**Deliverable D7.1 – WP 7**

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**Title: 16 Tesla Dipole Designed**

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**WP Number: WP 7**

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## Abstract

This document reports on the design of a 16 Tesla Dipole, i.e. verify the design studies, perform the magnetic analysis, mechanical structure design, coil stress analysis at the three stages of magnet operation (i.e. room temperature, after cooling down at the temperature of operation of 4 K, and at nominal magnetic field operation).


An important objective for the LHC energy upgrade or future Very High Energy Hadron Colliders, with INFN and FNAL as main actors, is related to the development of superconducting technologies for high field magnets to design and build a 16 Tesla $Nb_3Sn$ accelerator dipole. For INFN this activity is still at a preliminary step and secondments at FNAL have started in 2019. The challenge for high field $Nb_3Sn$ superconducting magnets is to push the design limit of these magnets to their superconducting potential (or Short Sample Limit SSL). To design and build a 16 Tesla $Nb_3Sn$ superconducting dipole, the design limit needs to be at least 17 Tesla. Within the cos-theta magnet geometry, i.e. the same design used in the Tevatron at Fermilab and at LHC at CERN, a number of strain management options were investigated.

The analysis of the dipole demonstrator being developed by the U.S. Magnet Development Program [4] has shown that the main limitation for achieving fields above 15 T in a 60 mm cold aperture design comes from unloading of the inner-layer pole under Lorentz forces and separation of the pole turn from the pole block at fields above 15 T. However, it is not possible to increase the coil preload to avoid the pole unloading since the equivalent stress in the coil midplane is already close to the stress limit for $Nb_3Sn$, which is a brittle conductor. Conceptual designs and analyses were performed for a 4-layer coil also based on a 60 mm cold aperture, but with a 17 Tesla design limit. To achieve this limit, a strain management mechanical solution was developed, that makes use of winding into slots with adequate spacers. To readily test the winding concept, plastic parts were produced using 3D printing technology.

## MAGNET DESIGN

The magnet design has graded coils based on the same two Rutherford cables as in [1]. 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 the best field quality using ROXIE code [2], 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 coil cross-section is shown in Fig. 1.

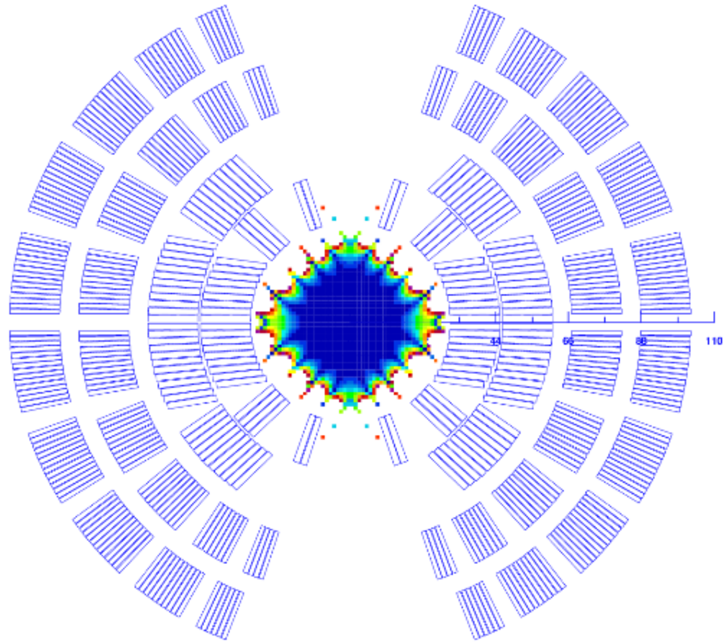



Figure 1: Cross-section of coil with field uniformity diagram ($dB/B_1<2\times10^{-4}$).

The 3D view of the outer coil with the cross-section through the body and ends 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.

