNET DESIGN

To compare the relative merits of the two yoke split directions a 1.8 m model magnet (DSS012), built and previously tested[10] at Brookhaven National Laboratory (BNL), was partially reassembled twice at Fermilab with the two yoke types. In the original assembly at BNL horizontally split yoke laminations which did not contact the collars were used. Similarly to long magnets DD0012 and DD0014[4] shims were placed between the yoke and the collars to fill the gap. This magnet was not the ideal vehicle for these tests because it is built with the low thermal contraction Kawasaki steel collars which work well with a horizontally split yoke, but, unlike the design discussed above and shown in Figure 1b, the collared coil is significantly oval in the vertical direction.

In the first reassembly the horizontally split yoke laminations used were the same as those used in other recent 40 mm SSC dipoles.[5] These are designed so that at room temperature there is "line-to-line" contact between the inner surface of the yoke and the outer surface of the undeflected collar and they are expected to result in mechanical behavior of the collar-yoke system equivalent to the original assembly. Because of deflections of the collar due to coil prestress there was approximately 170 μm radial interference in the vertical direction and 0-25 μm radial interference in the horizontal direction between the yoke and the free collared coil. When clamped in the yoke the collars contact the yoke around the full circumference and the yoke mid-plane gap is open. Because the collars shrink less than the yoke, similar conditions exist at 4 K. This configuration is shown in Figure 2a.

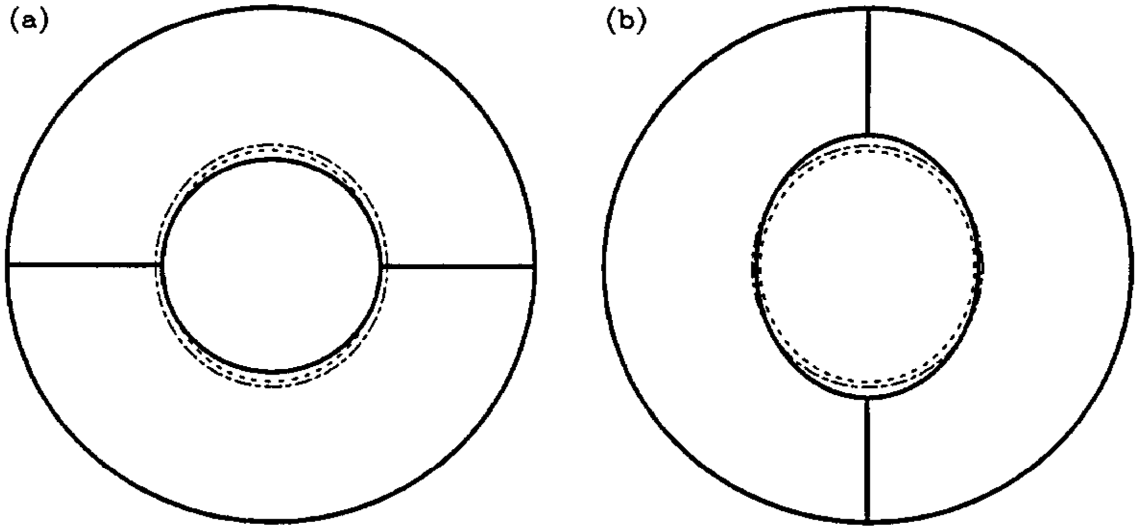

Fig. 2. Yoke-collar configurations used for the tests of DSS012: (a)horizontally split yoke with yoke-collar shims and "line-to-line" contact yoke and (b) vertically split yoke. The solid lines represent the yoke laminations, the dotted lines represent the free collared coil at T=300 K, and the dot-dashed lines represent the free collared coil at T=4 K. (The collared coil distortions relative to the yoke are greatly exaggerated.)

