Proof-of-Principle Design of a High-Field Overpass/Underpass Nb_3Sn Dipole

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***Abstract*—A block coil geometry is appealing in the body of particle accelerator dipole or quadrupole magnets, but less so in the ends of conventional designs, because conductors near the midplane of the beam tube must be bent in the hard direction to cross over to the other side of the tube. To avoid damage to brittle conductors such as Nb_3Sn or HTS, the bend must be very gradual, resulting in undesirably long magnet ends. An alternative design - "overpass/underpass" or "cloverleaf" - can ramp the conductor within a short length with bending only in the easy direction. Described here is a proof-of-principle design and analysis of an "overpass/underpass" coil geometry for a block coil dipole of 11 T or more.**

***Index Terms*—Dipole, coil design, superconducting.**

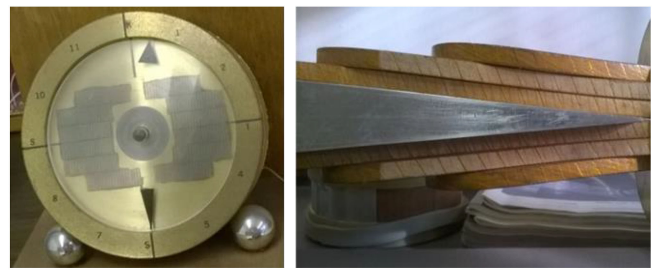

Fig. 1. Nb_3Sn block coil dipole cross-section (left) and splayed ends (right).

I. Introduction

THE High Energy Physics Advisory Panel (HEPAP) subpanel on Accelerator R&D has recommended to "Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider" [1]. Of current interest are dipoles capable of reaching well above 10 T. This field level necessitates the use of brittle conductors: Nb_3Sn or HTS, fabricated into cable (Rutherford, Roebel, etc.). The coil design may be conventional cosine theta or block [2]–[7]. Experience with cosine theta magnets is extensive, but the vast majority is with non-brittle NbTi. For brittle conductors, handling the large forces at high fields is difficult; the simplicity of block coil designs becomes appealing. This has also been recognized by CERN [8].

Several magnets based on various block coil designs have been designed, built, and tested for particle accelerators. These include (a) single-aperture, or conventional block coil designs with two independent coils and (b) 2-in-1 common coil [9] designs, in which a single coil serves two apertures. In both designs, to clear the bore tube, the ends of several blocks must depart from the simplicity of flat racetracks. The cable in the ends of those blocks needs to be splayed—lifted in the hard direction (edgewise)—and/or have a reverse bend, as in dog-bone ends, which is difficult to support during the coil winding and during assembly. Also, the conductor is prone to damage while winding the coil with adequate pre-tension, or when pre-stress is applied during the assembly. The complexity of the end geometry may contribute to degraded performance of block coil magnets, particularly those built with Nb_3Sn.

Block coil dipoles built to date have required the cable to be bent the hard way (edgewise) on each side of the midplane to clear the bore tube at the ends (see Fig. 1). Although most Nb_3Sn coils can be fabricated using the react-after-winding ("*wind and react*") approach, a hard-way bend of the unreacted cable can cause strands to become dislocated and thus susceptible to damage when the coils are handled and after the reaction heat treatment. In addition, it is difficult to provide adequate support of the turns in this hard-way bend transition area, and this may contribute to excessive magnet training. To avoid excessive strain, the ends are typically much longer in block coil designs than those in their counterpart cosine theta designs. This increase in end length degrades the average field strength of the magnet.

II. Overpass/Underpass Design

To overcome excessive strain and associated concerns on magnet performance, an alternative end geometry, called the overpass/underpass (or cloverleaf), has been proposed [2], [3] for accelerator magnets. In this design (see Fig. 2), the cable is slightly twisted (as in the end turns of layer-wound solenoids) and moved up or down (as in a highway overpass/underpass), to avoid the hard-way bend and thus reduce the strain on the cable. A major benefit of this design is a significant reduction in the length of the ends of the block coil designs. Shorter dipoles

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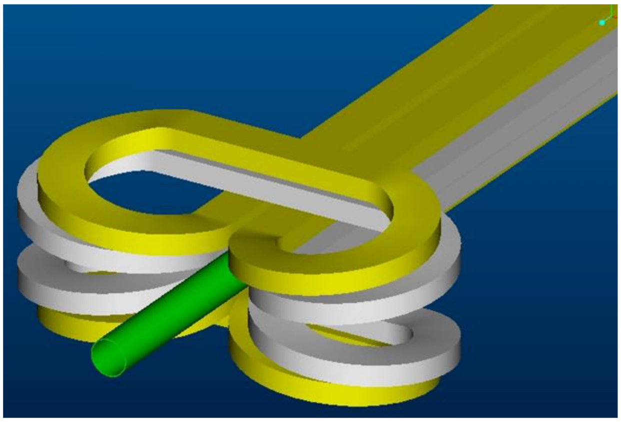

Fig. 2. Overpass/Underpass design concept [2] for dodging the bore tube in racetrack coil dipoles.