The magnet cross-section is shown in Fig. 3. Section A goes between the clamps and section B goes 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 aluminum I-clamps. The pads are placed inside a 4-piece iron yoke enclosed in a 55-mm thick aluminum shell. The coil axial support is provided by two thick end plates connected by four stainless steel rods.

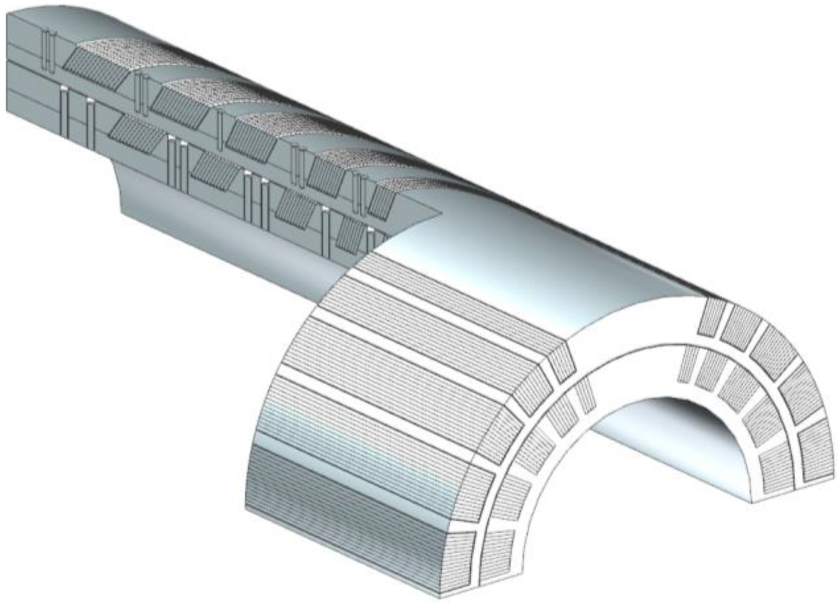


Figure 2: Transverse cross-section of the coil body and axial cross-section of the coil end of the outer coil with stress management structure.

The magnet is assembled using a key-&-bladder technique, which is widely used in high-field dipoles and quadrupoles [3]. This approach was developed and analyzed for the FNAL 15 T dipole demonstrator [4]. To provide coil support to higher fields and reduce stress in the skin, the aluminum 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.

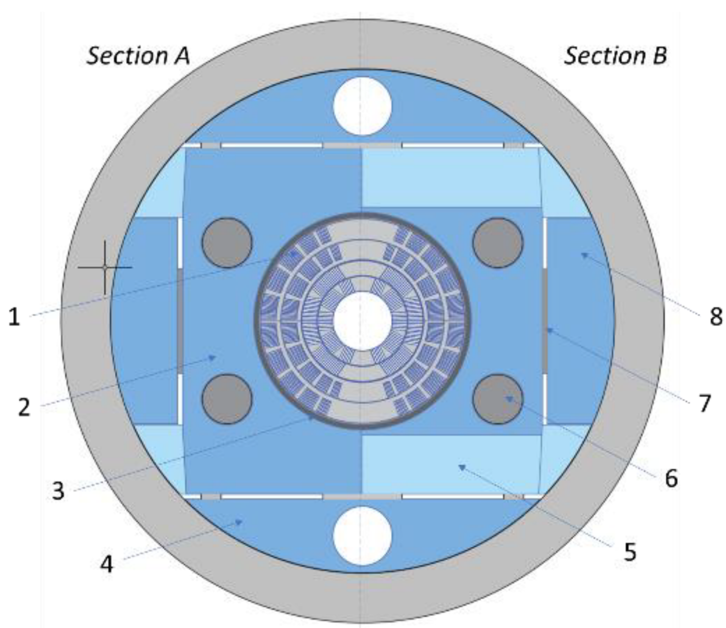



Figure 3: Magnet cross-section: 1 – 4-layer coil; 2 – iron pad; 3 – coil-pad stainless-steel spacer; 4 – vertical yoke block; 5 – aluminum clamp; 6 – stainless-steel rod; 7 - horizontal pad-yoke shim; 8 – horizontal iron block.