Vertically split yoke laminations were used in the second assembly. Because the collared coil is vertically oval and shrinks less than the yoke with cooldown, the design described in Figure 1c could not be used. To achieve the proper mechanical interface to the collars the inner surface of the yoke lamination deviated from that required by the magnetic design. The inner surface was made elliptical with the horizontal and vertical radii larger than the "line-to-line" contact yoke by 25 μm and 280 μm respectively. At room temperature the there was clearance between the yoke and the collars of 0-25 μm and approximately 110 μm in horizontal and vertical directions respectively. At 4 K the vertical clearance was reduced to about 80 μm and there was 0-25 μm of interference along the horizontal radius. This configuration is shown in Figure 2b.

The goal of this experiment was to compare the mechanical behavior of the horizontally and vertically split designs with each other and with expectations from calculations. In both configurations the magnet was extensively instrumented to measure coil azimuthal stress, force between the end of the coil and the end plate, and circumferential and axial stresses in the cold mass skin. Instrumentation used for coil stress and end force measurements are described in Reference 11. Strain gages were mounted directly on the cold mass skin to measure circumferential stress as a function of azimuth at two points approximately 8 cm apart near the center of the magnet and axial stress as a function of longitudinal position at an azimuthal position approximately 50° from the yoke parting plane.

MAGNET TESTS

In the horizontally split yoke case the skin gages were mounted before the skin was welded around the magnet and the strain-free resistance of all gages were measured at room temperature and 4.2 K. This allowed measurement of absolute strain and of absolute stress where no yielding occurred. Near the mid-plane weld the skin was observed to yield significantly. Far from the weld the azimuthal stress is 150-200 MPa at room temperature and grows to 300-350 MPa with cooldown due to the larger thermal contraction of the stainless steel skin than of the yoke. The clamping force of the skin at operating temperature is approximately 3×10^6 N/m or about twice the horizontal Lorentz force.

Tests were performed in pool boiling liquid helium in a vertical dewar at the Fermilab Superconducting Magnet R&D test facility at Lab 2. The data acquisition system is similar to that used at the Fermilab Magnet Test Facility.[12] Strain gage, dewar pressure and temperature were recorded at 10 minute intervals through cooldown, the cold testing period and warm-up to room temperature. Care was taken to continue data recording on the warmup cycle until the magnet had fully reached room temperature. (Because of the large difference between the thermal expansion coefficients of the coil and the high-manganese steel collars the coil prestress changes at a rate of approximately 140 kPa/K.) The magnet was cooled to approximately 80 K by flowing liquid nitrogen through copper tubes band-clamped to the outer surface of the skin. Final cooldown was achieved by filling the dewar with liquid helium. The magnet was warmed by blowing room temperature helium and then nitrogen gas through the dewar and the copper tubes and by powering the magnet coils with 10 A.

Cold tests emphasized strain gage data to compare the mechanical behavior of the different configurations. Strain gage data were recorded at roughly equal intervals of IxB in cycles to increasing peak current until a quench occurred. The magnet was then trained to the quench plateau at 4.2 K, and strain gage data were recorded up to a current just below the plateau. Recent 17 m model dipoles have been build with several different horizontally split yoke configurations. These magnets are instrumented similarly to DSS012, and a similar test procedure has been followed allowing comparisons among them and the various DSS012 configurations.

Figure 3 shows the quench history for the three tests. The first test, with yoke-collar shims, is a retest in the same configuration as the earlier tests at BNL[10] with no intervening disassembly and reassembly. In the tests at BNL no "retraining" was observed after a thermal cycle to room temperature. Here, in tests roughly a year after the tests at BNL, two retraining quenches occurred. In the next two tests the yoke was replaced but the collared coil was not changed. A similar number of training quenches occurred each time.

