Design and Fabrication of a Single-Aperture 11T Nb_3Sn Dipole Model for LHC Upgrades

A.V. Zlobin, N. Andreev, G. Apollinari, B. Auchmann, E. Barzi, R. Bossert, M. Karppinen, F. Nobrega, I. Novitski, L. Rossi, D. Smekens, D. Turrioni, R. Yamada

***Abstract*—The planned upgrade of the LHC collimation system includes additional collimators to be installed in the dispersion suppressor areas of points 2, 3 and 7. To provide the necessary longitudinal space for the collimators, a replacement of 8.33 T Nb-Ti LHC main dipoles with 11 T dipoles based on Nb_3Sn superconductor compatible with the LHC lattice and main systems is being considered. To demonstrate this possibility FNAL and CERN have started a joint program to develop a 2 m long single-aperture dipole magnet with the nominal field of 11 T at ~11.85 kA current and 60 mm bore. This paper describes the demonstrator magnet magnetic and mechanical designs and analysis, coil fabrication procedure. The Nb_3Sn strand and cable parameters and test results are also reported.**

***Index Terms*— LHC Upgrade, Nb_3Sn cable, Superconducting Dipole Magnet.**

I. Introduction

THE medium term plan for the LHC operation includes an upgrade of the LHC collimation system [1]. As part of this upgrade, additional collimators will be installed in the dispersion suppression (DS) regions around points 2, 3, and 7. To obtain the necessary longitudinal space of about 3.5 m for the additional collimators, a solution based on an 11 T dipole as a replacement for several 8.33 T LHC main dipoles (MB) is being considered. These twin-aperture dipoles operating at 1.9 K will be powered in series with the main dipoles and deliver the same integrated strength of 119 Tm at the nominal current of 11.85 kA. Recent progress in the development of Nb_3Sn accelerator magnets indicates that this technology can meet the requirements.

To demonstrate the feasibility, CERN and FNAL have started a development program with the goal of building a 5.5 m long twin-aperture Nb_3Sn dipole cold mass for the DS region upgrade. Two such cold masses will replace one 14.3 m long LHC MB dipole. The first phase of this program is the design and construction of a 2 m long demonstrator magnet, delivering 11 T in a 60 mm bore at the LHC nominal operating current of 11.85 kA with 20% margin on the load line [2]. The goal of this magnet is to demonstrate the quench performance, nominal field, and operation margin of the Nb_3Sn coils in a single-aperture structure. Then, two twin-aperture 2 m long demonstrator magnets will be fabricated and tested to study and optimize the quench performance, field quality, operation margin, and quench protection of Nb_3Sn collared coils inside the modified LHC iron yoke. The conceptual design studies of the twin-aperture 11 T dipole have been started [3].

The design and technology of the demonstrator magnet relies on results of Nb_3Sn magnet R&D programs at FNAL [4], and Nb-Ti LHC magnet development at CERN [5]. To meet the tight project schedule within the available budget, the demonstrator magnet is designed to make maximum use of the existing tooling, infrastructure, and magnet components at both laboratories.

II. Magnet Design

The design concept of the 11 T demonstrator dipole magnet features two-layer Nb_3Sn shell-type coils, stainless steel collars, and a vertically split iron yoke, surrounded by a stainless steel skin. To accommodate the beam sagitta in the long 11 T magnets and avoid the additional complication of curved Nb_3Sn coils, the coil aperture was increased from 56 to 60 mm so that these magnets could be straight.

For the twin-aperture 11 T magnet, the 550 mm outer diameter of the iron yoke, the heat exchanger location, and the slots for the bus bars shall be identical to the MB yoke. The demonstrator magnet will use the existing 400 mm yoke from Fermilab's dipole models of HFDA series [6] with the inner contour adapted to the collared coil design.

A. Magnetic Design

The cross-section of the demonstrator dipole coil was optimized using the ROXIE code [7] inside the preliminary twin-aperture configuration. The goal was to provide a dipole field above 11 T at 11.85 kA with 20% operation margin, and geometrical field errors below the 10^{-4} level. Figure 1 illustrates the 6-block coil cross-section with relative field errors in the aperture.

