STRESS MANAGEMENT IN HIGH-FIELD DIPOLES

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Abstract

The management of Lorentz stress and preload forces is the biggest single challenge in the effort to develop collider dipoles with ever greater field strength. Were the Lorentz forces permitted to accumulate through a coil, they would exceed the limit for strain degradation for the A15 and high-temperature superconductors which are capable of sustaining such field strength.

A strategy has been devised for intercepting Lorentz stress within the coil to overcome this problem in high-field block-coil dipoles. The coil is fabricated in multiple independent shells, in which a high-strength structure and a soft-modulus spring are used to bypass stress between succeeding layers. Finite-element analysis and experimental studies have demonstrated that this strategy can limit the maximum stress anywhere in a coil so that it nowhere exceeds strain degradation limits for fields at least to 20 Tesla.

1 STRESS IN A SUPERCONDUCTING DIPOLE

The field strength and field quality of superconducting dipoles are the primary challenge in extending the energy reach of hadron colliders. The design field of colliders has increased over the past two decades from 4.5 Tesla (4.2°K, Fermilab) to 8.65 Tesla (1.9°K, LHC) for NbTi cos θ dipoles. The state-of-the-art has now reached 11 Tesla (Twente) and 13 Tesla (LBL) for Nb_3Sn cos θ dipoles at 4.2 °K. Today groups at BNL, KEK, LBL, and Texas A&M are developing new approaches to high-field dipoles, aimed at 16 Tesla and beyond. A primary challenge in that effort is stress management.

The Lorentz stress in a coil accumulates through its thickness, with $\vec{\nabla} S_L = \vec{j} \times \vec{B}$, where j is the current density and B the field in the coil. If the coil is supported only at its boundaries, this stress accumulates to at least the stored energy density $S_0 = B^2 / 2\mu_0$ At 16 Tesla, S_0 = 100 MPa, which is the limit for strain degradation of Nb_3Sn even when the coil is vacuum impregnated to provide isostatic support of cable elements. The problem is compounded if we contemplate the use of high-temperature superconducting (HTS) inserts to extend operation beyond 16 Tesla, because the limits for strain damage of HTS is ~40 MPa, less than half that of Nb_3Sn. If this accumulation of stress within the coil were not intercepted, it would not be feasible to operate a dipole to fields greater than about the current 13 Tesla limit.

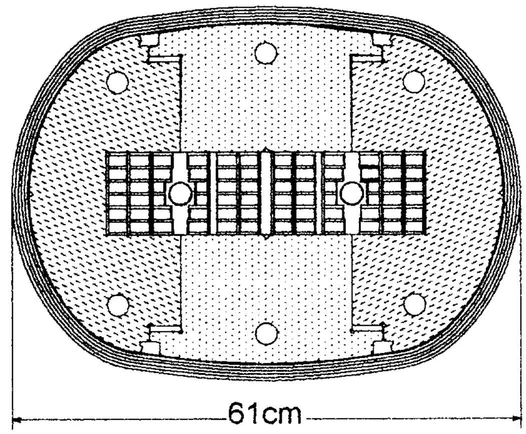


Figure 1. Block-coil dual dipole: 16 Tesla @ 4.2°K.

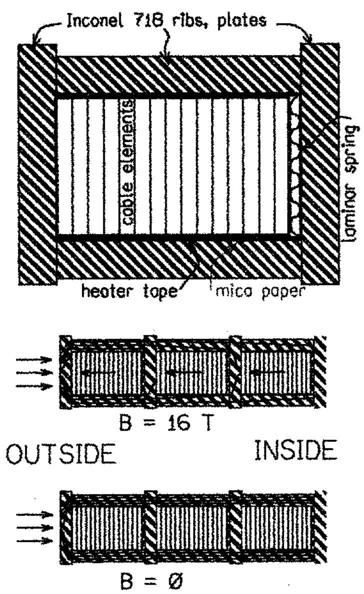


Figure 2. Detail of stress management in a coil block.

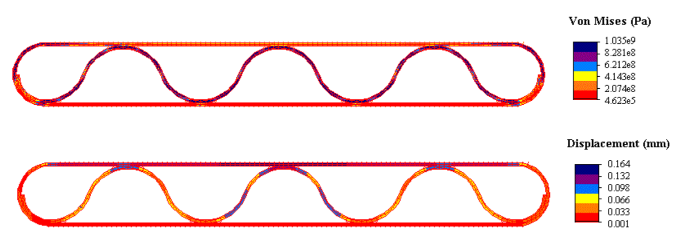


Figure 3. Laminar spring under 15 MPa load: stress and strain distributions.

