A CONCEPT FOR A HIGH-FIELD HELICAL SOLENOID

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Abstract

Helical cooling channels have been proposed for highly efficient 6D muon cooling to produce the required helical solenoidal, dipole, and gradient field components. The channel is divided into sections, each subsequent section with higher field. Simulations have shown that for the high-field sections the use of Nb3Sn superconductor is needed. A continuous winding method and novel stainless steel collaring system has been developed for use in the high field section of a helical cooling channel. Each collar layer is identical, for ease of fabrication, and assembled by both flipping and rotating the subsequent layers. Mechanical and magnetic simulations were performed using a combination of ANSYS and OPERA. The winding and collaring method has been demonstrated on a three coil prototype using a Nb_3Sn Rutherford cable. Details of the mechanical design and winding method are presented.

INTRODUCTION

Helical cooling channels (HCC) based on a magnet system with a pressurized gas absorber in the aperture have been proposed as a highly efficient way to achieve 6D muon beam cooling [1-2]. The magnet system superimposes solenoid (*Bs*), helical dipole (*Bt*), and helical gradient (*G*) fields. The cooling channel was divided into several sections to provide the total phase space reduction of muon beams on the level of 10^5-10^6, and to reduce the equilibrium emittance each consequent section has a smaller aperture and stronger magnetic fields. The field components (*Bt* and *G*) are a function of many geometric parameters as it was presented in [3-6].

The Helical Solenoids (HS) are formed by transverse displacements of short solenoid rings following a helix. Due to this unusual geometry, large transverse forces are generated. In order to intercept the forces a support structure must be designed accordingly. HS prototypes based on NbTi super-conductor were developed and are presented in [7-8]. HS models based on YBCO tape are presented in [9]. These materials do not need a reaction cycle, therefore the winding and impregnation are straight forward.

Nb_3Sn is required for the medium field sections of the HCC. That material requires a reaction cycle to the temperature of 650°C, which restricts the material choices for the support dramatically. In particular the outer support should allow for expansion during the reaction at the same time it should pre-stress the coil during the cool-down. A collar approach allows different materials to be used in each stage of the coil manufacturing and coil operation.

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MECHANICAL DESIGN

Nb_3Sn presents a more difficult path to finished product than either NbTi or HTS Tapes as it requires a reaction cycle to ~650°C before use. This is typically implemented in a wind and react configuration in which magnet coils are wound onto a temporary fixture and undergo a reaction cycle in an inert atmosphere. After the reaction cycle, the superconductor becomes extremely brittle and strain intolerant. Coils are typically transferred into an impregnation fixture then impregnated with epoxy, setting the final size of the coil. After impregnation, it is traditionally possible to assemble coils into the final magnet configuration.

As the concept for the helical solenoid as presented is for a long array of multilayer coils, the magnet assembly would ideally be splice-less, leading to a stepped structure that becomes impractical to remove the winding mandrel after winding. For this reason, the inner mandrel of the coil is integrated into the structure and must be able to withstand the reaction cycle with no ill-effects. As the superconductor is not tolerant of strain, the differential thermal expansion of the superconductor during reaction should be well matched to the inner support. For this reason, 316L Stainless Steel has been chosen as the material of the winding mandrel which is also the reaction fixture.

The Collaring Concept

A similar difficulty appears during coil winding in that while hoops may be installed after each layer of coil winding, they must be sufficient to support the hoop and shear forces generated during operation. Using a series of bolt on half structures was rejected due to the complex nature of the helical shape of the coil and the level of forces involved.

A novel mechanical structure has been developed to provide coil alignment and support along both the base helix of the solenoid system and the center axis of the helix. A collared lamination system with locking load keys has been explored to enable the fabrication of a continuously wound helical magnet while maintaining the ability to expand the helical solenoid indefinitely. The collared structure also allows for a temporary support structure to be used during reaction. The basis of the

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structure laminations is similar to the structure used in a collared coil in a traditional high field Nb_3Sn or NbTi accelerator magnet with alternating layers flipped to have an overlapping leg on each side. In order to provide the required rotational clocking between additional solenoid rings, the helix period has to be broken up into a discrete number of steps, totalling a full rotation. For this exercise, the rotational clocking between adjacent solenoid coils was set to 10°, leading to a cross section with base features occurring 36 times each lamination as shown in Figure 1. In addition to the collar keys, a number of axial through holes allow the application of ~200,000lbf of axial preload to prevent motion between laminations.