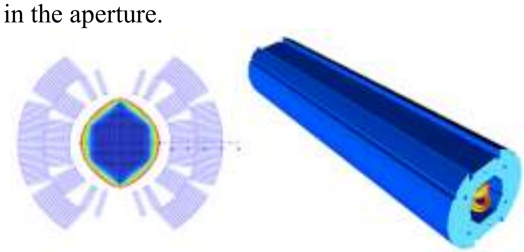

Fig. 1. Coil cross-section (left) with geometrical field errors (dark blue indicates relative errors below 10^{-4}) and 3D yoke magnetic model (right).

Manuscript received 12 September 2011. Work was supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy.

N. Andreev, G. Apollinari, E. Barzi, R. Bossert, F. Nobrega, I. Novitski, D. Turrioni, R. Yamada, A.V. Zlobin are with Fermilab, Batavia, IL 60510, USA (phone: 630-840-8192; fax: 630-840-3369; e-mail: zlobin@fnal.gov).

B. Auchmann, M. Karppinen, D. Smekens, L. Rossi are with CERN, CH-1211 Geneva 23, Switzerland.

TABLE 1 MAGNET DESIGN PARAMETERS.

Parameter	Value
Nominal current I_{nom}, A	11850
Nominal bore field, T	10.86
Short sample current I_c at 1.9 K, A	15030
Ultimate design field, T	12.0
Inductance at I_{nom}, mH/m	5.56
Stored energy at I_{nom}, kJ/m	473
F_x per quadrant at I_{nom}, kN/m	2889
F_y per quadrant at I_{nom}, kN/m	1570

The coil optimization was based on 14.85 mm wide and 1.3 mm thick Rutherford cable with 0.8 degree keystone angle [8] and 0.1 mm thick insulation, and a 30 mm thick round collar.

The coil consists of 56 turns, 22 turns in the inner layer and 34 turns in the outer layer. The thickness of the insulation between the coil layers is 0.506 mm. The mid-plane insulation thickness is 0.125 mm per coil. Coil end blocks were optimized for minimal integrated low-order field harmonics.

The calculated design parameters of the demonstrator magnet are summarized in Table 1. The strand nominal critical current density $J_c(12T,4.2K)$ is 2750 A/mm^2 and the nominal Cu fraction is 0.53. This calculation assumes a 10% critical current degradation in the cable with respect to the nominal strand parameters. In the single-aperture configuration with a 400 mm diameter iron yoke the calculated central field at the nominal current of 11.85 kA is 10.86 T, whereas in the twin-aperture configuration it reaches 11.23 T [3]. The demonstrator magnet's margin to quench on the load line is 21%. The iron yoke length is 1.9 m covering the entire coil, which results the conductor peak field being 1.5% higher in the ends than in the straight section.

The magnetic length of the demonstrator magnet is 1.79 m. Table 2 shows the transfer function and the expected field harmonics at injection and at nominal current with a standard LHC pre-cycle. The data include coil magnetization effect due to persistent currents in the Nb_3Sn filaments and the iron saturation effect. The yoke of the demonstrator magnet was not optimized to suppress the iron saturation effect. The comparison of the magnetic design with measurements will help to understand and optimize the field quality in the twin-aperture 11 T dipole magnet.

The Nb_3Sn RRP-108/127 strand [9] used in the demonstrator magnet has a relatively large effective filament diameter of ~50 μm as compared to ~5 μm in the Nb-Ti strands of the LHC main dipole cable [5]. As a consequence, the persistent current effect is significantly larger in the 11 T Nb_3Sn dipole than in the 8.3 T Nb-Ti LHC main dipoles. Measurements on the demonstrator magnet will provide experimental data to minimize this effect in twin-aperture magnets. The magnetization effects related to inter-filament and inter-strand coupling currents will also be experimentally evaluated during the demonstrator magnet test.

TABLE 2 TRANSFER FUNCTION AND FIELD HARMONICS (IN UNITS 10^{-4}) IN THE STRAIGHT SECTION AT R_{REF}=17 MM AFTER A NOMINAL LHC PRE-CYCLE.

Parameter	I_{inj} = 757 A	I_{nom} = 11850 A
B_1/I, T/kA	1.01	0.92
b_3	38.4	-0.8
b_5	5.3	0.1
b_7	0.0	0.0
b_9	1.0	1.0

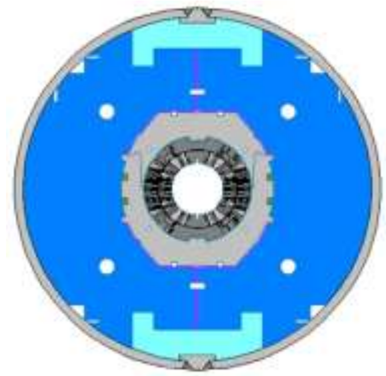

Fig. 2. 11 T demonstrator dipole cold mass cross-section.