## MAGNETIC ANALYSIS

The main magnet parameters are summarized in Table I. For a 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 operation at 1.9 K, a critical current margin of 10% is provided using state-of-the-art $Nb_3Sn$ wires.

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 [1] is due to the more optimal turn distribution in this last coil design.

Table I: 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 |

## 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 was 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 remained closed at all fields. The coils were pre-compressed during assembly by placing the 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, and there are 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.

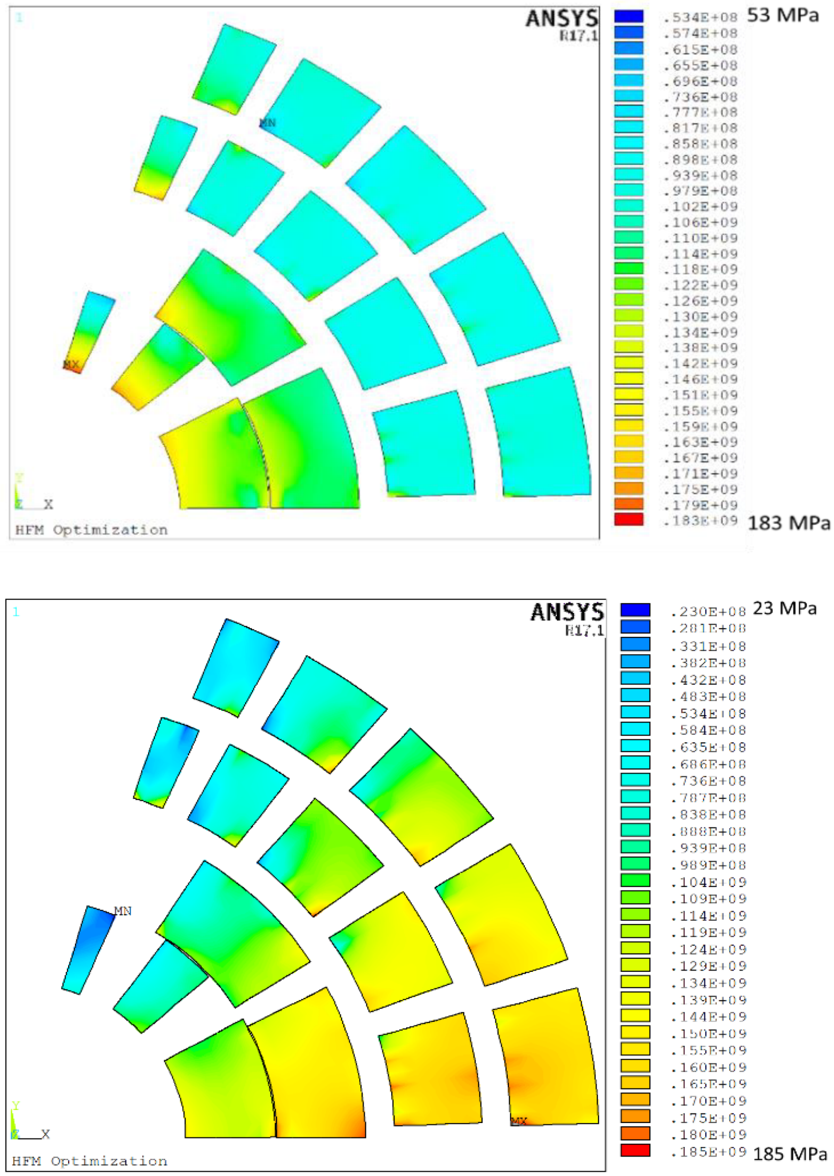



Figure 4: Coil equivalent stress after cool-down (top) and at a bore field of 17 T (bottom).