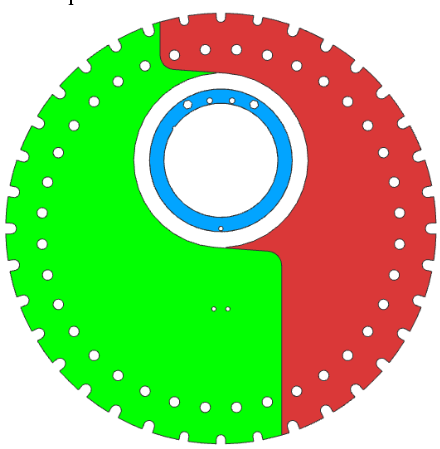

Figure 1: Lamination cross section.

The winding mandrel is also based on the same cross section and provides alignment through a full length pin along the helix axis, as well as proper clocking from layer to layer with captive alignment features. If additional rigidity is required, the center mandrel could be welded together with no effect on fabrication. Between structure laminations, a thin winding flange is used to isolate adjacent coils from each other and better define coil geometry. The flange also contains slots to allow smooth layer to layer transitions. These transitions are located at the tangent point of consecutive rings. The winding flange uses a similar configuration to the collar laminations for ease of assembly.

Mechanical Analysis

Magnetic and Mechanical analysis of the structure were completed to show pre-stress during cool-down and with coils energized. Results showing coil loading, and deformation during cool-down and energization are shown in Figure 2. Using Stainless steel collars, pre-stress was observed to be ~3000psi. When energized, the coil remains in compression on average (due to the hoop stress), but does exhibit some tension from out of plane bending. Out of plane bending is more severe on the end coils and can be reduced by a slight structure modification. Interlayer shear forces on a 4-coil model were found to have a magnitude of ~20,000 lbf, well within the capabilities of the structure.