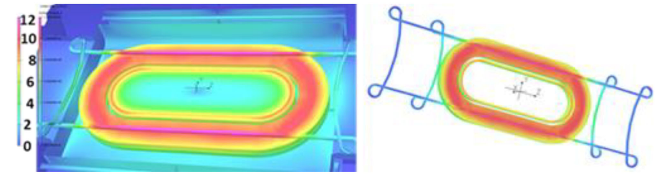

Fig. 3. A cutaway view to highlight field contours on the coil at 10 kA, with a convex connection between the overpass/underpass sections. All coils are connected in series. The model on the left shows the iron, whereas the one on the right hides the iron. These cutaway views emphasize the field contours on the overpass/underpass insert coil, as one can see that the ambient field is lower in the more complex section, giving it an extra margin.

provide space for other beam shaping elements or diagnostic devices.

The design, however attractive, has not yet been demonstrated in a magnet. This paper presents a proof-of-principle design where overpass/underpass (OP/UP) Nb_3Sn insert coils can be integrated with the BNL common-coil dipole to allow a low-cost demonstration at a field of $\sim$11 T. A detailed magnetic and mechanical analysis of this design in a support system will be presented, along with a preliminary engineering design.

III. Magnetic Design & Analysis

BNL's dipole DCC017 [10]–[12] is used in this study. It has a large, easily accessible open space in which new coils can be inserted and tested as an integral part of the magnet without any need for disassembly and reassembly [12]. The ends of these OP/UP coils will be located beyond the central field of the magnet (as expected in any overpass/underpass design) to reduce the magnetic forces in the end regions. The transverse ends between the "cloverleafs" of the coil were designed with a convex curve, as CERN employed [13], [14], to facilitate conductor contact with the winding surface in these regions. A minimum bend radius of 16 mm was maintained through the entire path. We also chose, located, and acquired the Nb_3Sn cable that can be used for winding these coils. This is a leftover Nb_3Sn cable that was used in the US LARP [15] magnets with good results.

The width of each OP/UP coil (including ends) must be at least two cable-widths plus enough for a small gap between the body and cloverleaf section at the crossover. Although DCC017 offers an opportunity to demonstrate a proof-of-principle OP/UP high field dipole, it also restricts and complicates the design. For example, to install the OP/UP coil without disassembling the magnet DCC017, we need an opening of at least two cable widths to insert one coil. To insert a two-coil package, the opening must be at least either (a) four cable widths, if the two coils have the same length, or (b) three cable widths, if a shorter coil rests within the central pocket of a longer coil.

The field from the DCC017 coils decreases toward its ends, which reduces the Lorentz forces (see Fig. 3). The 3D simulations are important for the design of the support structure for the complex end coil. A 2D analysis using ANSYS models a cross section of the DCC017 magnet with the coil in the straight section, where the field is maximum. The coil strain in the straight section will limit the performance of the coil. Both of these analyses depend on the mechanical properties of the materials used. Of particular importance is the Young's modulus of the epoxy impregnated Nb_3Sn coils; our modeling uses the magnet and Nb_3Sn coil material properties that were used in the US LARP [15].

The straight section of the OP/UP coils is in the high field region (see Fig. 3) and subject to large Lorentz forces. The strain in the coil conductor will potentially limit the performance of the coil.

IV. Mechanical Design & Analysis

A mechanical simulation of the 2D cross section was performed to evaluate the design. A magnetic simulation is first performed to predict the field and Lorentz force at each node, to generate input for the structural calculation. In the second phase of the simulation, stresses and strains are calculated from the Lorentz forces previously saved. Fig. 4(left) shows a contour plot of the displacement resulting from the forces. The maximum displacement, 128 μm, is in the vicinity of the OP/UP coil and the adjacent DCC017 coil. A contour plot of the von Mises stress over the OP/UP coil is shown in Fig. 4(middle). The peak von Mises stress is 217 MPa; the goal was to limit the Nb_3Sn stress to 200 MPa. The peak stress is localized and may be an artifact of the simulation rather than reality. Fig. 4 shows the von Mises strain at the OP/UP coil.

