DESIGN STUDIES AND OPTIMIZATION OF HIGH-FIELD Nb_3Sn DIPOLE MAGNETS FOR A FUTURE VERY HIGH ENERGY *pp* COLLIDER*

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Abstract

High field accelerator magnets with operating fields of 15-16 T based on the Nb_3Sn superconductor are being considered for the LHC energy upgrade or a future Very High Energy *pp* Collider. Magnet design studies are being conducted in the U.S., Europe and Asia to explore the limits of the Nb_3Sn accelerator magnet technology by optimizing the magnet design and performance parameters, while minimizing their cost. The first results of these studies performed at Fermilab in the framework of the US-MDP are reported in this paper.

INTRODUCTION

Accelerator magnet technology based on the Nb_3Sn superconductor has demonstrated a significant advancement during the past decade [1]. For that reason, the Nb_3Sn dipoles and quadrupoles with a nominal field of 11-12 T are being considered in the near future for the LHC luminosity upgrade (HL-LHC project) [2]. In the longer term, the cost-effective 15-16 T Nb_3Sn magnets will be needed for the LHC energy upgrade (HE-LHC) or a future Very High Energy *pp* Collider (VHE*pp*C) [3].

To demonstrate the feasibility of accelerator quality 15 T dipole magnets, Fermilab in collaboration with other members of the U.S. Magnet Development Program (MDP) is developing a 15 T Nb_3Sn dipole demonstrator based on a 4-layer graded cos-theta coil with a single 60 mm aperture and a 600 mm diameter cold iron yoke [4].

In parallel, magnet design studies are being conducted to explore the limits of the Nb_3Sn accelerator magnet technology while pushing the nominal bore field to 16 T in a 60 mm aperture. A preliminary analysis indicated that such a goal could not be achieved without internal stress management (SM). The first results of these studies, including a possible stress management technique are discussed below and compared with the baseline (BL) design parameters.

MAGNETIC ANALYSIS

The magnetic and structural designs for the 15-T dipole demonstrator have been reported elsewhere [4]. The BL design analysis has shown that the main limitation for achieving higher fields comes from unloading of the inner layer pole under Lorentz forces and a separation of the pole turn from the pole block at the fields above 15 T. The usual counter-measure would be to increase the coil preload. However, that possibility has already been exhausted in the BL design as the equivalent stress in the coil midplane was approaching 180 MPa, which is considered to be close to the limit for the brittle Nb_3Sn conductor.

To overcome these limitations, the following strategy was used: keep the shell type structure with the floating wedges for the inner coil; maximally unload the inner coil by moving turns to the outer coil; introduce the azimuthal and radial SM in the outer coil only. This approach builds upon the SM concept first proposed for the high field Nb_3Sn magnet coils of the block-type design [5] and recently used in the canted-cos-theta magnets [6]. It also allows decoupling the fine tuning of the field quality (which mostly depends on the inner coil geometry) from the SM optimization. In addition, it would later allow testing the new outer SM coils together with the inner BL coils (even though such configuration is not optimal) to save on the fabrication time and R&D cost.

In order to have a fair comparison, it was decided to use the BL cables with parameters, presented in Table 1, for the inner and outer coils of the SM design. The inner coil was optimized for the best field quality using ROXIE code [7] with the same number of coil blocks as in the BL design. The optimized block layout is different because of the larger number of turns in the outer coil.

Each layer of the outer coil was split into 5 blocks, with the number of turns approximately following the cos-theta distribution and the equal 5-mm spacing between the blocks. In addition, the outer coil layers were separated by 5 mm in the radial direction from each other and from the inner coil to create space for the support structure. The model included a cylindrical iron yoke with the outer diameter of 600 mm and non-linear magnetic properties.

The BL and SM coil geometries are presented in Fig. 1, the geometrical field quality is presented in Table 2, and the main magnet parameters are summarized in Table 3.

Table 1: Cable Parameters After Reaction

Parameter	**Inner Coil**	**Outer Coil**
Number of strands	28	40
Mid-thickness, mm	1.870	1.319
Width, mm	15.10	
Keystone angle, deg.	0.805	
Cu/nonCu ratio	1.13	
J_c(15T, 4.2K), A/mm^2	1500	

Table 2: Geometrical Harmonics at R_{ref}=17mm (10^{-4})

Harmonic	**BL**	**SM**
b_3	0.0018	0.0007
b_5	0.0154	-0.0087
b_7	0.0523	0.1170
b_9	0.0612	0.2626
b_{11}	0.3433	-0.0873

