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CONCEPTUAL DESIGN OF A 17 T Nb_3Sn ACCELERATOR DIPOLE MAGNET*

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Abstract

Nb_3Sn dipole magnets with a nominal field of 16 T and sufficient operation margins are being considered for the LHC energy upgrade or a future Very High Energy Hadron Collider. This paper describes the conceptual design of a 17 T dipole magnet with 60 mm aperture, 4-layer cos-theta coil and stress management techniques.

INTRODUCTION

Nb_3Sn accelerator magnet technology has made significant progress in the past decade. It allowed considering Nb_3Sn dipoles and quadrupoles with nominal field of 11-12 T for the LHC luminosity upgrade (HL-LHC) [1] in the near future. In the longer term, 16 T Nb_3Sn magnets will be needed for the LHC energy upgrade (HE-LHC) or the Future Circular Collider (FCC) [2]. Magnet design studies are being performed in the framework of the U.S. Magnet Development Program (MDP) to explore the limits of the Nb_3Sn accelerator magnet technology and the feasibility of such magnets [3].

The analysis of the dipole demonstrator being developed by the MDP [4] has shown that the main limitation for achieving fields above 15 T in this design comes from the unloading of the inner-layer pole under Lorentz forces and consequent separation of the pole turn from the pole block. However, it is not possible to increase the coil preload to prevent the pole unloading since the equivalent stress in the coil midplane is already close to the stress limit for brittle Nb_3Sn conductor.

Thus, special stress management (SM) techniques are needed to resolve this problem. This paper describes the design of a 17 T dipole magnet with 60 mm aperture and 4-layer cos-theta coil focusing on the magnet mechanical design and analyses.

MAGNET DESIGN

The SM design [4] has graded coil based on two Rutherford cables. The inner cable has 28 strands, each 1 mm in diameter, and the outer cable has 40 strands, each 0.7 mm in diameter. The bare cable mid-thickness is 1.870 mm and 1.319 mm for the inner and outer cable respectively. Both cables are 15.1 mm wide, have a keystoned cross-section with a keystone angle of 0.805 degree. The Nb_3Sn strands have a Cu/non-Cu ratio of 1.13 and a critical current density J_c at 15 T and 4.2 K of 1500 A/mm^2.

The inner 2-layer coil has three blocks separated by two wedges in layer 1 and two blocks and one wedge in layer 2. Each layer of the outer coil is split into five blocks, separated by 5 mm wide spacers, with the number of turns approximately following the cos-theta distribution. In addition, the outer coil layers were separated by 5 mm in the radial direction from the inner coil and from each other to provide space for the support structure.

The inner coil was optimized for best field quality using ROXIE code [5] and considering the field harmonics produced by the outer coil. The magnetic model included a cylindrical iron yoke with an outer diameter of 600 mm. The SM coil cross-section is shown in Fig. 1.

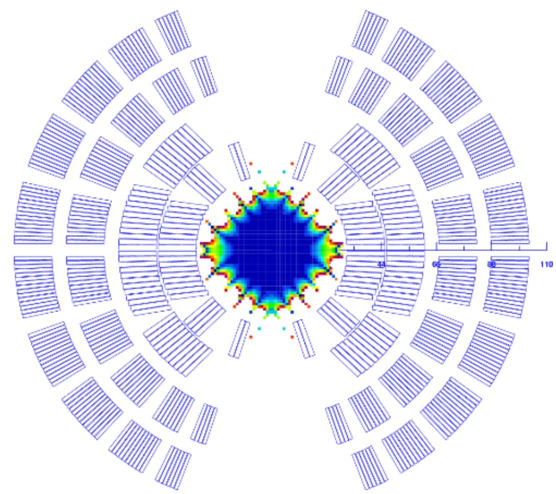

Figure 1: Cross-section of SM coil with the field uniformity diagram (dB/B1<2×10^{-4}).

