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15 T NB_3SN DIPOLE DEMONSTRATOR - DESIGN AND PARAMETER SPECIFICATION

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Abstract

A 100 TeV scale HC with a nominal operation field of at least 15 T is being considered for the post-LHC era. Practical demonstration of this field level in an accelerator-quality magnet and substantial reduction of the magnet costs are the key conditions for realization of such a machine. FNAL has started the development of a 15 T dipole demonstrator based on Nb_3Sn superconductor for a 100 TeV scale HC. The magnet design is based on 4-layer shell type coils, graded between the inner and outer layers to maximize the performance. The experience gained during the 11-T dipole R&D campaign is applied to different aspects of the magnet design. This document describes the design concept and parameters of the 15 T Nb_3Sn dipole demonstrator.

History of Changes

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1. INTRODUCTION

Hadron Colliders (HC) are the most powerful discovery tools in modern high energy physics. Interest in an HC with energy above the LHC reach has gained further momentum in the strategic plans recently developed in the U.S., Europe and China [1]-[3]. To build a ~100 TeV center of mass energy HC in a ~100 km tunnel, dipoles with a nominal operation field of ~15 T and ~20% margin are needed. A nominal field of ~15 T can be provided only by the Nb_3Sn superconductor pushing the Nb_3Sn magnet technology to its technical limit. A practical demonstration of this field level in accelerator-quality magnets and a substantial reduction of magnet costs are key conditions for the realization of such a machine.

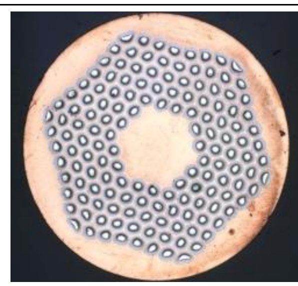
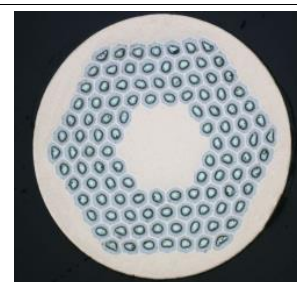
The foremost challenges for 15 T Nb_3Sn magnets include considerably larger coil volume, Lorentz forces and stored energy than in present accelerator magnets. The coil width, necessary to achieve the 15 T field level, requires 4-layer coil design [4]. The stronger forces produce higher stresses in the coil and in the magnet mechanical structure and, thus, stress control tools may be needed to keep stresses at an acceptable level for the brittle Nb_3Sn conductor. The large stored energy also leads to additional complications in the magnet quench protection.

FNAL has started the development of a 15 T Nb3Sn dipole demonstrator for a 100 TeV scale HC based on the optimized "cos-theta" coil design [4], [5]. The experience gained at FNAL during the Nb3Sn accelerator magnet R&D for VLHC and LHC upgrades [6], [7], will be applied to all stages of the magnet design and fabrication. The main objectives of this magnet are demonstration of the 15 T field level in an aperture suitable for future HC and study of the magnet quench performance and margins, quench protection and field quality. This document describes the design concept and target parameters of the 15 T Nb_3Sn dipole demonstrator.

2. NB₃SN STRAND

The magnet will use Nb_3Sn strands produced through the Restack Rod Process® (RRP) and supplied by Oxford SC Technologies (OST). The strand cross-sections and parameters are shown in Table 1.

Table 1. Strand parameters.

Parameter	Value	
		
Process	ternary RRP	ternary RRP
Strand diameter, mm	1.000±0.003	0.700±0.003
Strand cross-section design	150/169	108/127
Cu fraction, %	53±3	53±3
Effective sub-element diameter, µm	<60	<60
Critical current I_c(12T,4.2K), A	>800 (>400*)	>475

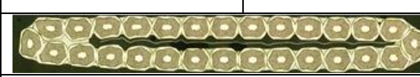
Critical current density J_c(12T,4.2K), A/mm^2	>2650 (>1500*)	>2650
RRR (after heat treatment)	>60	>60
Twist pitch, mm	14±2	14±2
Twist direction	right-hand screw	right-hand screw
Minimum piece length, m	>550	>550

