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Mechanical Utility Structure for Testing High Field Superconducting Dipole Magnets

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***Abstract*—The U.S. Magnet Development Program (MDP) collaboration is designing a Utility Mechanical Structure (UMS) for testing various high-field superconducting dipole coils. The design uses a shell-based structure concept, which allows applying pre-load in two steps: during a room temperature assembly and during a cool-down to a cryogenic temperature. The structure is designed to accommodate various coil designs - including Nb3Sn Cosine Theta (CT) and Canted Cosine Theta (CCT) magnets as well as hybrid magnets with High Temperature Superconductor (HTS) cables. Superconducting coils, enclosed by bolted pads to form an octagonal coil-pack, will be inserted into a reusable yoke-shell subassembly and precisely pre-loaded during the assembly using a bladder-and-key technology. Due to a differential thermal contraction between an external aluminum shell and the magnet core, the coil pre-load increases during the cool-down up to level required for 17 T excitation. Such a reusable structure will serve as a testing fixture supporting goals of the MDP program, decreasing cost and simplifying coil performance testing at different pre-load levels. We present a finite element analysis of the structure pre-loading various coil designs and examine the predicted coil stress at each step of the magnet assembly and excitation.**

***Index Terms*— dipole magnet, finite element analysis, Nb3Sn, support structure.**

I. Introduction

EXPLORATION of the performance limits of Nb_3Sn accelerator magnets is one of the main goals of the U.S. Magnet Development Program (MDP) that started in June 2016 [1]. The scope of the program includes the investigation of the fundamental aspects of magnet design and technology, with a particular focus on minimizing operating margins, reducing training and supporting future efforts of reaching fields beyond 16 T using hybrid LTS/HTS magnets. Two of the main milestones of the Nb_3Sn part of the program involve a development of a 4-layer 16 T Cos-Theta (CT) magnet and using a stress management approach of the Canted Cosine-Theta (CCT) to build a 2-layer 10 T magnet. The work on a Utility Magnet Structure (UMS) design was initiated to achieve the program goals by providing a versatile coil-testing platform that can:

- accommodate various coil designs with a minimum number of custom parts;
- apply an adjustable and precise pre-load to a coil without causing a performance degradation;
- allow for a magnet to be assembled and disassembled in a rapid and reproducible manner.

At the field level beyond 16 T, Lorentz forces acting on the superconductor produce high stresses in the coil as well as in the magnet structure. Therefore, the mechanical design of a support structure becomes just as critical and challenging as the design of a coil to maintain the stress and the strain in a brittle Nb_3Sn conductor at an acceptable level.

The proposed structure uses a shell-based method of pre-loading the magnet coils, which was developed at LBNL for the high field dipole program [2]. It uses an aluminum cylinder surrounding a magnet yoke and coil-pack. Water-pressurized bladders and load-keys are placed between the structure internal components and are used to pre-tension the cylinder and, at the same time, compress the magnet coils. While this type of structure was initially developed and tested for a racetrack and a block-coil dipole magnets [3], it was successfully adapted to quadrupole magnets by LARP [4] and to sextupoles in ECR ion source magnets [5]. Presently, it is being adapted to cos-theta accelerator dipole magnets [6].

The initial design of the UMS (see Fig. 1) is made compatible with a coil of a single-aperture, 15 T Nb_3Sn dipole demon-

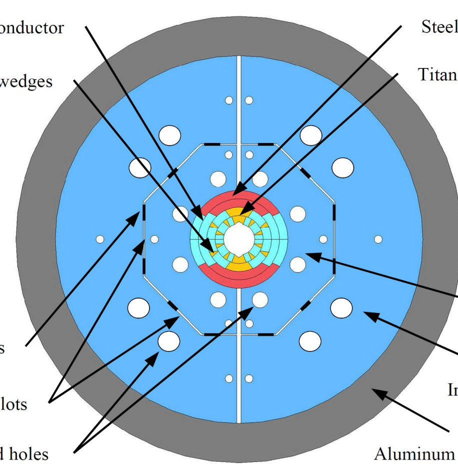

Fig. 1. Cross-section of the Utility Structure with Nb_3Sn 4-layer cos-theta coil.

