DEVELOPMENT AND COMPARISON OF MECHANICAL STRUCTURES FOR FNAL 15 T Nb_3Sn DIPOLE DEMONSTRATOR*

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Abstract

Main design challenges for 15 T accelerator magnets are large Lorentz forces at this field level. The large Lorentz forces generate high stresses in the coil and mechanical structure and, thus, need stress control to maintain them at the acceptable level for brittle Nb_3Sn coils and other elements of magnet mechanical structure. To provide these conditions and achieve the design field in the FNAL 15 T dipole demonstrator, several mechanical structures have been developed and analysed. The possibilities and limitations of these designs are discussed in this paper.

INTRODUCTION

Nb_3Sn magnets with a nominal operating field of 15-16 T are being considered for the LHC energy upgrade (HE-LHC) and a post-LHC Very High Energy pp Collider (VHEppC) [1]. To demonstrate feasibility of the 15 T accelerator quality magnets, FNAL has started the development of a single-aperture Nb_3Sn dipole demonstrator based on a 4-layer graded cos-theta coil with 60 mm aperture and cold iron yoke [2].

Main design challenges for 15 T accelerator magnets include large Lorentz forces at this field level. The large Lorentz forces generate high stresses in the coil and mechanical structure and, thus, need stress control to maintain them below 150 MPa, which is acceptable for brittle Nb_3Sn coils. To provide these conditions and achieve the design field in the FNAL 15 T dipole demonstrator, several mechanical structures have been developed and analyzed. The possibilities and limitations of these designs are discussed in this paper.

BASELINE MAGNET DESIGN

The baseline design of the 15 T dipole demonstrator being developed at FNAL is described in [3]. It consists of a 4-layer 60-mm aperture graded coil and cold 587 mm ID iron yoke separated from the coil by 2 mm spacer. The baseline mechanical structure of the dipole demonstrator is shown in Fig. 1. The coil uses two 15 mm wide cables with 28 strands in the two innermost layers and 40 strands in the two outermost layers. The inner and outer cables are based on 1.0 mm and 0.7 mm Nb_3Sn strands respectivelly. The magnet maximum design bore field is 15.61 T at 4.2 K and 17.04 T at 1.9 K.

The coil assembly is surrounded by a 2 mm thick stainless steel spacer and supported by a vertically split iron yoke locked by aluminum clamps. The yoke is surrounded by a 12 mm thick stainless steel skin. The I-shaped clamps interleave with the iron yoke laminations in the top and bottom sectors of the iron yoke, thus reducing the iron filling factor in these areas to ~50%.

The axial Lorentz forces are supported by two thick end plates connected by eight stainless steel tierods placed in the dedicated holes in the iron yoke. This support structure provides better stress management then the original concept with stainless steel C-clamps and a thick skin [4]. The cold mass transverse size is 610 mm. It is limited by the inner diameter of the FNAL test cryostat.

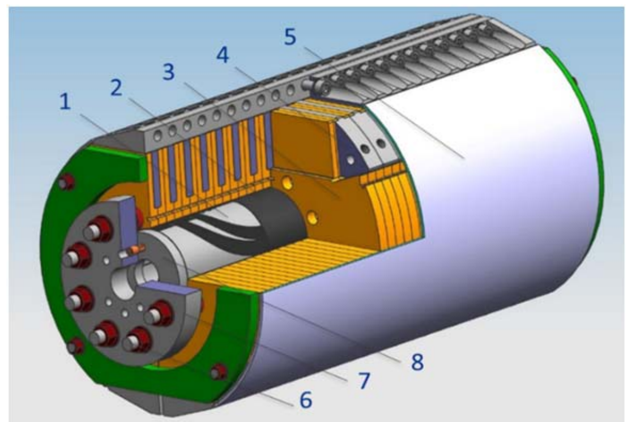

Figure 1: Baseline mechanical structure of FNAL 15 T dipole demonstrator: 1 – Nb_3Sn coil; 2 – stainless steel coil-yoke spacer; 3 – iron yoke laminations; 4 – aluminum I-clamp; 5 – stainless steel bolted skin; 6 – axial tie rod; 7 – stainless steel end plate with instrumented bullets; 8 – pusher ring.

The average transverse (azimuthal) stress in the pole and mid-plane turns of the coil layers after assembly, cooldown and at the design bore field of 15 T is shown in Table 1. The peak equivalent stress after assembly and after cooldown in pole 1 turn is 133 and 176 MPa respectively. The increase of pre-stress in the pole turns after cooldown is achieved by optimizing the gap between the two iron yoke halves during assembly. The gap is closed after cooldown and stays closed up to 15 T. At the design bore field of 15 T, the peak equivalent stress is in the innermost layer mid-plane turns and is less than 170 MPa.