The 3D view of the outer coil with the cross-section through the body and end is shown in Fig. 2. The structure is made of stamped stainless steel laminations providing precise and reproducible coil geometry. Coil ends include a support tube with special profile to provide turn radial alignment, end spacers and saddles.

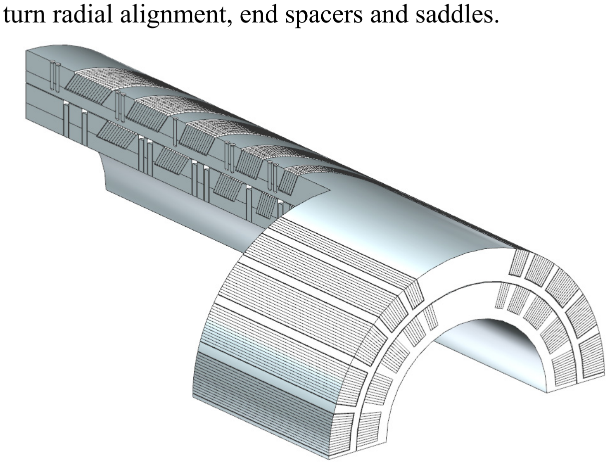

Figure 2: Transverse cross-section of the coil body and axial cross-section of the coil end of the outer coil with SM structure.

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The magnet cross-section is shown in Fig. 3. Section A is between the clamps and section B is through the clamp center. The coil assembly is surrounded by a 2-mm thick stainless steel spacer and pre-compressed by two vertically-split iron pads locked by aluminium I-clamps. The pads are placed inside a 4-piece iron yoke enclosed in a 55-mm thick aluminium shell. The coil axial support is provided by two thick end plates connected by four stainless steel rods.

The magnet is assembled using key-&-bladder technique which is widely used in high-field dipoles and quadrupoles [1, 6]. This approach was developed and analysed for the 15 T dipole demonstrator [7]. To provide the coil support to higher fields and reduce stress in the skin, the aluminium clamps were added and the skin thickness was increased to 55 mm while keeping the shell OD of 630 mm to fit into the VTMF dewar at FNAL.

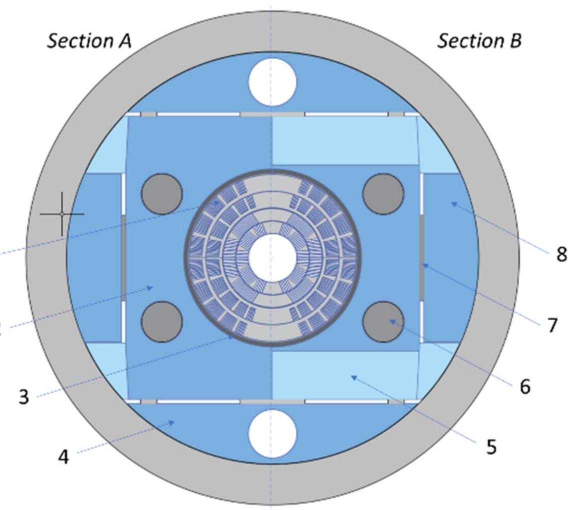

Figure 3: Magnet cross-section: 1 – 4-layer coil; 2 – iron pad; 3 – coil-pad stainless-steel spacer; 4 – vertical yoke block; 5 – aluminium clamp; 6 – stainless-steel rod; 7 - horizontal pad-yoke shim; 8 – horizontal iron block.

MAGNETIC ANALYSIS

The main magnet parameters are summarized in Table 1. For the nominal J_c(15T,4.2K) of 1500 A/mm^2 (which is close to 3 kA/mm^2 at 12 T and 4.2 K), the bore field is 16.01 T and 17.5 T at 4.2 K and 1.9 K respectively. Considering 16 T as the nominal field for the operation at 1.9 K, the critical current margin of 10% is provided.