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 design at 15 T which is located in the layer 1 mid-plane block and reaches 180 MPa [1].

The calculated gaps between the 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 which is considered acceptable.

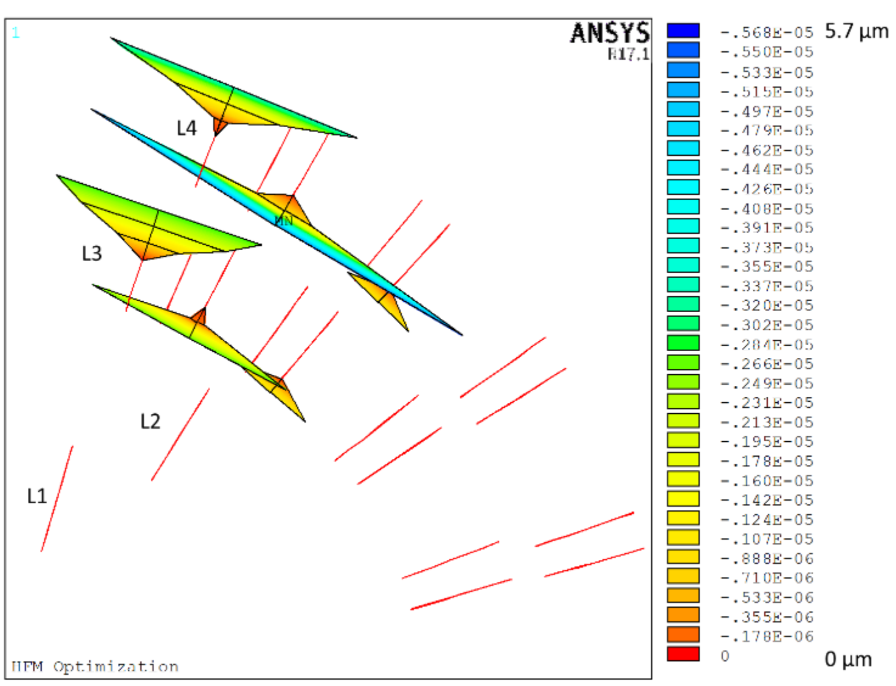
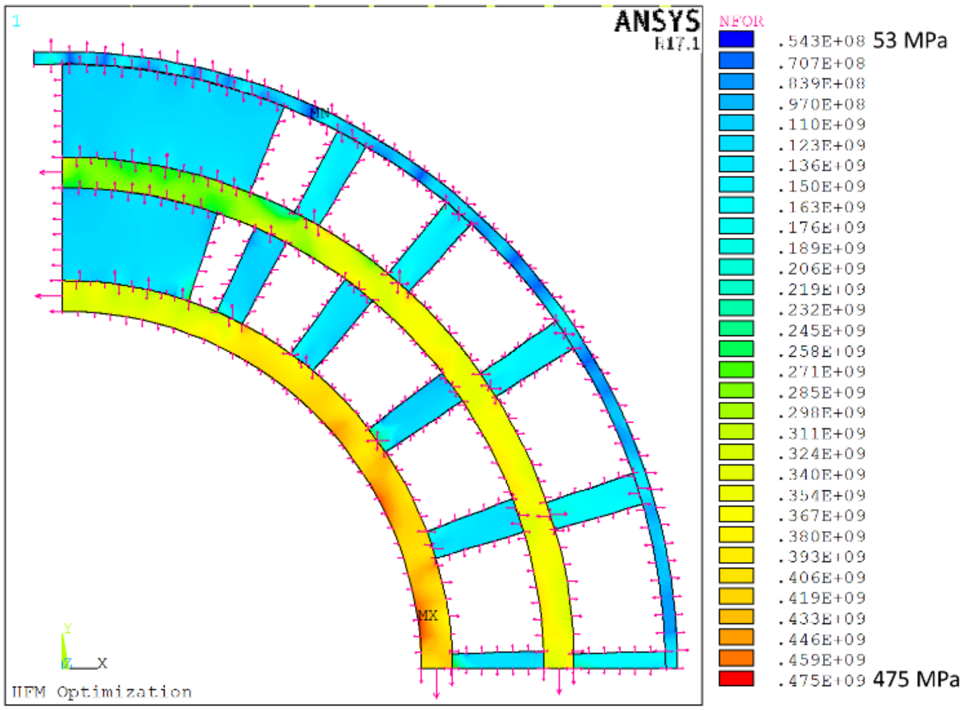