Coil stress is a function of the current squared (proportional to IxB) is plotted in Figure 4a. The prestress and stress versus I^2 slope are almost identical for the two horizontally split yoke cases. In both cases there is sufficient vertical interference between the yoke and the collars that the yoke mid-plane gap is open under all circumstances. The force from the skin tension is transferred to the collared coil increasing the coil prestress by about 15 MPa. Full circumferential yoke-collar contact occurs in both cases. In the vertically split case there is a small yoke-collar horizontal interference and vertical clearance. The coil prestress is essentially that of the free collared coil and, with the large (35 MPa) cooldown loss, is quite small at the operating temperature. As a consequence the coil unloads at the pole at 5.5 kA (5.6 T). The prestress change with excitation is displayed in Figure 4b along with data from two 17 m magnets.[5] DD0017 and DD0015 both use Nitronic

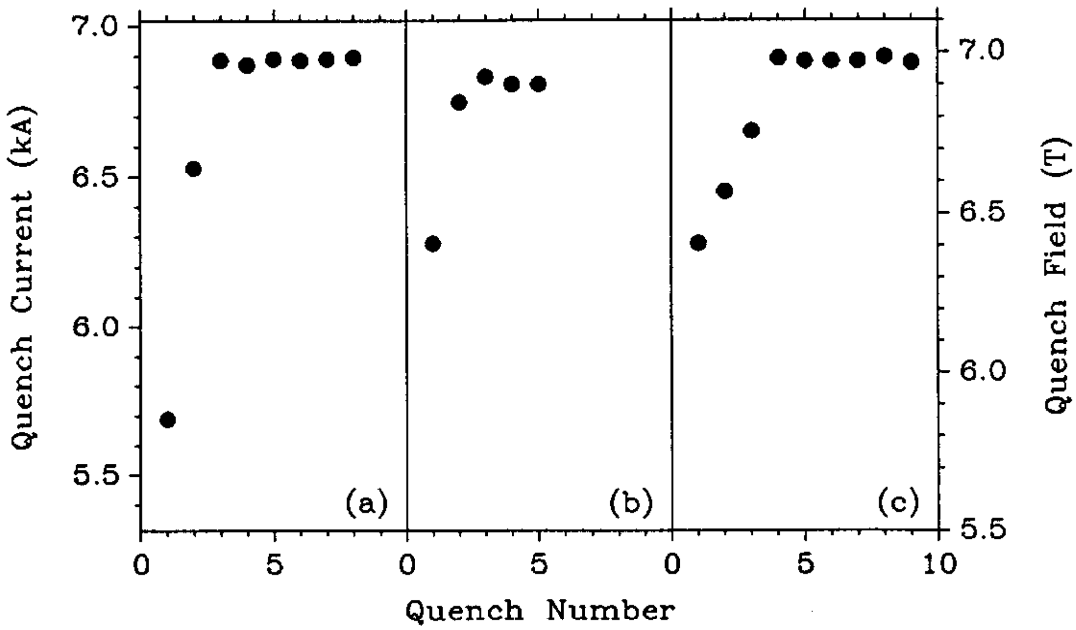

Fig. 3. Quench histories for DSS012 on three assemblies: a) original assembly with a horizontally split yoke and yoke-collar shims, b) second assembly with a horizontally split "line-to-line" contact yoke, and c) third assembly with vertically split yokes.