Table 1: Magnet Parameters at SSL and 4.2 K

Parameter	Inner coil	Outer coil
Bore field, T	16.01	
Peak field, T	16.38	
Current, A	10.96	
Inductance, mH/m	34.52	
Stored energy, MJ/m	2.07	
F_x, MN/m/quadrant	4.92	4.56
F_y, MN/m/quadrant	-0.52	-3.67

The values of normalized geometrical harmonics are smaller than 10^{-4} at the reference radius of 17 mm. The maximum absolute value of b_3 due to the persistent current effect is ~ -23 units at a bore field of ~1 T. The relatively low persistent current effect in this design with respect to the 15 T dipole demonstrator [4] is due to the more optimal turn distribution in the SM coil design.

MECHANICAL ANALYSIS

To evaluate turn displacements and stresses in the coil and in the coil structure, a mechanical analysis was performed using an ANSYS parametric model. The inner coil included Ti poles and wedges. The outer coil is integrated into the stainless steel structure with 5 mm thick radial and azimuthal spacers. The coil blocks could separate from the spacers and the structure to capture the effect of unloading under Lorentz forces. In addition, each layer could slide with respect to the adjacent layers and to the iron yoke. The vertical gap in the iron pads remains closed at all fields. The coils were pre-compressed by placing appropriate radial shims between the inner and outer coils and between the outer coil and the iron pads.

The goal of the mechanical analysis was to find the maximum field at which the coil maximum stress is still acceptable for brittle Nb_3Sn superconductor with no azimuthal separations of coil blocks from the structure. The calculated distributions of coil equivalent stress after the cool-down and at 17 T bore field are shown in Fig. 4.

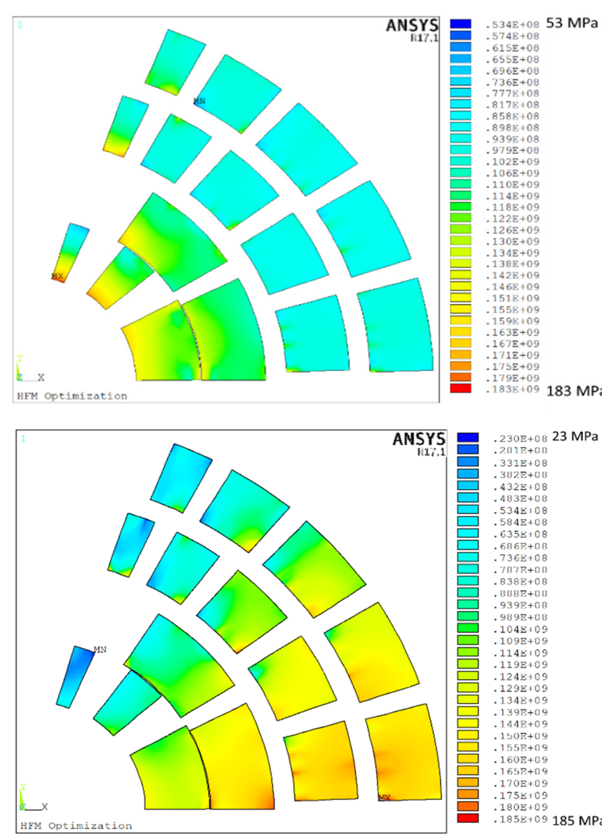

Figure 4: Coil equivalent stress after cool-down (top) and at the bore field of 17 T (bottom).

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The peak equivalent stress after cool-down is 183 MPa in layer 1 pole blocks. At the bore field of 17 T, it moves to layer 4 mid-plane block (low field region) and approaches 185 MPa. It is lower than the peak stress in the inner-coil of the baseline (BL) design at 15 T, which is located in the layer 1 mid-plane block and reaches180 MPa [4].