Figure 5: Gaps between the pole turns and poles in layers 1 and 2, and between the turns and the structure in layers 3 and 4 at the bore field of 17 T.

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. The 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 when using state-of-the-art $Nb_3Sn$ composite wires is ~16 T at 4.5 K and ~17.5 T at 1.9 K. A stress management structure was used in layers 3 and 4 to reduce large coil deformations under the 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 the stresses in the coil and support structure within acceptable limits up to 17 T in the magnet bore.



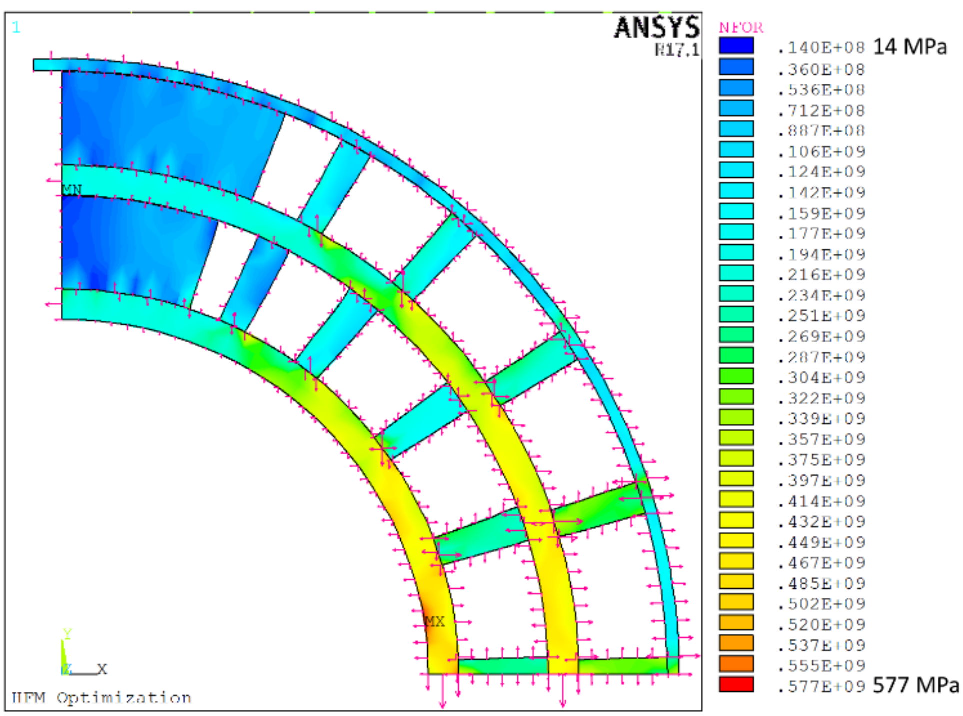



Figure 6: Equivalent stress in the outer coil structure after cool-down (top) and at 17 T bore field (bottom).

REFERENCES

[1] I. Novitski et al., “Development of a 15 T $Nb_3Sn$ Accelerator Dipole Demonstrator at Fermilab,” IEEE Trans. on Appl. Supercond., vol. 26(4), 2016, 4001007.

[2] ROXIE code for electromagnetic simulation and optimization of accelerator magnets, http://cern.ch/roxie.

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