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The Structural Design for a "Canted Cosine–Theta" Superconducting Dipole Coil and Magnet Structure—CCT1

Aurelio Hafalia, Shlomo Caspi, Helene Felice, Lucas Brouwer, Soren Prestemon, and Arno Godeke

***Abstract*—The Superconducting Magnet Group, at Lawrence Berkeley National Laboratory (LBNL), has been developing a canted cosine–theta (CCT) superconducting dipole coil as well as the coil's supporting magnet structure. This contribution reports on the progress in the development of the coil's winding mandrel and its fabrication options. A comprehensive study of the coil's Lorentz forces was performed to validate the winding mandrel's "stress interception" attributes. The design of the external structure and the application of the "Bladder & Key" technology is also discussed. Additionally, the application of these studies to a curved ion-therapy CCT dipole magnet is reported.**

***Index Terms*—Bladder & key, canted cosine–theta (CCT), dipole, superconducting.**

I. Introduction

IN ORDER to explore the CCT concept presented in [1], the Superconducting Magnet Group at LBNL is developing the CCT1 Dipole Magnet—a first prototype magnet using NbTi superconductor cable.

Conventional cosine–theta coils, wound with key stoned Rutherford cable, is composed of several solid parts—the island/pole, end shoes, and, when required, end spacers & wedges. These components define the placement of the cable turns but may move during excitation—causing quenches. The CCT design requires only a solid winding mandrel which constrains each cable turn. Relative movement is reduced (Fig. 1).

The CCT1 coils, (Fig. 2), are being wound with NbTi rectangular, Rutherford cable made from eight 0.648 mm diameter SSC strands. The bare cable measures 2.718 mm wide-by-1.067 mm thick, with zero keystone angle. The cable was insulated with braided-on S-Glass.

II. "Rib & Spar" Concept

Each conductor turn is supported in its own, individual, channel-machined into a thick-wall, cylindrical aluminum mandrel. The Lorentz forces in a single turn are diagrammed in Fig. 3.

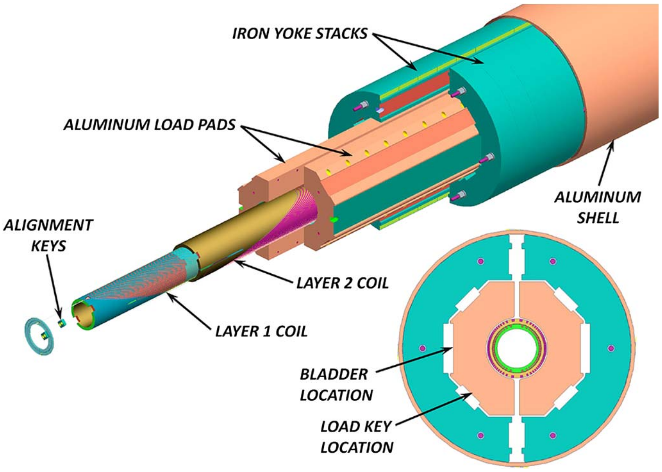

Fig. 1. CCT1 magnet structure, exploded view.

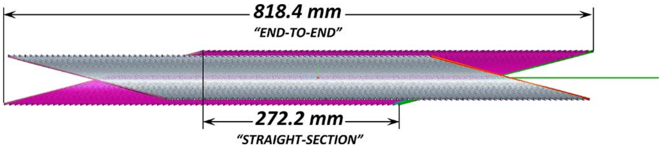

Fig. 2. CCT1 side-section view, coils only.

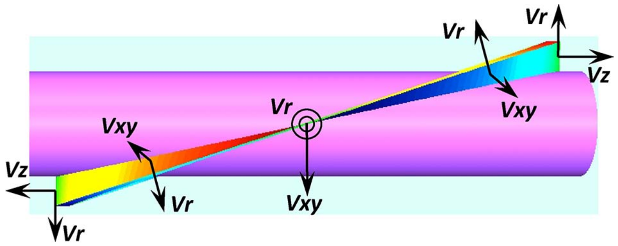

Fig. 3. Force vectors in a single turn. Vr = Radial forces; Vz = Axial longitudinal Forces; Vxy = Side Forces normal to the conductor sides.