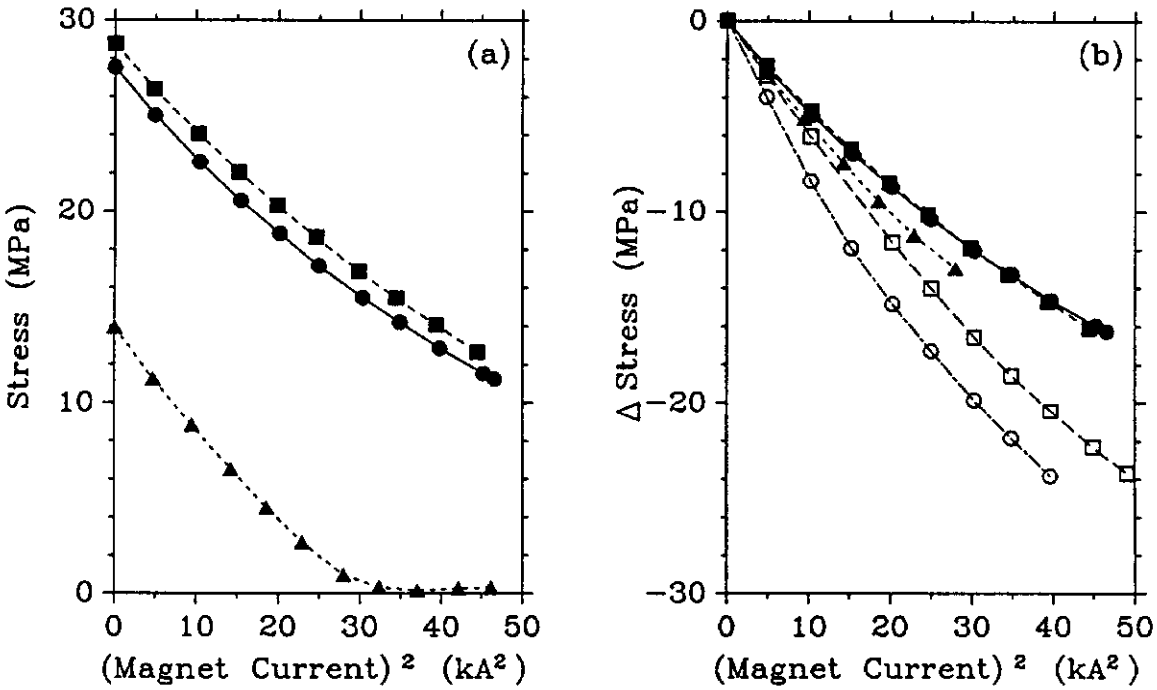

Fig. 4. Inner coil stress (a) and stress change (b) at the pole as a function of magnet current squared for the three assemblies of DSS012 and two 17 m magnets. The filled circles are DSS012 with a horizontally split yoke and yoke-collar shims, the filled squares are DSS012 with a horizontally split "line-to-line" contact yoke, the filled triangles are DSS012 with a vertically split yoke, the open squares are DD0017, and the open circles are DD0015.

40 collars. DD0017 uses horizontally split yoke laminations identical to those used for the second assembly of DSS012. DD0015 uses yoke laminations similar to those used for the first assembly of DSS012; however, no shims are placed between yokes and collars so the collars are unsupported by the yoke. The smallest collar deflection and hence the smallest prestress change with excitation occurs with the horizontally split yoke and Kawasaki steel collars. The prestress decrease is somewhat more with the vertically split yoke because the collars contact the yoke over less of the circumference. With Nitronic 40 collars and a horizontally split yoke (DD0017) there is also less than complete circumferential contact, but because the yoke-collar gap is now at the horizontal radius, the collar deflection is larger than in the vertically split case. With free-standing collars (DD0015) the deflection and prestress decrease are the largest.

The skin stress change with excitation is plotted in Figure 5. Azimuthal stress changes may result from bending of the yoke, which causes the radius of curvature of the skin to change, or from changes in the yoke mid-plane gap, which cause the skin to stretch. The former will have its largest effect 90 degrees from the yoke parting plane and the latter will have its largest effect near the parting plane. Longitudinal stress changes result from the axial Lorentz force transferred from the coil to the skin through the end plates and through coil-collar-yoke-skin friction. Because there are active stress changes in both directions, account must be taken of the Poisson effect in converting the measured strains into stresses. This is done assuming that the longitudinal stress is independent of azimuth. In the vertically split yoke case longitudinal strain is measured at the same point as one of the azimuthal gages. The