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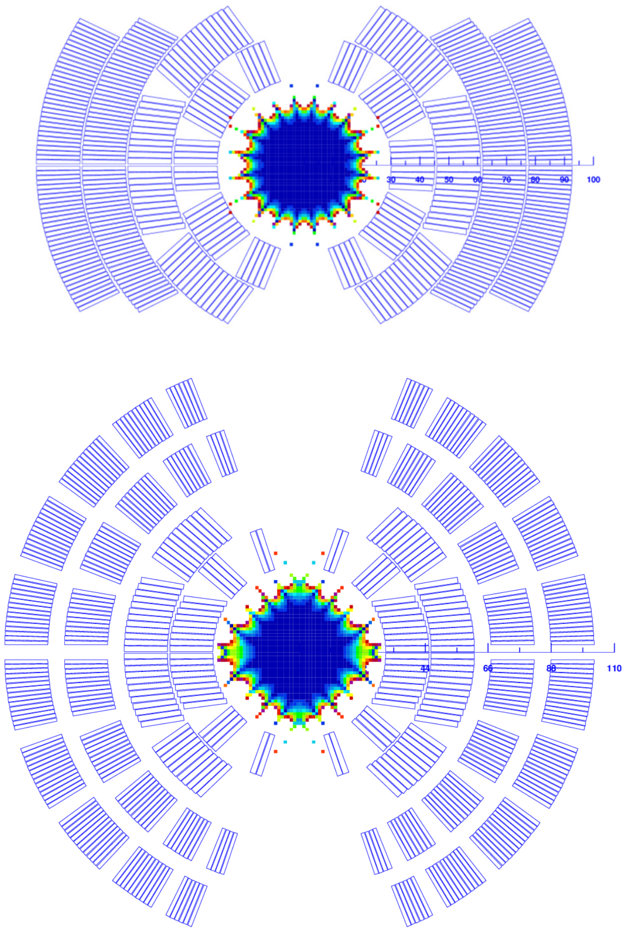

Figure 1: Cross-sections of BL (top) and SM (bottom) coils with field uniformity diagrams ($\Delta B/B1<2\times10^{-4}$).

Table 3: Magnet Parameters at SSL and 4.2 K

Parameter	BL		SM	
	IC	OC	IC	OC
Bore field, T	15.61		16.07	
Peak field, T	16.25		16.44	
Current, A	11.34		10.80	
Inductance, mH/m	25.61		35.42	
Stored energy, MJ/m	1.65		2.06	
F_x, MN/m/quadrant	5.8	1.6	4.8	4.7
F_y, MN/m/quadrant	-1.2	-3.3	-0.5	-3.6
Number of turns	44	65	38	102

Both designs provide the normalized geometrical field harmonics smaller than 10^{-4} at the reference radius of 17 mm. Since the SM design has 30% more turns, it reaches a higher field at a lower current, and consequently has a larger inductance and stored energy. Due to the turn redistribution between the coils, the horizontal Lorentz force per the inner coil is a factor of 1.2 smaller and the vertical force is a factor of 2.4 smaller than in the BL design, which is consistent with the adopted SM strategy. However, the horizontal force on the outer SM coil is a factor of 3 higher than that for the outer BL coil, while the vertical force is practically the same. This additional horizontal force is intercepted with a special support structure as described in the next section.

Sensitivity of the magnet bore field to the operation temperature and the superconductor critical current density is shown in Fig. 2. For the nominal J_c(15T,4.2K) of 1500 A/mm^2 (which is close to 3000 A/mm^2 at 12 T, 4.2 K), the SM design reaches 16.1 T and 17.6 T fields 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% can be provided using the state-of-the-art Nb_3Sn wires.

The bore quench field varies by about 0.5 T for every 500 A/mm^2 change in the critical current density. To consider 17 T as the nominal field at 1.9 K, the strand critical current density has to be increased by ~30%.

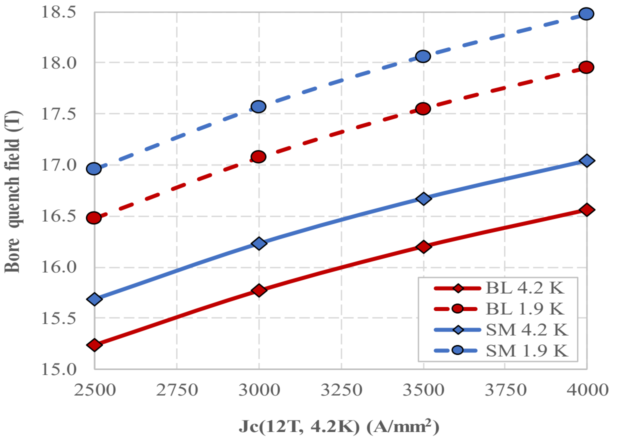

Figure 2: The maximum field in magnet aperture vs. the Nb_3Sn wire J_c at 12 T and 4.2 K.

STRUCTURAL ANALYSIS

A structural analysis was performed with ANSYS code to evaluate displacements and stresses in both designs using a simplified parametric model. The material properties were assumed to be the same as in the BL design [4]. The inner coil included Ti poles and bronze wedges between the coil blocks. The outer coil with SM is completely surrounded by the stainless steel structure which consists of half-cylinders with radial ribs for both layers. In practice, it will be achieved by winding each SM coil layer into the described slotted structure.

The coil blocks were allowed to separate from the spacers and the structure to capture the effect of unloading under the Lorentz forces. In addition, each layer could slide with respect to the adjacent layers and to the iron yoke. It was also assumed that the vertical gap in the iron yoke remains closed at all fields. The coils were pre-compressed during the assembly by placing the appropriate radial shims between the inner and outer coils and between the outer coil and the iron yoke.