Separating each turn are the channel side-walls—the "ribs". These ribs are part of a central mandrel tube—the "spar". The transfer of forces to the mandrel tube can be compared to the way aerodynamic forces are distributed onto an airplane wing structure. Forces are carried from the wing skin (conductor cable) to the wing ribs (channel walls), which are directly attached to the main wing spar (central mandrel tube) (Fig. 4). The ribs are thicker at the pole regions and will adequately transfer the forces to the spar (Fig. 5). These forces were verified by ANSYS structural analyses after mapping and overlaying the computed Lorentz force matrices from TOSCA simulations [2], [5].

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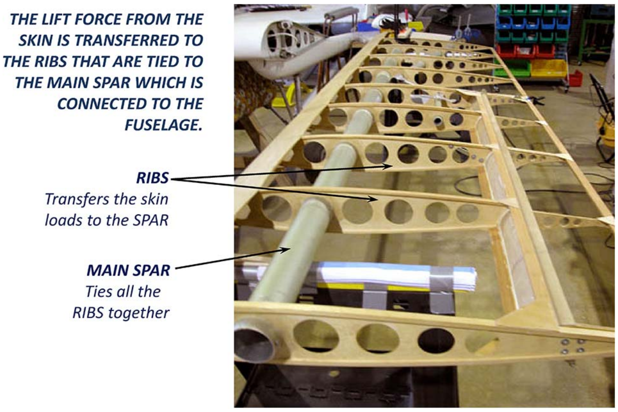

Fig. 4. Aircraft wing structure example.

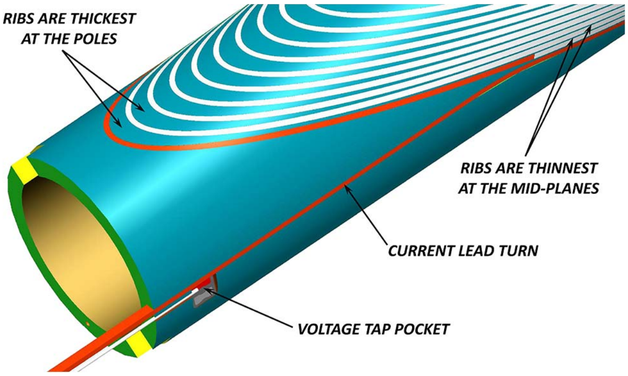

Fig. 5. Rib and voltage tap features.

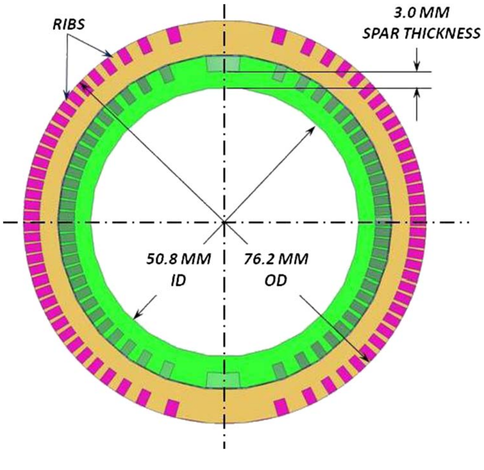

Fig. 6. Cross section of the CCT1 coil. Showing ribs and spar.

The longitudinal forces from each turn are transferred to and accumulated in the mandrel spar. The CCT1 mandrel spars are 3.0 mm thick—for both layers 1 and 2 (Fig. 6). The larger, longitudinal force vectors are along the top and bottom poles, and in opposite directions—shown as "Vz" in Fig. 3. Since both the layer 1 and layer 2 coils will be impregnated together, ANSYS structural simulations were run with all the components "glued" [5].

The majority of the radial forces are constrained by the external structure of the yoke/shell subassembly [1], [6]. Part of the layer 1 radial component of the Lorentz forces are intercepted by the layer 2 spar/mandrel. The layer 2 radial force components are constrained by the external structure.

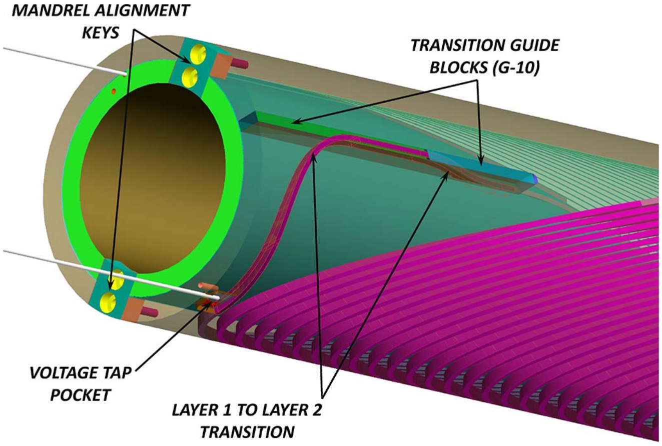

Fig. 7. Layer 1 to Layer 2 transition and G11 support blocks.