B. Mechanical Structure

The cold mass cross-section of the 11 T demonstrator dipole is shown in Figure 2. Coil mechanical pre-stress and support in the magnet is provided by the optimized stainless steel collars (slightly elliptical, 25 mm wide near coil midplanes), vertically split 400 mm iron yoke, Al clamps and 12.5 mm thick stainless steel skin. Two 50 mm thick end plates restrict the longitudinal coil motion under axial Lorentz forces. The pre-stress, applied to the magnet coils at room temperature during assembly, has to be sufficient to compensate for the difference in the coil and structure thermal contractions during cool-down, and Lorentz forces during magnet excitation.

Finite element analysis using a fully parametric ANSYS model (Fig. 3, left) has been performed to optimize the stress in the coil and major elements of the magnet support structure, and to minimize the conductor motion and magnet cross-section deformation at room and operation temperatures. The materials used in the magnet and their properties are listed in Table 3. The mechanical structure was optimized to maintain the coils under compression up to the ultimate design field of 12 T and the coil stress below 165 MPa at all times, which is considered a safe level for brittle Nb_3Sn coils [10].

TABLE 3 MATERIAL PROPERTIES

Structural element	Material	Thermal contract. (300-2 K), mm/m	Elasticity modulus, GPa		Yield stress, MPa	
			warm	cold	warm	cold
Coil* (rad/azim)	Composite	2.6/3.5	44/44	44/50	n/a	n/a
Pole blocks	Ti-6Al-4V	1.7	115	125	650	>900
Collar	Nirosta high-Mn steel	2.9	190	210	650	>1000
Key	Phosp. Bronze	3.3	110	123	360	>500
Clamp	Al 7075-T6	4.1	70	85	460	650
Yoke	Soft Iron 1045	2.0	205	225	350	>400
Skin	304L	2.9	190	210	230	500

*- including stainless steel wedges

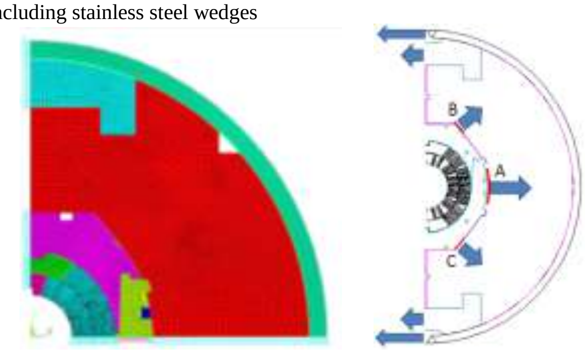

Fig. 3. Demonstrator dipole ANSYS model (left) and forces and reactions in the demonstrator dipole mechanical structure (right).

The required coil pre-stress in the 11 T demonstrator dipole is created in three steps.

The initial coil pre-load is provided by ~0.100 mm mid-plane and 0.025 mm radial shims during the coil collaring. Due to the relatively large coil width and high rigidity the maximum achievable pre-stress in the pole region is limited at this stage by the maximum coil stress near the mid-plane, which is approximately a factor of two higher than in the pole turns. Then, during the collared coil assembly inside the iron yoke, the coil pole pre-stress is increased by horizontal deformation of the collared coils (coil bending) using ~0.125 mm horizontal collar-yoke shims (A in Fig.3 right) and restricting the vertical collared coil deformation within the iron yoke in areas B and C (see Fig. 3, left). The horizontal shims also provide the collar-yoke contact after the magnet cool-down. The final coil pre-stress is achieved after magnet cool-down to operation temperature. To avoid a coil pre-stress reduction during cool-down due to a larger thermal contraction of the stainless steel skin and the collared coil relative to the iron yoke, the vertical gap between the two yoke halves stays open at all stages. It is controlled by the Al clamps and the collar-yoke shims near the top and bottom horizontal surfaces of the collared coil (B and C in Fig. 3).