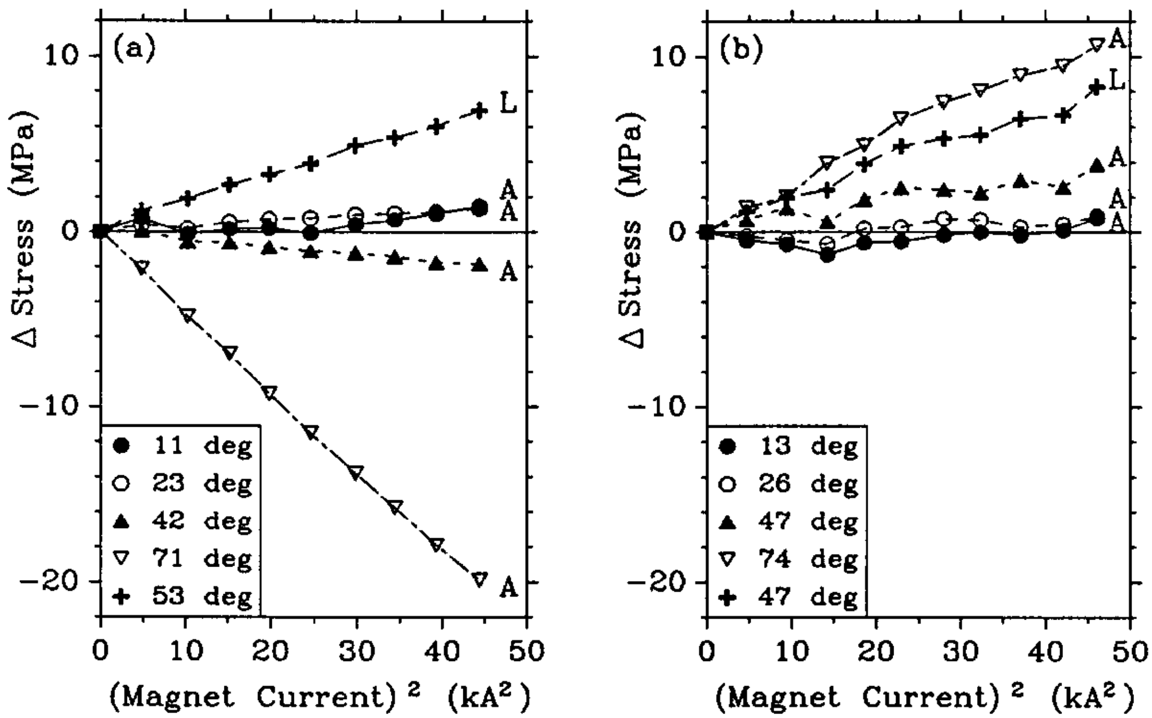

Fig. 5. Azimuthal and longitudinal skin stress changes with excitation near the center of DSS012 with a) a horizontally split "line-to-line" yoke and b) a vertically split yoke. The angles listed in the legend represent the distance from the yoke parting plane. Data labelled "A" and "L" are azimuthal and longitudinal stresses respectively.

Poisson resolution is done at this point and the resultant longitudinal stress is used to correct the other azimuthal measurements. In the horizontally split yoke case the longitudinal strain was measured between two of the azimuthal gages. The azimuthal strain at the location of the longitudinal gage was gotten from a quadratic interpolation among the three nearest azimuthal gages. Because of the uncertainty of the interpolation, there are uncertainties in the stresses that are roughly proportional to I^2 and reach approximately 0.7 MPa and 0.2 MPa for longitudinal and azimuthal stress respectively.

In the horizontally split case (Figure 5a) the azimuthal stress becomes progressively more compressive with increasing distance from the horizontal mid-plane. This is the behavior expected if the yoke bends outward at the horizontal mid-plane under the Lorentz load. The stress near the yoke parting plane (gages at 11 and 23 degrees) appears to be slightly tensile. This may result from the yoke mid-plane gap opening slightly at the outer radius as the yoke bends outward. In the vertically split case (Figure 5b) the azimuthal stress becomes more tensile with increasing distance from the vertical mid-plane. Here yoke bending tends to decrease the skin radius of curvature in the horizontal direction. The azimuthal stress near the vertical mid-plane is essentially zero even at the highest current, demonstrating that the yoke mid-plane gap remains closed. With the gap closed, the yoke bending, as measured by the azimuthal stress far from the parting plane, is much smaller than in the horizontally split case in which the mid-plane gap is open. In either case, however, the stress change is small compared with the total azimuthal tension of 300-350 MPa and with the stress change of 150 MPa that would result if the entire Lorentz force were balanced by the skin.