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strator [7] developed within the MDP program. This 60 mm aperture coil is using a graded 4-layer cos-theta design. At the field level of 15 T, magnetic forces acting on the conductor in one quadrant of the coil will be in the order of 6.35 MN/m in the horizontal direction and -3.65 MN/m in the vertical direction. Dimensions of the Utility Structure were chosen so that it can provide up to 12 MN/m pre-load in the horizontal direction to a quadrant of the coil with a maximum outer diameter of 260 mm. This design provides sufficient margins for preloading up to 6-layer CT, CCT or hybrid coils at the field level up to 17 T.

II. Support Structure Components and Pre-load Operation

The main components of the structure are shown in Fig. 2. In this particular design variant, the structure is shown with abovementioned 15 T dipole demonstrator coil. The coils are surrounded by an arrangement of bolted iron pads that form a coil-pack. In the current design, external dimension of the coil pack of 320 mm provides a sufficient space for a 6-layer coil design. The coil-pack has an octagonal shape with keys and bladders slots for the magnet assembly and pre-load procedure. The holes in iron pads are available for axial rods insertion for 4-layer coils, while for bigger coils, an alternative set of axial rod holes are available in the magnet yokes.

The iron yokes are inserted in an aluminum cylinder having an outside diameter of 750 mm and a wall thickness of 75 mm. The vertical gap between yokes are used to support bladders and temporary yoke keys during the yoke-shell sub-assembly construction. Slots at the interface between pads and yokes are used for supporting keys and bladders during assembly and preloading operations. Three types of load-keys are installed between the yoke and the octagonal coil-pack:

- horizontal keys – providing majority of the pre-load;
- diagonal keys – used for pre-load adjustment and increasing the structure rigidity;

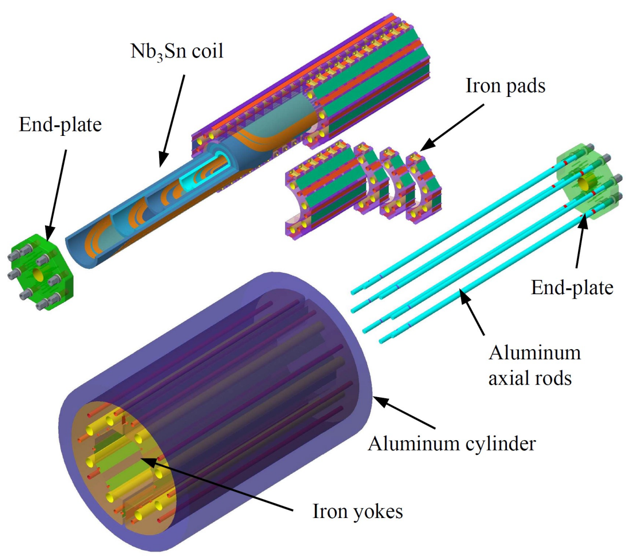

Fig. 2. Exploded view of the Utility Structure with Nb_3Sn 4-layer cos-theta coil.

- vertical keys – used mainly coil-pack centering.

The vertical gaps between yokes and yoke-locking keys could also be used for CCT type coils to limit coil deformation during the cool-down and minimize the stress level in the coil mandrel.

An arrangement of aluminum axial rods pre-tensioned against two stainless steel end-plates is used to apply the axial pre-load to the magnet coil-ends. Depending on the outer diameter of a multilayer coil, aluminum rods can be installed either in the coil-pack or in the yoke holes.

In this type of structure, the applied pre-load level is closely monitored during the assembly and magnet operation with the use of strain gauges, which are attached to the pole-island of each coil, axial rods and the aluminum shell. During the assembly, water pressurized bladders compress the coil and pretension the shell. The shimmed load-keys are installed in gaps between pads and yoke, and keep the coil compressed after bladders are deflated. Axial rods are pre-tensioned using a hydraulic piston system. The assembly is fully reversible and pre-load level can be adjusted without removing the coils from the structure. For bigger coils that require axial rods to be inserted in the yoke, the axial pre-load system will have to be removed before adjusting the azimuthal pre-load. Room temperature pre-load targets are determined from results of the finite element analysis so that the nominal pre-load is reached at cryogenic temperature due to a high thermal contraction of the aluminum cylinder.