In the example considered here, the total strain in the ends of the OP/UP design (a combination of strain from the twisting and from the bending) is smaller by approximately a factor of five despite a five-fold reduction in the length of the overpass/underpass ends as compared to that of the conventionally lifted ends. This estimate is made for a cable having a width of 15 mm and thickness of 2.0 mm and the length/radius of the OP/UP ends being 50 mm compared to 250 mm for conventional lifted ends. The OP/UP approach may also allow Nb_3Sn magnets to be fabricated using a wind-after-reacting approach, because the strains are much reduced.

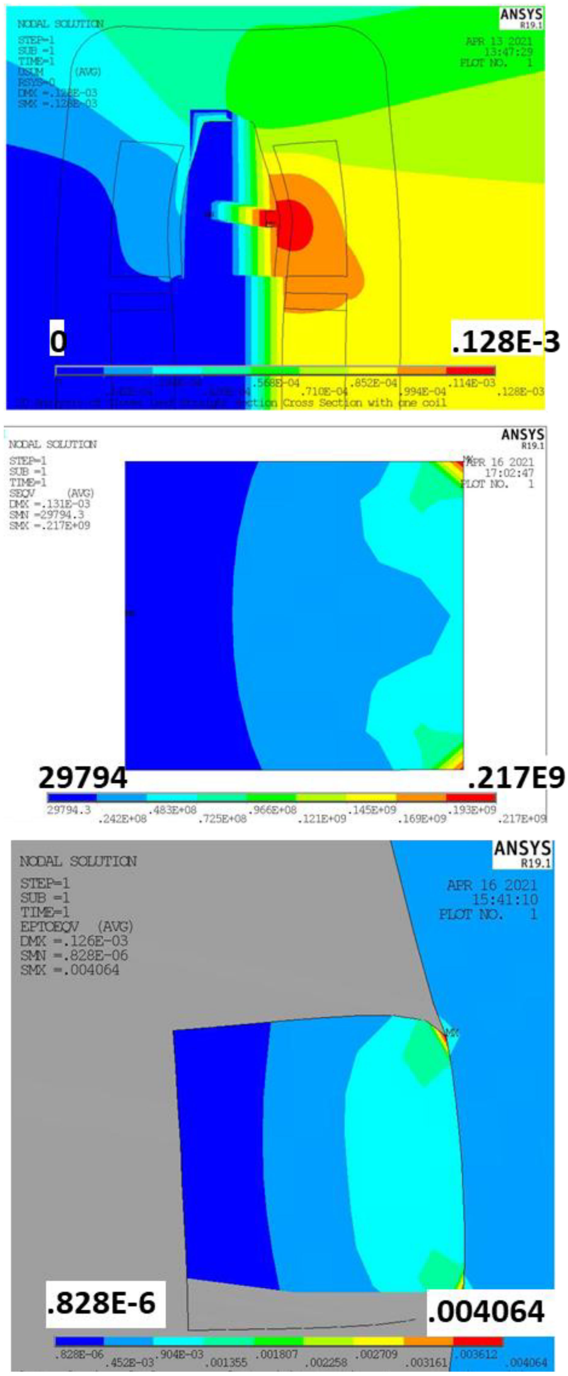

Fig. 4. Tot: Contour plot of the displacements, Middle: Contour plot of von Mises stress over the OP/UP coil, and Bottom: Contour plot of the von Mises strain.

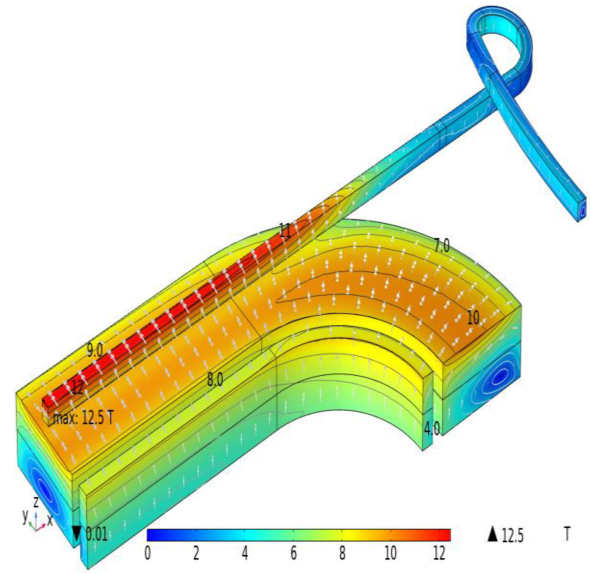

Fig. 5. Magnetic field direction (arrows) and magnitude with 10.8 kA in all coils. Contours are 1 T to 12 T in steps of 1 T.