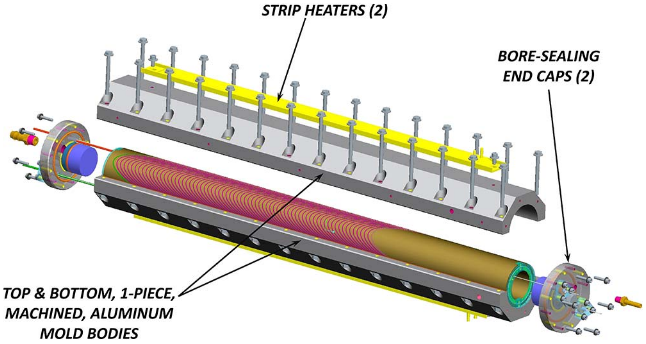

Fig. 8. CCT1 coil potting fixture (conceptual).

III. BASIC COIL ASSEMBLY

The basic CCT1 coil assembly consists of two layers of single, continuous NbTi cable around a precision-machined, cylindrical, aluminum mandrel. The layer 1 mandrel has an ID (clear-bore) of 50.8 mm, an OD of 62.99 mm and is 841.13 mm long. The mandrel is machined for 78 conductor turns. At the mid-planes, of both mandrels, the ribs are nominally 0.38 mm thick. (Figs. 5 and 6).

The layer 2 mandrel has a 63.5 mm ID, a 76.2 mm OD and is also 841.13 mm long. Layer 2 has 72 conductor turns. The layer-to-layer, hard-way bend transition will be supported and guided by machined NEMA G-11 guide blocks. These transition guide blocks will be inserted into a retaining slot machined into the return end of the layer 2 mandrel (Fig. 7).

The length of the coils and the magnet structure were determined by the depth capability of LBNL's Magnet Test Facility's test cryostat.

Between the mandrels, there is a 0.25 mm–0.38 mm, radial, inter-layer gap. for a 1.27 mm-thick fiberglass-tape insulation wrap. Clearance is also provided in the gap to allow the layer 2 mandrel to be slid over the wound and insulation-wrapped layer 1 mandrel.

The mandrels are keyed together, at both ends, with NEMA G-11 keys which prevent relative movement between the mandrels (Fig. 7).

After the coil assembly has been wound, it will be vacuum, epoxy-impregnated in a specially designed potting fixture (Fig. 8).

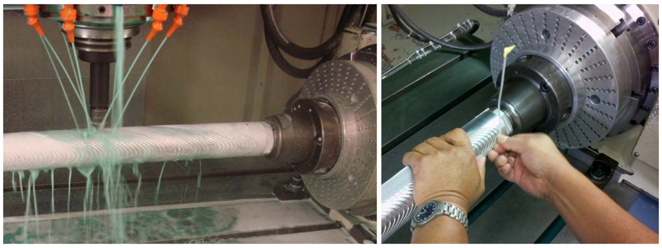

Fig. 9. Layer 1 mandrel machining in-process (left); conductor test-fit (right).

Note that there is no quench protection requirement for this coil. However, voltage tap provisions are designed into each mandrels' return end (monitoring the last turn) (Fig. 7) and at the lead end (along the groove guiding the current-leads) (Fig. 5).

IV. MANDREL FABRICATION

A. CCT1 One-Piece Mandrel

Both the 841.13 mm-long CCT1 mandrels were machined from one-piece aluminum tubes. The machine setup turned out to be straight-forward. Since the broad side of the Rutherford cable cross-section was designed to be normal to the centerline of the coil bore, the cutting tool's axis had to be stationary, pointing at the bore axis. Therefore, the cutting tool axis was always normal to the tube's cylindrical surface as the mandrel simultaneously rotated (around the bore axis) and translated longitudinally [Fig. 9(a)].