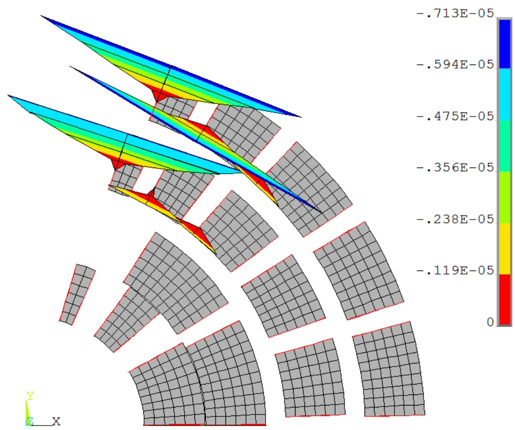

Figure 5: Gaps between pole turns and poles in layers 1 and 2, and between the turns and the structure in layers 3 and 4 at the bore field of 17 T.

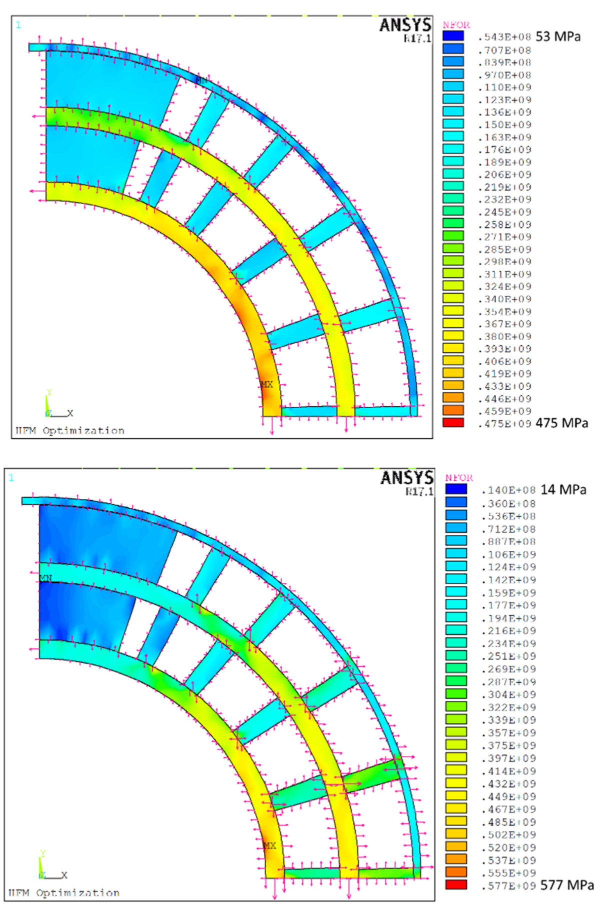

Figure 6: Equivalent stress in the outer coil structure after cool-down (top) and at 17 T bore field (bottom).

The calculated gaps between pole turns and poles in layers 1 and 2, and between the turns and the structure in layers 3 and 4 at the bore field of 17 T are shown in Fig. 5. The pole turns of the inner coil remain in contact with the pole blocks at bore fields up to 17 T. In the three pole blocks of layer 3 and layer 4, partial gaps are seen on some interfaces between the ribs and the coil turns. However, the maximum value of these partial gaps is less than 5 μm. Moreover, the gap width is less than the cable half-width.

The calculated distributions of the equivalent stress in the outer coil structure after cool-down and at the bore field of 17 T are shown in Fig. 6. The peak equivalent stress in the support structure of the outer coil at the 17 T bore field is less than 600 MPa. This level of stress can be reduced by slightly increasing the radial thickness of the layer 3 spacer.

CONCLUSION

A 17 T Nb_3Sn dipole design based on a shell-type (aka cos-theta) coil with stress management has been developed and analyzed. Magnet design consists of a 4-layer graded coil with 60-mm aperture, a cold iron yoke and a thick aluminum shell. The structure was mechanically reinforced by aluminum clamps. The maximum bore field for state-of-the-art Nb_3Sn composite wires is ~16 T at 4.5 K and ~17.5 T at 1.9 K. The SM structure was used in layers 3 and 4 to reduce large coil deformations under Lorentz forces and, thus, the excessively high stresses in the coil and the separation of pole turns in layer 1 and 2 at high fields. It was shown that this design has stresses in the coil and support structure within acceptable limits up to 17 T in the magnet bore.

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