*At 15T 4.2 K

3. CABLE

The 4-layer graded coil was designed based on the two cables with the same 15 mm width and various thicknesses. To reduce eddy current effects both cable use resistive core made of 11 mm wide 0.025 mm thick stainless steel tape. The main parameters of the Rutherford-type cables are listed in Table 2, together with the illustration of the cable cross-section. During the reaction cycle, the Nb_3Sn strands expand due to the phase transformation. Therefore, the cable cross-section parameters are specified for both, un-reacted and reacted cables. The dimensioning of the coil winding and curing tooling is determined by the cable cross-section prior to reaction, whereas the geometrical parameters of the coil-reaction and impregnation tooling are based on the reacted cable's dimensions. The latter ones are also used for the electromagnetic and structural optimization.

Table 2. Cable parameters.

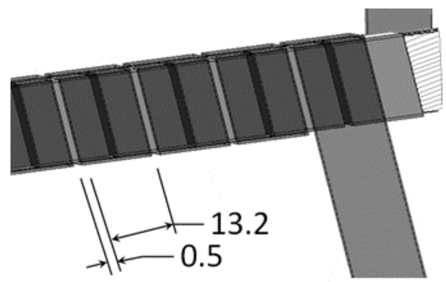
Parameter	**Value**			
	Unreacted	**Reacted***	**Unreacted**	**Reacted***
				
Cable unit length, m	110			
Number of strands	40		28	
Transposition angle, degree	15		15	
Transposition direction	Left-hand screw		Left-hand screw	
Mid-thickness, mm	1.268	1.319	1.798	1.870
Thin edge, mm	1.166	1.213	1.696	1.764
Thick edge, mm	1.370	1.425	1.900	1.976
Width, mm	14.8	15.1	14.8	15.1
Key-stone angle, degree	0.79	0.805	0.79	0.805
Insulation thickness, mm	0.150	0.125	0.15	0.125

*assuming an expansion factor of 4% in thickness and 2% in width.

4. CABLE INSULATION

The cables are insulated with E-glass tape. The insulation scheme and main dimensions are shown in Table 3.

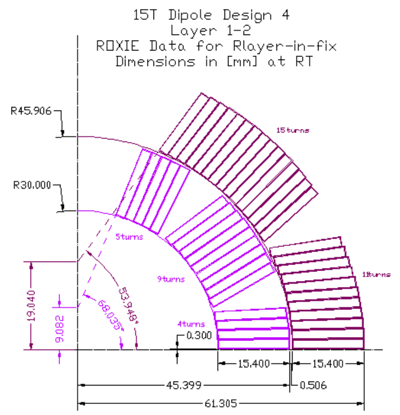
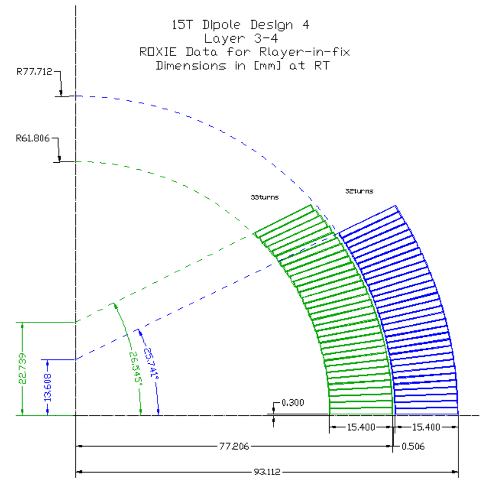
Table 3. Cable insulation.

Parameter	
Material	E-glass
Type	Tape
Number of layers	2
Wrap direction	Right-hand screw
Tape Width, mm	12.7
Tape thickness, mm	0.075

5. COIL

The coil cross-section was optimized to deliver the highest possible dipole field with relative systematic field errors at 10^{-4}-level. The inner and outer layers are wound from a single cable length and the layer-jump is integrated in the first end spacers of the lead-end. The metallic end spacers and their position have been optimized for low strain in the winding blocks, and to minimal integrated low-order field harmonics in the end regions. The inter-layer insulation is made of three layers of ceramic cloth, impregnated and cured with ceramic binder. The coil power leads are made of 28-strand cable made of 1.0 mm NbTi-strand. The electrical connection between the Nb_3Sn and the NbTi cables is done in the lead-end after the reaction process and prior to vacuum-impregnating the coil with epoxy resin. The coil cross-section and parameters are shown in Table 4. The coil outer wrap replaces the mica glass sheets used during the coil reaction and consist of 0.125 mm cloth impregnated with epoxy.