The voltage tap pocket features and grooves (two per coil layer) were machined in the same machine-tool setup used for the helical, conductor grooves. The layer 1 mandrel took about 18 hours to machine. The cut-depth was set to 0.13 mm for each pass of the 1.60 mm diameter ball-end mill. The finish groove depth was 3.380 mm—for both layer 1 and 2 mandrels.

Upon completion of the Layer 1 mandrel, a test-fit of a length of insulated cable was performed in the finished-machined grooves. The depth and width of the grooves were deemed satisfactory [Fig. 9(b)].

Machining the second layer mandrel took a little over 10 hours because the depth-of-cut per pass was doubled—to 0.254 mm.

B. Laminations—An Alternate Assembly Method

An alternate method of mandrel fabrication was also considered, especially for a longitudinal scale-up. Identical segments of the mandrel can be machined and stacked together. This "lamination" method of assembly was demonstrated in a CCT Curved Dipole designed for a carbon therapy gantry system [4]. The thickness of each lamination is precisely the length of an axial period of a turn. For longer sections of mandrel, the lengths must be in exact multiples of a turn period. For the CCT Curved Dipole, the laminations' end-planes are at a wedge-angle. For the straight-bored CCT1, the laminations' end-planes are parallel. When identical laminations are stacked, the grooves align to form a continuous groove for the conductor to lay in (Fig. 10).

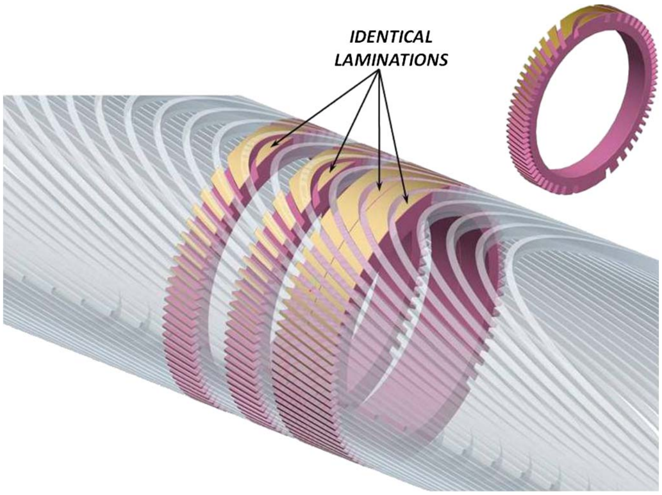

Fig. 10. Example, lamination stack-up.

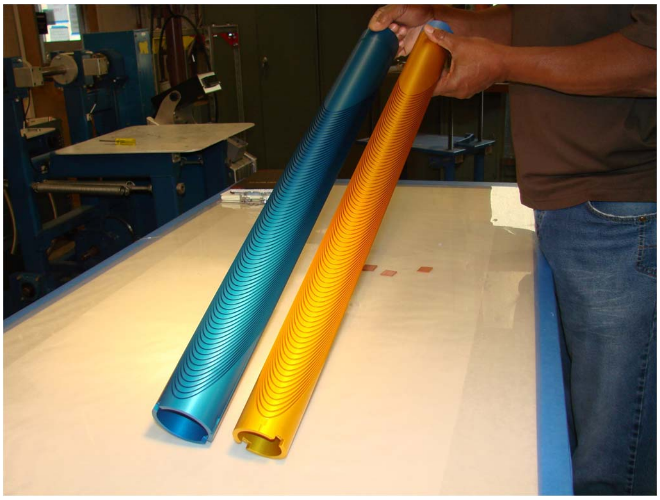

Fig. 11. Finished CCT1 coil winding mandrels.

V. WINDING THE COILS

A. Finished Mandrels

Both finish-machined mandrels were cleaned and anodized (the Layer 1 mandrel was gold-anodized and the layer 2 mandrel was blue-anodized) (Fig. 11). The anodized finish provides an additional 300–500 volt electrical stand-off between the conductor and mandrel.

B. Coil Winding

For the winding process, the layer 1 mandrel is inserted over a special spindle and set-up, horizontally, on a winding table that rotates around a vertical axis. The spindle/mandrel assembly will be driven to rotate 360-degrees around its horizontal axis. As the mandrel rotates, the table will swing so that the tensioned cable can be guided into the machined groove in the mandrel. As the mandrel continues to rotate and the cable reaches the opposite pole, the table must reverse and swing 180-degrees the other way (Fig. 12).