III. Mechanical Analysis

A. *Initial Results with Various Coil Types*

The initial study of the UMS pre-load capability was performed using three different coil types:

- 4-layer cos-theta coil designed for the 15 T dipole demonstrator;
- conceptual 4-layer graded CCT coil designed for 17 T field level;
- conceptual 6-layer CT-CCT hybrid coil designed for 18 T field level.

The same model of the yoke-shell assembly was used in the analyses, while the pads' inner diameters was adjusted appropriately for different coil dimensions. Thickness of pre-load key shims were adjusted individually for each case.

The main objective of the pre-load shim optimization was to

TABLE I
Material Types and Stress Limits Assumed in Analysis

Material	Stress limit (MPa) at RT / CD[a]
Coil (Nb_3Sn)	100 / 200[b]
Steel (316LN)	350 / 1050
Aluminum (7075)	480 / 690
Iron (ARMCO®)	230 / 720
Titanium (Ti6Al4V)	800 / 1650

[a]RT – room temperature; CD – cool-down (1.9 K)
[b]Stress limits assumed to prevent superconductor degradation

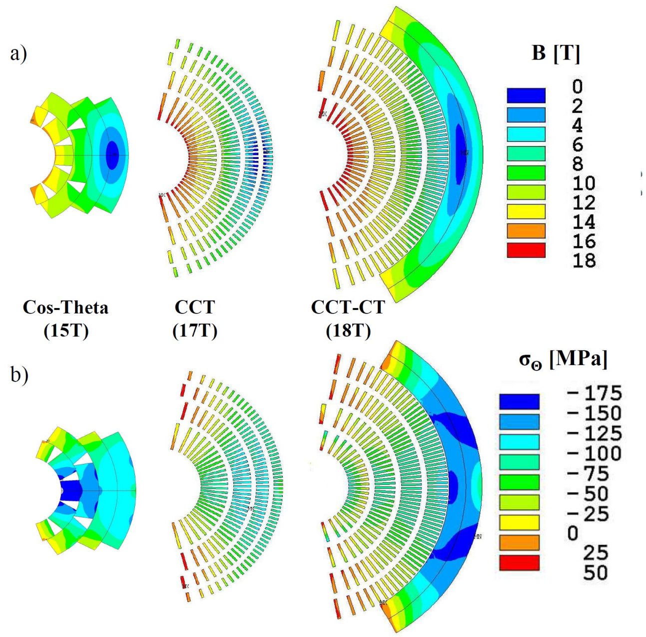

Fig. 3. Distribution of a) magnetic field in the conductor and a corresponding b) azimuthal stress due to magnetic forces for a Cos-Theta coil (left) at the 15 T field level, a conceptual CCT coil (center) at 17 T field and a hybrid CCT-CT coil (right) at 18 T field.

limit the coil maximum stress to 100 MPa at the room temperature and to 200 MPa at the cryogenic temperature. The stress criteria for the superconductor as well as the stress limits of materials used in the support structure are summarized in Table I. In the cos-theta coil design, it is critical to prevent the coil from separating from the pole. Therefore, the azimuthal pre-load was adjusted to keep pole-turns under compression. In case of canted cos-theta coils, it is critical to maintain the mid-plane region of the coil under azimuthal compression while the pole region is naturally under azimuthal tension.

Only the room temperature pre-load level can be adjusted, while increase of pre-load during the cool-down depends only on the geometry of the structure and differential thermal contraction of its components. Distribution of the magnetic field and azimuthal stress distribution when magnetic forces are applied is shown in Fig. 3. Maximum stress levels obtained for each coil type after pre-load key optimization is summarized in Table II.

As the cos-theta coil design lacks an internal support, the pre-load key shims were chosen so that the conductor stress was below 50 MPa during the magnet assembly. The stress level after the cool-down and at the 15 T excitation, was in the range of 190-200 MPa. The results of the analysis indicate that

TABLE II
MAXIMUM STRESS IN THE SUPERCONDUCTOR OF DIFFERENT COIL TYPES PRE-LOADED WITH THE UTILITY MAGNET STRUCTURE

Coil	Magnetic field	Maximum stress (MPa) at RT / CD / MF[a]
CT	15 T	50 / 200 / 190
CCT	17 T	60 / 200 / 160
CCT-CT	18 T	100 / 200 / 170

[a]RT – room temperature; CD – cool-down; MF – magnetic forces

main difficulty in sufficiently pre-loading a multi-layer coil will be distributing the applied force between layers. Features of the cos-theta coil that were modeled in order to optimize the force distribution will be discussed in the next section.