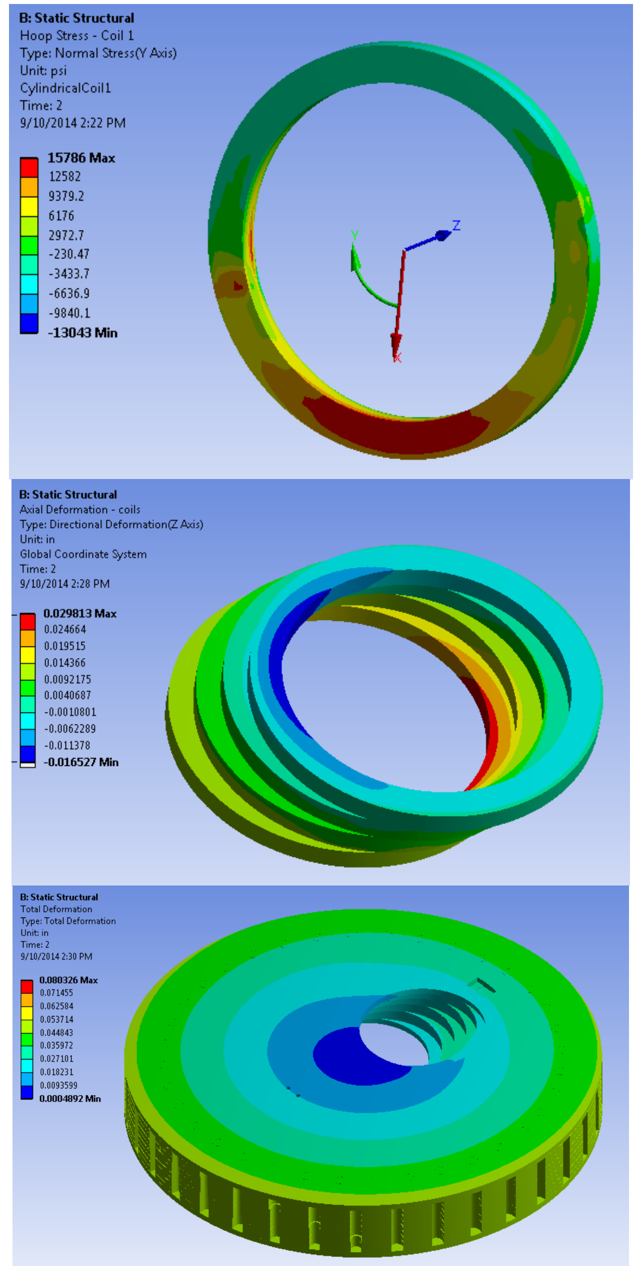

Figure 2: Coil Hoop stress while energized (top). Coil deformation while energized (middle). Coil and structure deformation on cool-down and energization (bottom).

MODEL COIL

In order to validate the collaring methodology, a model coil using acrylic parts was constructed implementing the major design features for this concept. The plastic parts were used because of the low cost and rapid fabrication. Both top and bottom plates, as well as collar laminations and winding flange were laser cut from acrylic sheet. The laser cut components allowed tight tolerances to be held on design features to faithfully represent the assembly characteristics of a stainless steel or aluminium structure.

A copper practice cable was used that had the same nominal dimensions as the Nb_3Sn cable including fiberglass insulation. The model was constructed to have 3 coils with two layers of conductor.

Winding began by setting the cable end into the splice block, then winding 10 turns (hard-way) onto the first step of the mandrel. To keep cable from flipping to easy way bend during the winding operation, spacer blocks were used to push the cable to the winding flanges.

After completing the first layer of the first coil, the second and third coils were wound (also only the first layer) as shown in Figure 3. The first layer of the third coil contains 9.5 turns as half turn is occupied by the layer jump transitions. After completing the layer jump, the second layer was wound on top of the first layer.

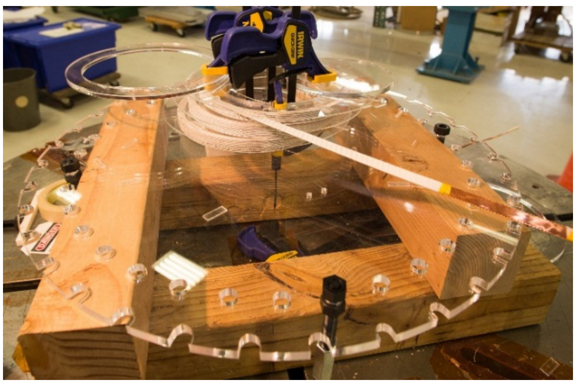

Figure 3: Winding of layer 1.

During winding of the last 10 turns, the conductor became too unstable to keep in the hard way orientation and rolled over; leading to only 8 turns in the last coil.

After winding was complete, collars were installed from return to lead end, installing pins and keys as required as shown in Figure 4. The completed model structure is shown in Figure 5.

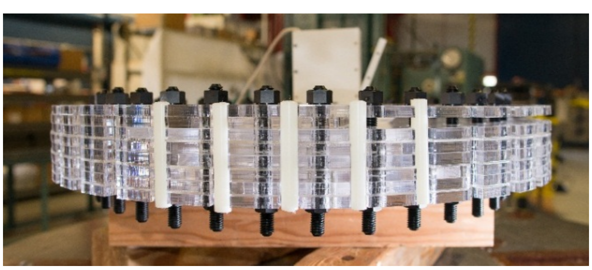

Figure 4: Detail of key and axial rod configuration.

SUMMARY

A novel structure for helical solenoids that uses Nb_3Sn has been designed. FEM analysis using ANSYS shows that the level of stresses during operation are within the allowable stress of stainless steel 316L.

A model coil has been built using dummy cable as well as plastic parts in order to test its practical feasibility. The collared coil assembly shows promise, however some issues still need to be addressed. In particular, winding a coil of this geometry is not practical using a wide aspect ratio cable in a hard-way bend configuration. However, the same concept allows for easy-way bend.

Figure 5: Completed practice winding showing axial studs and keys.

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