DISCUSSION

Successful magnets can and have been built with both horizontally and vertically split yokes. In this sense the choice of yoke split direction may not be crucial. However, each system offers different advantages and disadvantages in meeting the requirements of the collar-yoke system:

1) The yoke and skin can be used to increase the coil prestress.

2) At T = 4 K, B = 0, there should be close contact between the yoke the collars near the horizontal mid-plane to minimize collar deflection under excitation and to provide axial restraint.

3) Yoke mid-plane gap should be closed under all circumstances: at T = 4 K to well above the operating field and at room temperature. A closed gap improves the field quality and eliminates the possibility of non-reproducible behavior with thermal cycling if the gap opens and closes.

A horizontally split yoke is more efficient in increasing the coil prestress because the yoke and skin load the collars vertically. It is more straightforward to achieve close horizontal contact with vertically split yokes, particularly with collars whose thermal expansion coefficient is larger than that of the yoke. It is easier to guarantee that the yoke gap is closed at assembly with the a vertically split yoke for two reasons. First, the collared coil radius varies from magnet to magnet less in the horizontal than the vertical direction. Second, the collared coil is significantly more compressible if it is free to expand in the direction orthogonal to the direction it is being clamped. In the vertically split yoke case there is no reason that the collars must make contact near the vertical radius, but in the horizontally split yoke case the collars must contact the yoke at the horizontal radius (requirement 2). Once such contact is made, it is difficult to compress the collars further. The mid-plane gap is less likely to open with excitation with a horizontally split yoke because the horizontal Lorentz force is opposed by the yoke acting as a C-frame. However, at 4 K the skin tension supplies a clamping force about twice the Lorentz force at full field, so the mid-plane is likely to stay closed with a vertically split yoke as well. In addition, finite element calculations[13] indicate that even with the mid-plane gap closed, there is enough bending of the yoke and hence the collars that about half the Lorentz load is taken by the collars. This adds an additional factor of two mechanical margin and ensures that the mid-plane gap will stay closed.

The effect on quench training behavior of coil prestress and collar deflection (or any other mechanical property) is not well demonstrated at a detailed level. Indeed short (1-4 m) model SSC magnets have been built that unloaded at the pole well below 5 T yet reach their critical currents with little training. On the other hand, early 17 m SSC dipoles with low preload trained very poorly and several never reached their critical currents. Quench performance improved dramatically when the collars were firmly clamped in the yoke. This clamping serves to increase the prestress, decrease collar deflections with excitation and improve the axial restraint. Which of these has the dominant effect or whether all three are necessary for good performance is unknown. However, it seems likely that a structure in which the coil prestress is maximized and all deflections - radial, azimuthal, and longitudinal - are minimized is likely to perform well. Minimizing radial collar deflections requires close yoke-collar contact at the horizontal radius. This is difficult to achieve with a horizontally split yoke and collars made of material with a higher coefficient of thermal expansion than the yoke. This is demonstrated by the larger coil stress decrease with excitation in magnets with Nitronic 40 collars than those with Kawasaki steel collars. (See Figure 3). On the other hand, use of low thermal expansion collars result in a larger prestress loss with cooldown. With a vertically split yoke, close horizontal yoke-collar contact at 4 K can be achieved using collar material of any thermal expansion coefficient, allowing both prestress loss with cooldown and collar deflection with excitation to be minimized. In the vertically split yoke test discussed here the collars and yoke made contact only near the horizontal mid-plane, as they would with collars with a larger thermal expansion coefficient. The collar deflection, inferred from the coil stress decreased in Figure 3, is less than with Nitronic 40 collared magnets and a horizontally split yoke. Recent finite element calculation,[13] done since this experiment was designed, suggest that the horizontal yoke-collar interference can be increased somewhat and still maintain a closeed yoke mid-plane under all conditions. This should improve the collar support and allow it to approach that of the Kawasaki steel collar, horizontally split yoke case. Collar and yoke laminations for this improved design have been ordered for several 1 m long, 40 mm aperture models to be built later this year. A similar design will be used for both short and long 50 mm aperture SSC dipoles to be built at Fermilab.

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