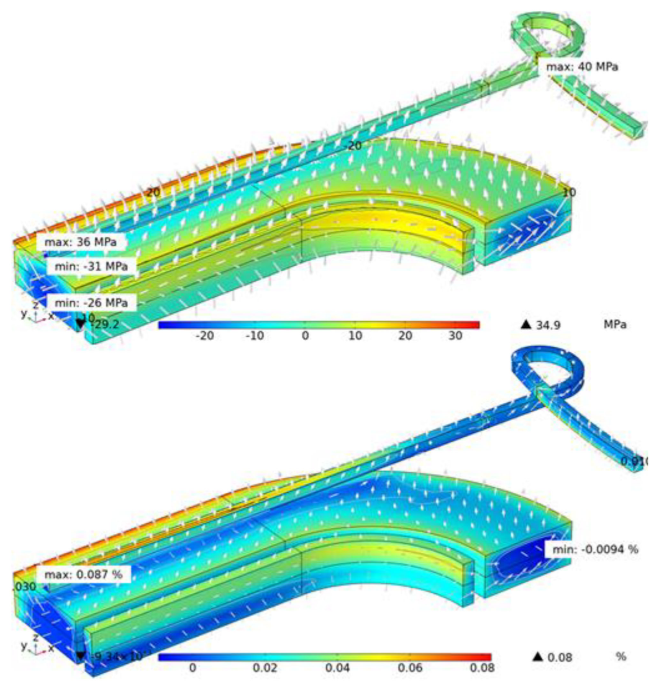

Fig. 6. 1st principal stress and strain in Nb_3Sn. Top: 1st principal stress; MPa contours are −20 to 20 in steps of 10. Bottom: 1st principal strain; contours are [0, 0.01%, 0.03%, 0.06%].

Because forces and stress on the ends need to be examined, we have modeled the section where the coil bends clear the beam tube. Magnetic field analyses are shown in Figs. 4 and 5, and a stress analysis in Fig. 6.

Fig. 6. plots the direction and magnitude of the 1^{st} principal stress and strain in the Nb_3Sn of both DCC017 and the OP/UP coil, including the magnitudes and locations of the extreme values in each.

V. Preliminary Engineering Design

The preliminary mechanical engineering design for the fabrication and installation of a Nb_3Sn OP/UP coil in the aperture of the existing Common Coil DCC017 magnet was completed. The design follows the magnetic model for the placement of the OP/UP coil blocks. The ends of the OP/UP coils were located beyond the central field of the magnet to reduce the magnetic forces in the end regions. The transverse ends between the “cloverleafs” of the coil were designed with a convex curve,

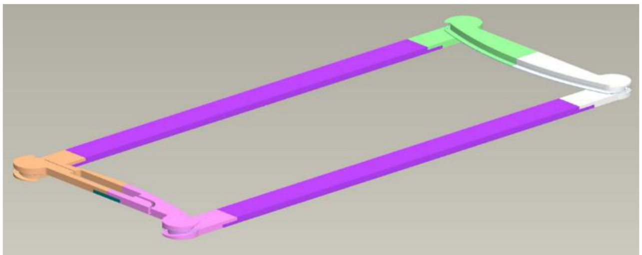

Fig. 7. Coil winding form.

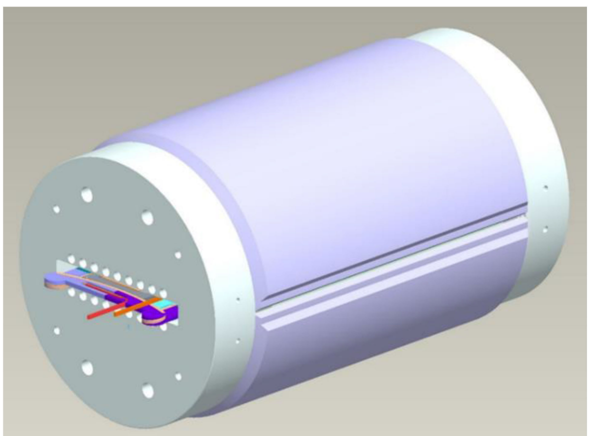

Fig. 8. Design view of the OP/UP coils assembled in the magnet DCC017.