2 STRESS MANAGEMENT STRATEGY

Figure 1 shows a block-coil dipole in which the coil stress is managed by introducing a structural matrix within the coil. The matrix intercepts the Lorentz stress from the inner coil elements and shunts it past the outer coil elements. No coil element sees more than the Lorentz stress in its own coil layer, ~40 MPa.

In order for this strategy of stress management to be feasible, three important elements must be incorporated into the coil assembly, as shown in the detail of Figure 2: a support matrix which has much greater yield strength than the coil package; a spring element which has much lower elastic modulus than either the coil or the support matrix; and a shear relief layer that releases shear between the sides of the coil and the support matrix when the ribs are compressed. Table I presents the materials used in each of these functional units and their mechanical properties.

One last requirement of the strategy is particularly demanding: *all elements of the coil assembly must be added as the coil is wound; so all elements must survive the reaction bake (650^{o}C for Nb_3Sn, 800^{o}C for HTS) and subsequent epoxy impregnation.* The complete coil assembly then can be fabricated in one operation, passed through reaction bake (when both superconductor and insulation are extremely fragile), and then immediately epoxy impregnated without intermediate disassembly and handling.

1.1. Preload

Preload is delivered by wrapping banding around the magnet structure as shown in Figure 1. The resulting circumferential stress is transformed into a horizontal compression of the two side segments of the flux return structure. In the stress management strategy, the ribs are compressed by this preload, and by the magnetic load when the magnet is energized. A preload of ~1.5 S_0 is required in order to prevent coil motion from the magnetic load. The preload is optimally divided between two strain patterns in the magnet (Figure 1): ~1/3 of the preload compresses the ribs within the coil assembly; the remaining 2/3 compresses the steel flux return assembly. The sharing of preload is controlled by a vertical gap separating the center and side sections of the flux return. Thus we deliver only part of the preload into the coil assembly at room temperature, and hold most of it in reserve in the steel, available as required to counter Lorentz stress.

1.2. Ribs and plates

A pattern of Inconel ribs and plates is integrated into the coil package to provide the path by which stress developed in one block of the coil can bypass the next block. The ribs and plates are able to sustain the concentration of preload and magnetic loading to ~1 GPa. This bypass strategy is complicated by the fact that the rib and the coil block form parallel elements in the stress circuit. The elastic modulus of the impregnated coil is about half that of the ribs, while the span between ribs is ~5 times the rib thickness. In order to decouple the coil package from the strain in the ribs when they are under load, there must also be a soft-modulus element at the inner end of each coil block. We have devised the laminar spring shown in Figure 3 for this purpose.

Table I. Material properties of the coil structure.

element	material	modulus GPa	yield strength MPa
impregnated cables	Nb_3Sn, Cu, epoxy	40	100
ribs, plates	Inconel 718	210	1.300
laminar spring	Inconel X750	210	900
flux return	1008 steel	170	200

1.3. Laminar spring

The springs are constructed of 75 μm thick Inconel X-750 foil, and are laser welded to form a sealed assembly. The spring has an overall thickness of 1.5 mm, a working range of 0.2 mm, and an effective modulus of 100 MPa - 400 times smaller than that of the coil assembly. Thus as a rib is compressed by the magnet stresses, the spring compresses likewise so that the load on each coil block is just its own Lorentz stress (<35 MPa) plus the spring preload (~5 MPa).

A spring is located at the inner boundary of each coil block, and compressed sufficiently to deliver ~5 MPa preload. When the coil is vacuum impregnated with epoxy, the springs are sealed so that they are not impregnated and retain their spring moduli. The springs are later opened at the magnet ends, and provide a second benefit as helium cooling channels throughout the coil.

We have built and tested models of the laminar spring. We cold-formed a 1 mm thick, 2-convolute spring from annealed foil, laser-welded the assembly, then performed a re-annealing and precipitation hardening. The spring was then constrained across its wide dimension and cycled in face-loading on a dynamometer. Figure 4 shows a 10,000 cycle test, in which the spring exhibited some creep but retained most of its spring memory. We have since improved the design to a 1.5 mm thick, 3-convolute spring to reduce peak stress in the foil of the spring and to increase its elastic stroke to 0.2 mm.

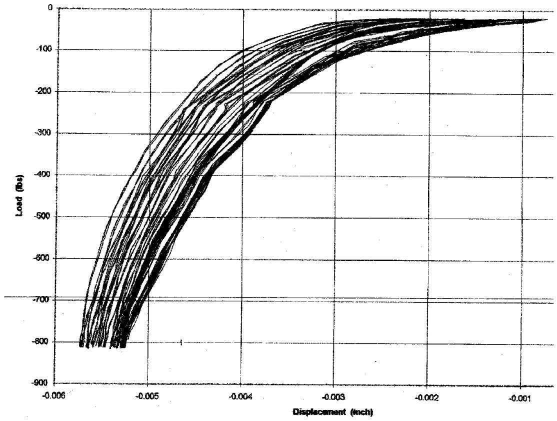


Figure 4. Laminar spring stress/strain: 10,000 cycles.