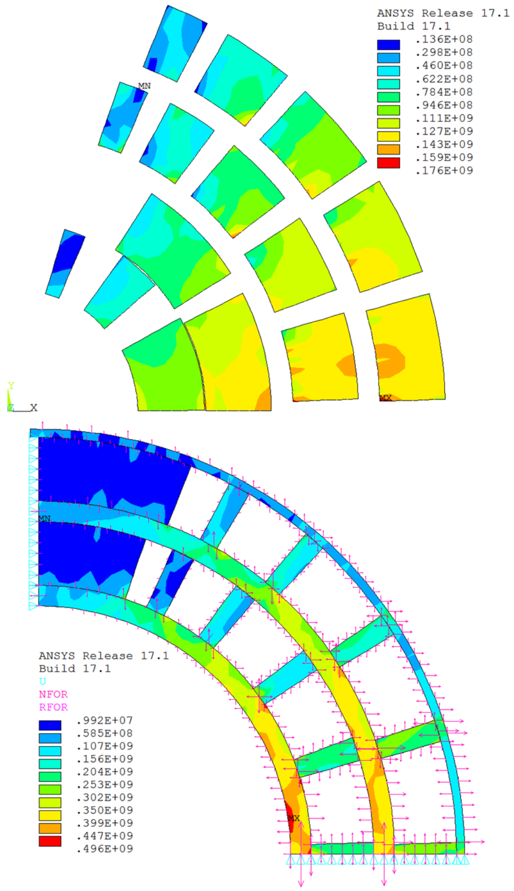

Figure 3: Equivalent stress (Pa) in the SM coil (top) and the outer coil structure (bottom) at the bore field of 16 T.

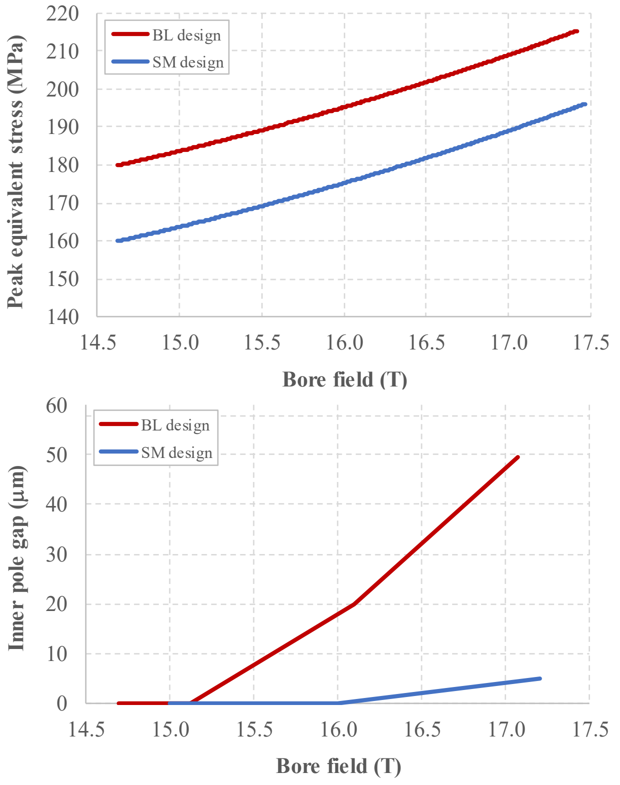

Figure 4: The peak stress (top) and the gap between the inner pole turn and the pole (bottom) vs. the bore field.

Distributions of the equivalent stress in the coil and the support structure of the outer coil after the cool-down and energizing to 16 T bore field are shown in Fig. 3. For the inner SM coil, the peak equivalent stress is located in the outer-layer midplane block and approaches 150 MPa. It is lower than the peak stress in the BL design of 180 MPa at 15 T, located in the inner-layer midplane block.

The pole turn in the SM design remains in contact with the pole at the fields up to 16 T whereas in the BL design the pole turn separates from the pole at the fields above 15 T and the gap reaches ~20 μm at 16 T.

For the outer SM coil, the peak equivalent stress at 16 T is under 180 MPa and located in the midplane block of the outer layer. A further optimization will be done to reduce the stress concentrations at the block corners in the next design iteration.

The peak equivalent stress in the support structure of the outer SM coil is ~500 MPa. This level of stress requires using stainless steel for this structural element. It can be also reduced by increasing the radial spacer thickness.

CONCLUSION

The goal of the design studies presented in this paper was to demonstrate the possibility of achieving the nominal bore field of ~16 T in a 60-mm aperture using the currently available state-of-the-art Nb_3Sn superconductor. To increase the level of magnetic field, a stress management technique has been used together with the turn re-distribution between the inner and outer coils. It was found that the stresses in the inner and outer coils are below 150 MPa and 180 MPa respectively, and that the inner pole turns stay in contact with the poles up to 16 T bore field. Given the 10% margin at 1.9 K, it can be considered as the nominal operating field for this design.

The studies and optimization of this design will continue.

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