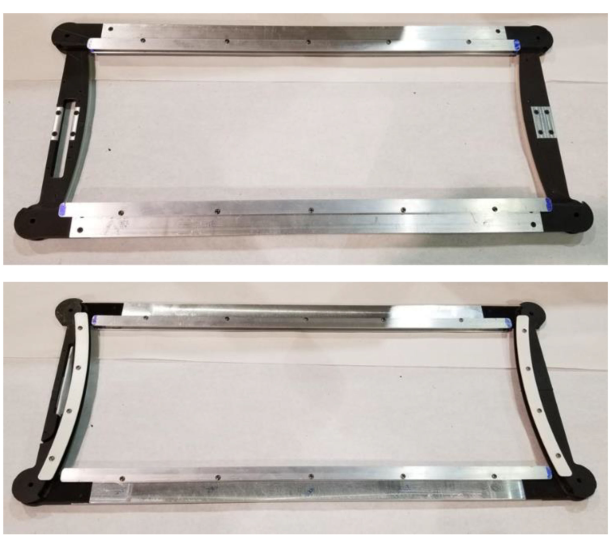

Fig. 9. OP/UP coil wound with the Nb_3Sn Rutherford cable. Two pictures (upper and lower) are of the same coil, turned over to show the two sides.

as done in the CERN OP/UP coil, to facilitate conductor contact with the winding surface in these regions.

The design is based on a continuous winding form to ensure proper dimensions and shape of the completed coil. This form, as is seen in Fig. 7, becomes a permanent part of the coil support structure; as such, it needs to be compatible with all the fabrication steps involved.

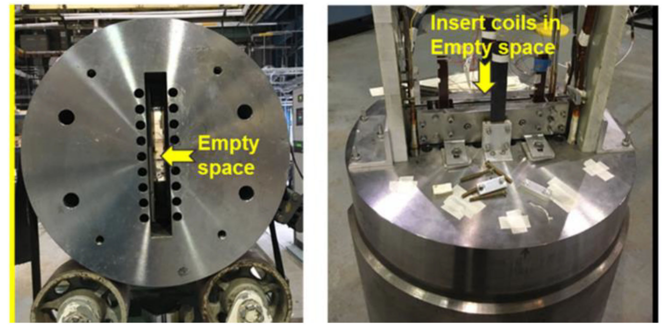

Fig. 10. Left: BNL common coil dipole with a large open space (left); Right: the magnet with insert coils as tested in another PBL/BNL STTR.

In particular, because the niobium tin coil uses the wind-and-react process, the coil form must be compatible with the 665°C reaction temperature. Therefore, all components are designed to be made from titanium, including the 3-D end shapes, which will be fabricated using additive machining, and that survives the heat treatment and is well matched to the thermal expansion of the conductor during reaction.

The winding form does include some temporary components, namely lateral guide plates, which are subsequently removed. After winding, additional clamping is introduced to the exposed edges of the wound coil to ensure proper dimensioning and positioning of the coil block during reaction, and the coil is installed in an oven and heated using a prescribed heat treatment schedule to a plateau of 210°C for 48 hours, followed by 395°C for 48 hours, and then finally 665°C for 50 hours for the reaction to be completed. The coil is then cooled using a similar prescription. The structure will not be made of a single piece; gaps between the parts in the straight sections and in the convex sections of the ends will allow for the differential thermal expansion between various metals and the conductor during reaction. Fig. 8 shows the 3-D rendering of the OP/UP coils inside the magnet DCC017 assuring that the OP/UP coils integrate well.

VI. Discussion

The use of overpass/underpass coils in a block coil dipole represents a practical approach to building high-field dipoles with brittle materials. An OP/UP coil wound with the Nb_3Sn Rutherford cable is shown in Fig. 9. Two pictures (upper and lower) are of the same coil, turned over to show the two sides of the coil. The left of Fig. 10 shows the BNL common coil dipole [11] with a large empty space for inserting the OP/UP coil. The right of Fig. 10 shows the magnet with insert coils as tested in another PBL/BNL STTR.

VII. Conclusion

Several advantages of the overpass/underpass design have been outlined. A magnetic, mechanical and preliminary engineering design of a proof-of-principle dipole for a demonstration of this design have been presented. This can be tested at a relatively low cost at a field of 11 T.

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