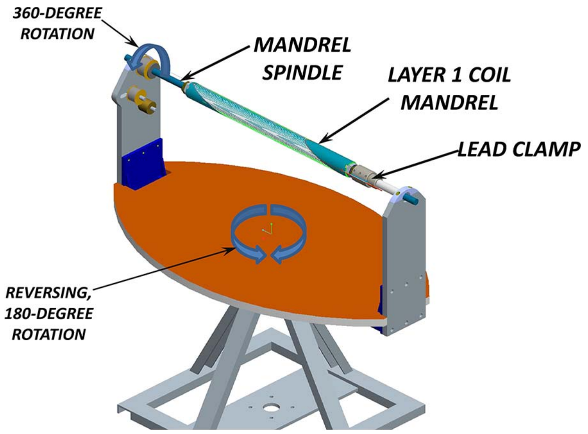

Fig. 12. Winding cable onto the CCT1 mandrel.

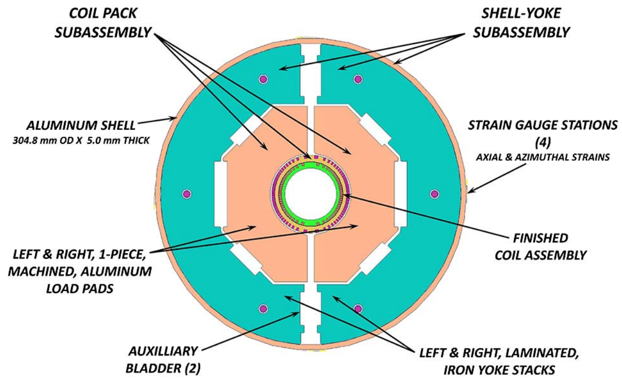

Fig. 13. CCT1 magnet structure cross-section.

VI. External Structure

A. Support Structure Components

The coil-pack subassembly is made up of two “load pad” halves bolted around the impregnated coils (Figs. 1 and 13). For the CCT1, each load pad half is made of a one-piece, aluminum, precision-machined plate.

The load pad profiles include keyways that place and guide the preload bladders and load keys to pre-compress the coil assembly (Fig. 1 and 13). The bladders and keys are oriented in such a way so that the outer subassembly structure can uniformly compress the coil assembly.

The outer structural subassembly is composed of iron yokes and an aluminum shell. The yokes are comprised of flat, semi-circular, yoke laminations (each 50.8 mm thick), stacked and tied together to form full-length halves that fit inside the cylindrical shell. Each yoke lamination is aligned to the next lamination with 3 sets of precision-machined bushings. Tie-rods are inserted through the bushings. Each lamination stack is compressed by a special hydraulic fixture, pulling on the tie-rods while compressing the stack. The tie-rods are stretched, preloaded, and then locked-in with jam nuts.

The outer shell is a cylindrical aluminum tube, with an OD of 304.8 mm and a wall thickness of 5.0 mm. To monitor the strain-state of the shell (and, indirectly, the coil) the shell is equipped with strain gauges.

B. Magnet Preload Process

The preloading assembly process will be performed vertically. The shell and yoke stacks will be assembled on-end, setting on a pedestal. The yoke stacks are propped up against the ID of the outer shell as the pre-assembled coil-pack is lifted and inserted into the cavity between the yoke stacks. Then the bladders, bladder shims and nominal load keys are inserted in their keyways (Figs. 1 and 13).

While monitoring the shell strain gauges, the bladders are inflated with pressurized water. As the inflating bladders push the yokes against the shell ID, stretching it, the re-action compresses the load pads against the coils—compressing the coils and preloading them.

VII. Conclusion

The ultimate goal of superconducting magnet design is to minimize or eliminate coil training. Management of the forces and stresses in the superconductor by the structure holds the key to attaining this goal—short of the discovery of a superconducting material that is impervious to strain. The CCT design attempts to manage the stresses in the superconductor by supporting the individual turns rather than relying on substantial external structure to compress and constrain the “turn-wound-on-turn” construction of existing, conventionally wound, magnet coils. As presented, the winding mandrels in the CCT1 supports and constrains each conductor turn in the layer 1 and 2 coils. The CCT1 coils are made from NbTi, Rutherford cable and will be wound by hand onto the machined mandrels. The external structural components and impregnation tooling are presently being fabricated. The intended CCT1 magnet assembly, cool-down and test is targeted for the fall of this year.

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