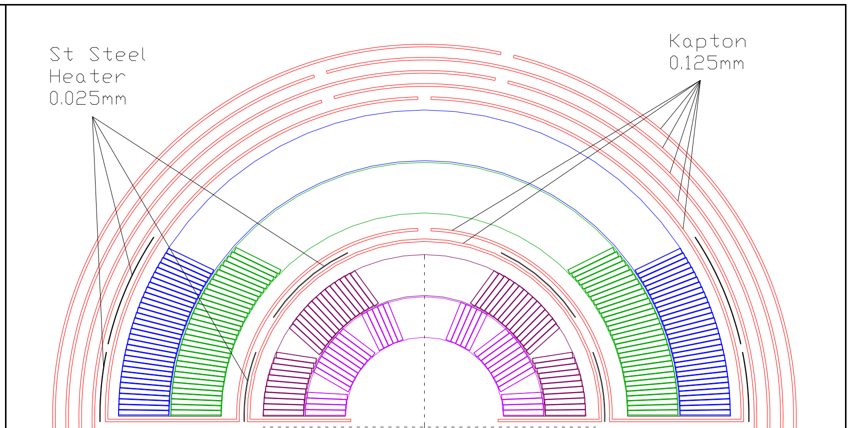
Table 4. Coil parameters.

Parameter	Value	
		
Coil	1-2	3-4
Number of layers	2	2
Number of blocks	5	2
Number of turns/coil	18+26	33+32
Mid-plane spacer at nominal coil pre-stress, mm	0.300	0.300
Interlayer insulation (after HT), mm	0.506	0.506
Coil wrap, mm	0.125	0.125
Coil Inner radius, mm	29.875	61.681
Coil outer radius (impregnated), mm	61.430	93.237
Coil winding length, mm	TBD	TBD
Inner-layer winding direction	Clock-wise	Clock-wise
Outer-layer winding direction	Counter clock-wise	Counter clock-wise
Lead splice length, mm	110	110

6. COIL GROUND INSULATION AND QUENCH HEATERS

The ground insulation insulates the poles electrically from each other and from the collar structure sitting at ground potential. A multilayer design of the ground insulation increases the insulation robustness and allows the incorporation of the quench protection heaters. Preliminary quench analysis indicates that this demonstrator magnet can be protected by quench heaters located on the two outer-layer blocks. Quench protection heaters composed of stainless steel strips are placed between the 2nd and 3rd coil layers and on the coil outer layer. The heaters are composed of stainless steel strips, co-laminated in a sandwich of polyimide foils, and placed on top of the corresponding coil blocks. The layout and basic characteristics of ground insulation and quench protection heaters are given Table 5.

Table 5. Ground insulation and quench heater characteristics.

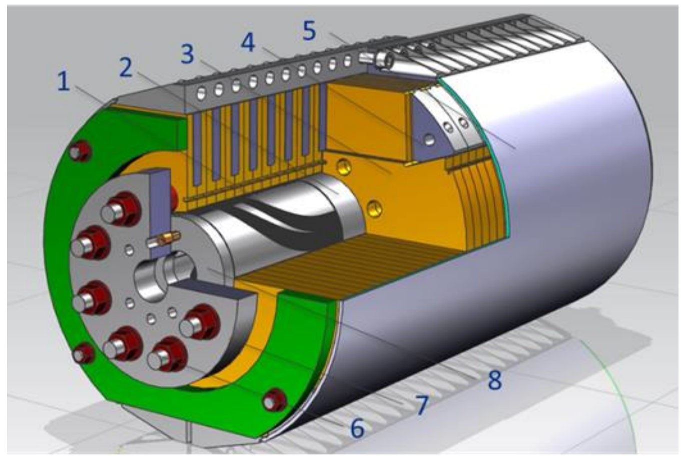
Parameter		
Insulation type	Inter-coil	Ground
Number of layers	2	5
Insulation material	Kapton	Kapton
Layer thickness, mm	0.125	0.125
Number of heaters/coil	4	4
Heater material	316	316
Heater width, mm	TBD	TBD
Heater thickness, mm	0.025	0.025