1.4. Shear relief

As a rib is stressed under preload and Lorentz loading, it strains longitudinally. Even though the spring decouples the linear stress in the adjacent coil block, there would be unrelieved shear at the side interface between coil block and rib. Such shear is a potential source of stick-slip friction as the magnet is energized, which can cause training.

Inspired by the technology developed at MIT for Nb_3Sn solenoid coils, we relieve this shear by inserting a layer of mica paper between the coil block and the rib, as shown in Figure 2. We selected a particular mica paper which does not produce smoke or ash during a reaction bake. We assembled a prototype coil block, and passed it through the processes of reaction bake and epoxy impregnation. We then mounted the block in a 2-axis dynamometer and measured the shear required to release the mica paper to be 4 MPa. This shear would be provided in the first preloading of the completed coil, so that the coil blocks would be released from shear even before the first cooldown.

STRESS DISTRIBUTION

We have implemented the above strategy in an optimized design for a 16 Tesla dual dipole for future hadron colliders, shown in Figure 1. The coil is configured in rectangular block elements which can be wound as pancake coils. The coil is segmented into three current circuits, and the circuits are separately current-programmed to produce collider-quality field (all multipoles $b_n < 10^{-4}$ cm^{-n}) over a 20:1 dynamic range of field strength. Figure 5 shows the field distribution at full field, calculated using the code PE2D.

We used the code ALGOR to calculate the distribution of stress and strain in the magnet, including the effects of preload, differential contraction during cooldown, operation of the laminar springs, and shear relief at the mica paper boundaries. The results are shown in Figure 6 for three cases: preload at room temperature, cooldown to 4.2 ^{o}K, and operation at 16 Tesla.

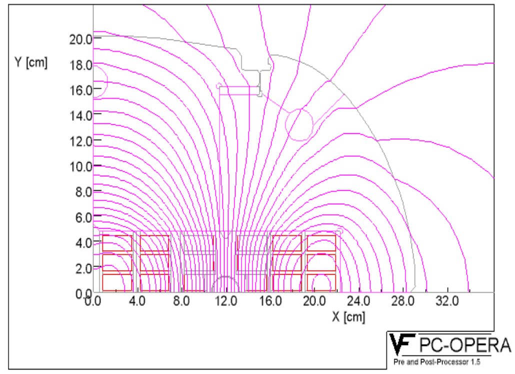
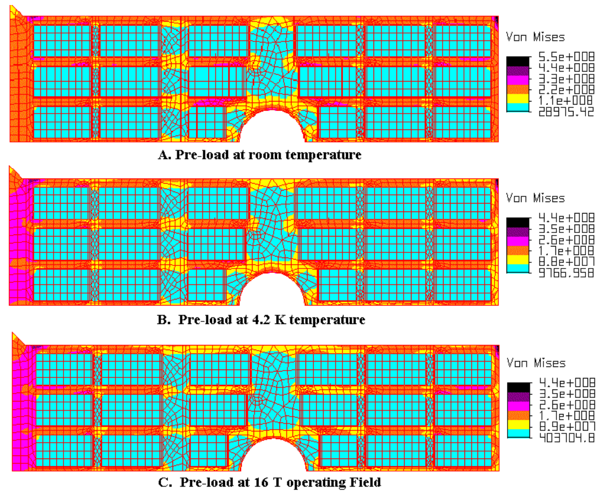


Figure 5. Calculated field distribution in 16 Tesla block-coil dual dipole.



	Pre-load	Temperature	Magnetic Field	Maximum Stress (MPa) Cable	Inconel Alloy
A	65 Mpa	300 K	0	33.8 MPa	290 MPa
B	65 Mpa	4.2 K	0	27.0 MPa	206 MPa
C	65 Mpa	4.2 K	16.0T	33.0 Mpa	220 Mpa

Figure 6. Finite-element calculations of the stress and strain distributions in the 16 Tesla dual dipole.

In no case does the stress in any coil element exceed 40 MPa, the sum of the maximum Lorentz stress in a single block and the spring preload. This stress level would be comfortable for impregnated Nb_3Sn cable, and is even tolerable for HTS conductor. The same strategy could be employed for fields well beyond 16 Tesla, simply by adding additional blocks.

ACKNOWLEDGMENTS

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