The other two conceptual coils that were analyzed were based on a CCT coil type. By design, their internal structure intercepts the azimuthal force acting on the conductor due to the magnetic field. The external UMS intercepts the radial force and prevents the coil from developing an azimuthal tension in the mid-plane region. For a CCT coil at 17 T and a CCT-CT coil at 18 T, the maximum stress after the room temperature assembly was below 60 and 100 MPa, respectively. After the cool-down the maximum stress for both coils was below 200 MPa and when magnetic forces were applied, the stress in the CCT was below 160 MPa and in the CCT-CT below 170 MPa. Future study of pre-loading a CCT type coil in the UMS will be focused towards controlling the deformation on the coil during cool-down and minimizing the stress in the coil mandrel by closing the vertical gaps between the iron yokes.

B. *Detailed Analysis of the 15 T Cos-Theta Coil Pre-Load*

A 3D finite-element model of the UMS was developed in order to analyze a distribution of the pre-load applied along the length of the coil and to its ends. The geometry of the 15 T dipole demonstrator coil was used for the analysis. In order to balance the amount of pre-load distributed between the coil layers and minimize the stress level, the following coil features, showed in Fig. 4, were implemented in the numerical model:

- layer 1&2 poles made of titanium, which has lower thermal contraction than steel used in layer 3&4 poles;
- titanium wedges and coil-end spacers;
- stress relieve notch in the inner radius face of the layer 1 pole.

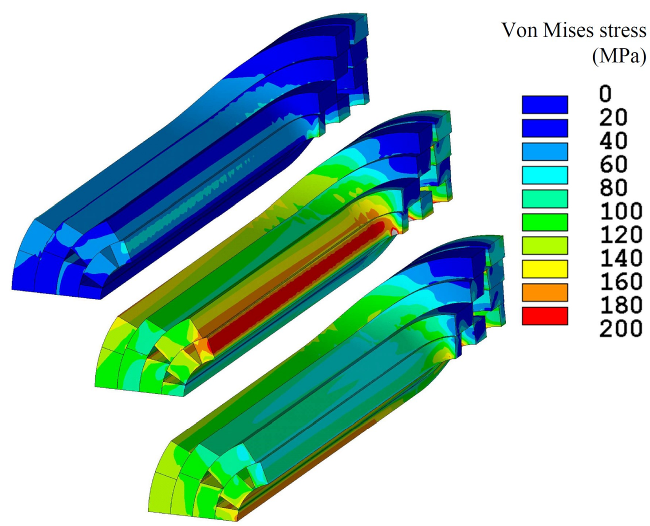

Fig. 5. Von Mises stress in the coil after the room temperature preload (top), after the cool-down (middle) and with magnetic forces at 15 T excitation are applied (bottom).

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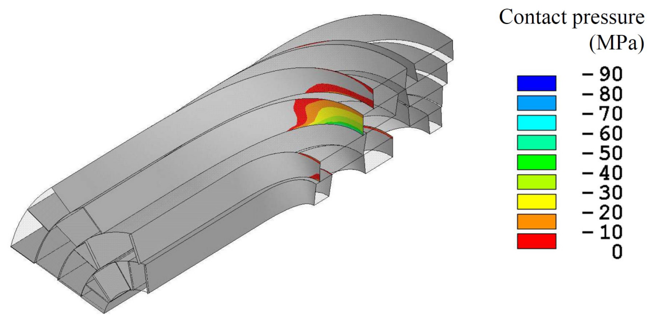

Fig. 6. Contact pressure between the superconductor and coil components when magnetic forces are applied. Negative values represent tension. Gray surfaces show interfaces under compression.

Fig. 5 shows the stress levels in the coil for the three computation steps: after a room temperature pre-load was applied, after the cool-down to the cryogenic temperature and with the magnetic forces applied to the conductor at the 15 T excitation. The thickness of the load-key shims was optimized for Lorentz forces at this field level in order to meet the superconductor maximum stress criteria.