7. COLD MASS

The coil assembly is surrounded by a 2 mm stainless steel spacer and supported by a vertically split iron yoke and aluminum clamps. The yoke is surrounded by a 12.7 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 on the coil ends are intercepted by two 50 mm thick end plates connected by eight tie rods running through the dedicated holes in the iron yoke. The magnet cold-mass is ~1 m long. The maximum cold mass transverse size is ~612 mm, which is limited by the inner diameter of the FNAL test cryostat. The cold mass design and preliminary parameters are shown in Table 7.

Table 6. Cold mass parameters

Parameter	
1 – 4-layer Nb_3Sn coil; 2 – coil-yoke stainless steel spacer; 3 – iron yoke laminations; 4 – aluminium I-clamp; 5 – stainless steel bolted skin; 6 – axial tie rod; 7 – stainless steel end plate with instrumented bullets; 8 – pusher ring.	
Yoke ID, mm	192.3
Yoke OD, mm	587
Yoke length, mm	~1050
Yoke material	AISI 1018 HR
Number of alignment keys	2
Alignment keys material	Bronze
I-Clamp length, mm	~500
I-Clamps material	AL 7075 T6
Skin thickness, mm	12.7
Skin material	~~304L~~ 316
End plate thickness, mm	50
End plate material	316
Number of axial tie rods	8
Tie rod diameter, mm	30
Tie rod material	316
Cold mass diameter, mm	612
Cold mass length, mm	~1150

8. MAGNETIC PARAMETERS AND PERFORMANCE GOALS

The design parameters are shown in Table 8. Table 9 lists the expected geometrical field harmonics and the transfer function.

Table 7. Magnetic parameters and performance goals.

Parameter	Value
Short sample current I_c at 4.2 K, A	11.34
Short sample current I_{max} at 1.9 K, A	12.52
Maximum design field at 4.2 K, T	15.61
Maximum design field at 1.9 K, T	17.04
Peak field / central field at I_{nom}	1.041
Inductance at Ic, mH/m	25.61
Stored energy at Ic, MJ/m	1.65
Horizontal force Fx/quadrant at Ic, MN/m	7.36
Vertical force Fy/quadrant at Ic, MN/m	-4.50
Longitudinal force Fz/magnet end at Ic, MN/end	1.59

Table 8. Geometrical field harmonics (R_{ref} = 17 mm).

	Value
b_3	0.0018
b_5	0.0154
b_7	0.0523
b_9	0.0612

9. REFERENCES

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[2] Future Circular Collider Study Kickoff Meeting, Geneva, Switzerland, February 12-14, 2014, http://indico.cern.ch/event/282344/timetable/#20140212

[3] CEPC/SppC study in China, http://indico.cern.ch/event/282344/session/1/contribution/65/material/slides/1.pdf

[4] A.V. Zlobin et al., “Design concept and parameters of a 15 T Nb_3Sn dipole demonstrator for a 100 TeV hadron collider,” Proc. of IPAC2015, Richmond (VA), May 2015.

[5] V.V. Kashikhin et al., “Magnetic and structural design of a 15 T Nb_3Sn accelerator dipole model,” Proc. of CEC/ICMC2015, Tucson (AZ), 2015. IOP Conf. Ser.: Materials Science and Engineering (MSE), submitted for publication.

[6] A.V. Zlobin, “Status of Nb_3Sn Accelerator Magnet R&D at Fermilab”, EuCARD - HE-LHC'10 AccNet mini-workshop on a “High-Energy LHC”, 14-16 October 2010, FERMILAB-PUB-11-001-TD, CERN Yellow Report CERN-2011-003, p. 50. [arXiv:1108.1869]

[7] A.V. Zlobin et al., “11 T Twin-Aperture Nb_3Sn Dipole Development for LHC Upgrades,” IEEE Trans. Appl. Supercond., v. 25, Issue 3, June 2015, 4002209.