ALTERNATIVE STRUCTURE

Mechanical structure based on cold iron blocks inside a thick aluminium cylinder and key&bladder assembly technique was selected as an alternative mechanical structure for the FNAL 15 T dipole demonstrator [5]. This structure concept was used for the HD magnet series at LBNL [6] and by US-LARP for several large-aperture high-field quadrupole models [7].

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Table 1: Average Azimuthal Stress in Selected Turns

Position in coil	Azimuthal coil stress, MPa			
	Assembly	Cooldown	B=15 T	
Pole 1	88	138	9	
Pole 2	46	75	21	
Pole 3	64	97	36	
Pole 4	62	95	62	
Mid-plane 1	64	95	153	
Mid-plane 2		65	107	127
Mid-plane 3		62	92	153
Mid-plane 4		66	103	153

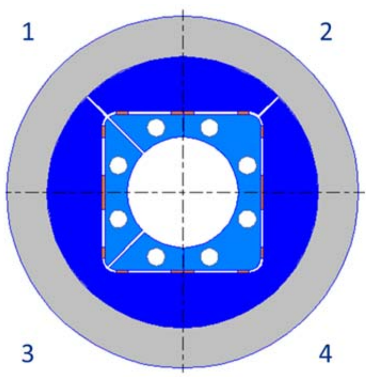


Figure 2: Four possible iron yoke configurations inside the aluminum shell: 1 – 4-piece yoke and 4-piece pad; 2 - 4-piece yoke and 2-piece pad; 3 – 2-piece yoke and 4-piece pad; 4 – 2-piece yoke and 2-piece pad.

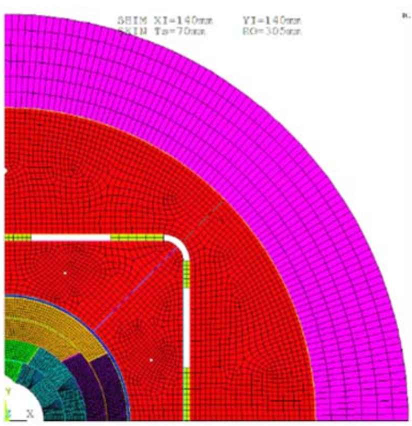


Figure 3: ANSYS model of FNAL 15 T dipole demonstrator with the alternative mechanical structure.

Four possible iron yoke and pad configurations, shown in Fig. 2, and two aluminium shell thicknesses, 50 mm and 70 mm, were studies. Finite element analysis using a parametric 2D ANSYS model was performed for each iron configuration and shell thickness to optimize the stress in the coil and support structure, and to minimize the magnet cross-section deformation during assembly, cooldown and operation up to the design bore field of 15 T.

The ANSYS model of the FNAL 15 T dipole coils and the alternative mechanical structure is shown in Fig. 3. The material properties used in the analysis are reported in [3]. The variables were yoke-pad key sizes and positions. The key criteria of the mechanical analysis were a) maintaining the coils under compression up to the design field of 15 T, and b) keeping the peak coil stress below 150 MPa during magnet assembly and below 200 MPa during operation.

Analysis has shown that configuration #2 with 2-piece pad and 4-piece iron yoke inside the 50-mm aluminum shell meets the design criteria and is the most suitable for the FNAL 15 T dipole demonstrator from both the assembly and operation standpoints. Distributions of the equivalent stress in the coil after assembly, cooldown and at the bore field of 15 T for this configuration are shown in Fig. 4.