Fig. 6 shows the contact pressure between the conductor and other components of the coil. The presented interfaces were modeled as fully bonded to identify areas of the coil with insufficient pre-load, where tension might cause the epoxy to de-bond. The pole-turn remained in compression along the straight section of the coil (gray interfaces), while tensile contact pressure (negative values) developed at the return-end of layers 3 and 4 with their poles made of stainless steel. At this level of tension, pole-turns of the outer coil layers will separate from the pole, which might limit the performance of the coil. Increasing the axial pre-load or decoupling the application of the pre-load between inner and outer layers might not eliminate this issue due to friction between the magnet components. An alternative coil design with additional end-spacers in the outer layers will be investigated to minimize the tension at the pole-turn interface.

The maximum stress in the aluminum cylinder was below 140 MPa at room temperature and below 210 MPa after cool-down and with magnetic forces. The stress in the iron pads and yokes was below 150 MPa at the room temperature and below 260 MPa at the other two steps.

Even though the magnetic forces applied to the coil analyzed with a 2D and a 3D model were calculated at the same

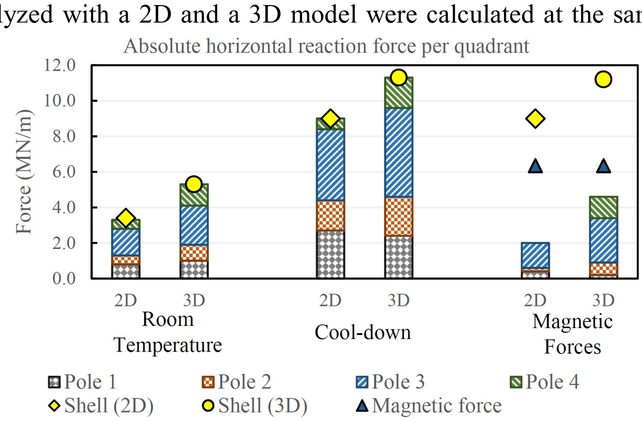

Fig. 7. Comparison of the horizontal reaction force per magnet quadrant necessary to pre-load the coil and maintain its pole-turn under compression.

field level of 15 T, the pre-load applied to the 3D model was higher. The horizontal reaction force on the vertical symmetry plane of the magnet components and the magnetic force acting on the coil quadrant are shown in Fig. 7. At the field level of 15 T, the horizontal magnetic force per coil quadrant is 6.35 MN/m. In order to sufficiently pre-load the inner two layers of the coil in the 2D model, an overshoot of the applied force of 2.6 MN/m was required due to the force was being intercepted by the outer two layers. In the 3D calculation, an excess of force of 4.8 MN/m was required to keep the inner layer pole-turns under compression. The excess of the force was intercepted by layer 4 and increased its azimuthal stress to 200 MPa. Using titanium for the poles of layer 1 and 2 is one of the reasons why the excess force was higher in the 3D analysis. The lower thermal contraction of the titanium pole pieces allowed an increase of azimuthal compression in the conductor. At the same time, since the conductor is epoxy impregnated to the pole, it was being tensioned axially due to a high differential thermal contraction between these two materials. In order to minimize the excess of force required to keep the inner layers of the coil under compression, it will be necessary to provide other means of balancing the force distribution between the coil layers.

IV. Conclusion

In this paper, we have presented a preliminary design of the new Mechanical Utility Structure, which will serve as a versatile coil-testing platform for the U.S. Magnet Development Program. Results of the numerical analysis show that the structure is capable of pre-loading various coil types with the superconductor stress level within assumed criteria.

Detailed analysis of the structure pre-loading the 15 T dipole demonstrator coil showed the necessity of implementing coil features for distributing the applied forces throughout the coil layers. Even though materials with different thermal contractions were used in the poles of different layers to improve the force distribution, a significant overshoot of applied pre-load was necessary in order to keep the pole-turn of the inner layer under compression.

Further studies will be performed to minimize the required pre-load overshoot by implementing additional assembly features such as coil mid-plane shims. Furthermore, a study of the maximum and minimum fabrication tolerances impact on the structure pre-load capabilities is planned.

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