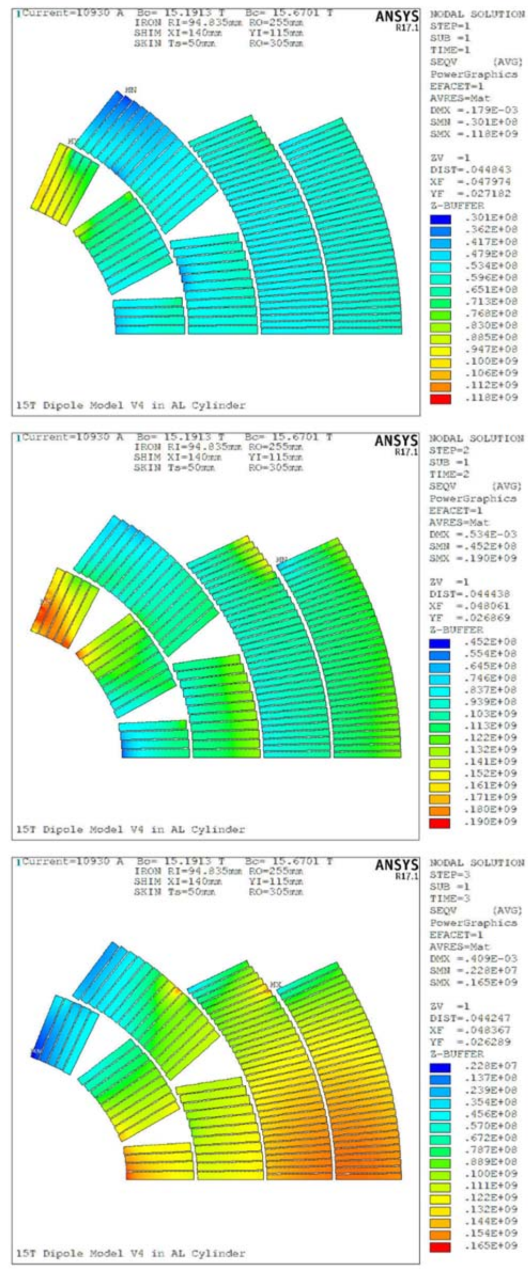


Figure 4: Coil stress diagrams in structure configuration #2 with 50 mm thick Al shell.

Table 2: Average Azimuthal Stress in Selected Turns.

Position in coil	Azimuthal coil stress, MPa		
	Assembly	Cool down	B=15 T
Pole 1	89	168	3
Pole 2	45	87	21
Pole 3	65	123	37
Pole 4	61	113	63
Mid-plane 1	59	99	149
Mid-plane 2	66	134	127
Mid-plane 3	61	107	153
Mid-plane 4	67	131	157

Table 3: Peak Equivalent Stress in Coil and Key Structural Elements (MPa).

Structural element	Baseline design			Design with Al shell		
	Assem-bly	Cool down	15 T	Assem-bly	Cool down	15 T
Coil	133	176	168	118	190	165
Yoke	115	353	448	174	308	364
Clamp	118	280	292	-	-	-
Skin	280	404	428	206	339	366

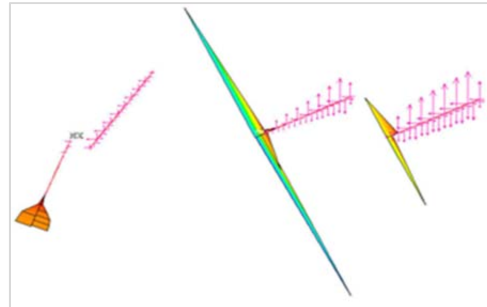
The average transverse (azimuthal) stress in the pole and mid-plane turns of the coil layers at the reference stages for the design with aluminum shell is summarized in Table 2. This numbers are consistent with the numbers for the baseline design shown in Table 1.

The peak equivalent stress in the coil and in the structural elements after magnet assembly, cooldown and at the design field of 15 T is presented in Table 3. The peak equivalent coil stress at room temperature is ~120 MPa and after cooldown is ~190 MPa. It occurs in the innermost-layer pole turn. The pre-stress rise in the pole-turns is provided by the contraction of the Al shell. In this structure the gaps between iron pieces are always open. To limit the maximum coil stress in the Pole 1 turn after cooldown a 5 mm cutout was introduced to the Pole 1 block. As in the baseline structure at the bore field of 15 T, the peak equivalent stress is in the innermost layer mid-plane turns and is close to 165 MPa. The peak stress in the key structural elements of both designs is also at an acceptable level for the materials used.

Figure 5 shows the calculated gaps on the interface between pole turns and pole blocks of all the four coil layers at the bore field of 15 T in the structure with aluminum shell (top) and in the baseline structure (bottom). It can be seen that both structures provide contact of pole turns with pole blocks at operation fields up to 15 T.

CONCLUSION

An alternative magnet support structure based on a thick aluminum shell, 4-piece iron yoke and 2-piece iron pad for the FNAL 15 T dipole demonstrator has been studied and optimized to manage the large level of Lorentz forces. It was shown that the new structure allows keeping the stresses in the coil and support structure within acceptable limits during magnet assembly and operation.



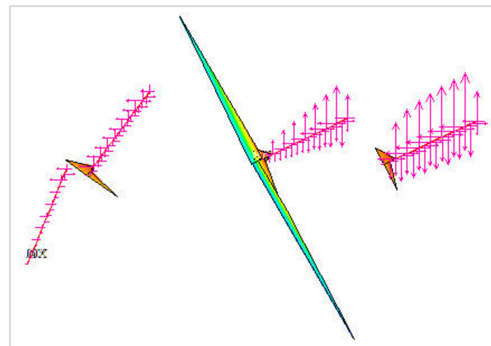


Figure 5: Pole turn gaps at the bore field of 15 T in the alternative (top,) and in the baseline structures (bottom,). The largest partial gap, seen in both cases on the inner edge of layer 3, is only 4 µm and 8 µm respectively.

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