The calculated maximum coil stress in the pole and mid-plane turns of the inner and outer layer in the demonstrator dipole model after collaring and cold mass assembly at room temperature, cooling down to operating temperature, and maximum design field of 12 T is summarized in Table 4. Stress distribution diagrams in the coil at the aforementioned stages are shown in Figure 4. With the chosen coil pre-load approach the pole turns remain under compression at all stages and the maximum coil stress remains below 162 MPa.

TABLE 4 NOMINAL COIL PRESTRESS IN POLE AND MIDPLANE REGIONS

Position in coil	Azimuthal Coil Stress, MPa			
	Collared coil	Cold mass	Cool down	Max design field B=12T
Inner pole	-44	-120	-136	-2
Outer pole	-64	-87	-110	-17
Inner midplane	-97	-79	-97	-141
Outer midplane	-51	-108	-124	-153

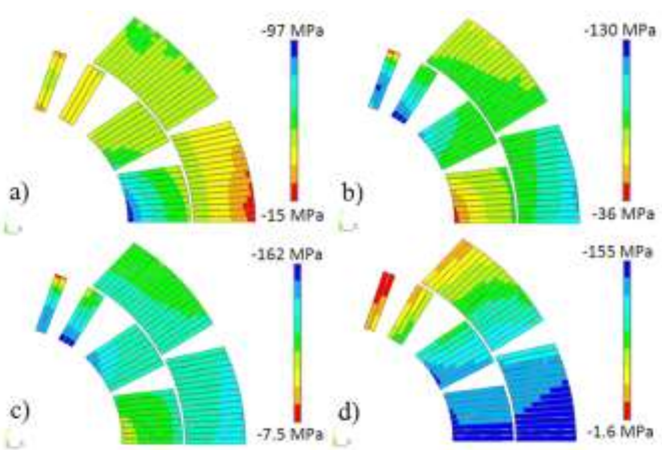

Fig. 4. Azimuthal stress distribution in the coil after collaring (a) and cold mass assembly (b) at room temperature, cooling down to operating temperature (c) and at the ultimate design field of 12 T (d).

TABLE 5 MAXIMUM STRESS IN STRUCTURE COMPONENTS.

	Maximum Stress, MPa					
	Poles (inner/outer)	Collar	Key	Yoke	Clamp	Skin (average)
Collaring	176/101	630	350	n/a	n/a	n/a
Assembly	564/179	524	198	334	190	176
Cooldown	648/275	588	134	420	212	272
B_{max}=12 T	91/144	781	244	388	209	276

The maximum stress values in the major elements of the magnet support structure calculated at different assembly and operation stages are shown in Table 5. All these values are below the yield stress of the chosen structural materials.

The calculated coil bore deflections due to the coil pre-stress and Lorentz forces from the warm unstressed round geometry at room temperature and from the cold unstressed round geometry (magnetic design) at operation temperature in the demonstrator dipole straight section are shown in Table 6. The maximum radial cross-section deflection from the magnetic design decreases from 0.135 mm at low (injection) current to less than 0.04 mm at the nominal operation current.

TABLE 6 COIL INNER RADIUS DEFLECTIONS.

	Bore radial deflection, μm		
	Pole	Midplane	45 degrees
Collaring	46	-17	29
Assembly	74	-130	9
Cooldown	70	-135	4
B_{max}=12 T	32	-41	23

C. Quench Protection

Magnet quench protection in accelerators is provided by internal quench heaters. The 11 T Nb_3Sn dipoles have larger stored energy and inductance than the regular LHC dipoles and thus need special attention to their quench protection. Results of the preliminary quench analysis suggest that the quench protection scheme with efficient outer-layer heaters could provide adequate protection of the 11 T Nb_3Sn dipoles. Experimental studies and optimization of quench heaters are an important part of the demonstrator dipole test program.

Quench protection heaters composed of 0.025 mm thick stainless steel strips are placed between the 2^{nd} and 3^{rd} layers of ground insulation, covering the outer-layer coil blocks (Fig. 5, left). The heater strips on each side of each coil are connected in series forming two circuits connected in parallel (Fig. 5, right). The quench protection study will include the minimal heater quench energy, the coil response time, the maximum coil temperature and quench voltages, etc.

During magnet training the demonstrator dipole will be protected by using a 60 mΩ external dump resistor. In this case the coil to ground voltage will be below 1 kV and the coil maximum temperature in a hot spot below 400 K at all currents up to the magnet short sample limit.

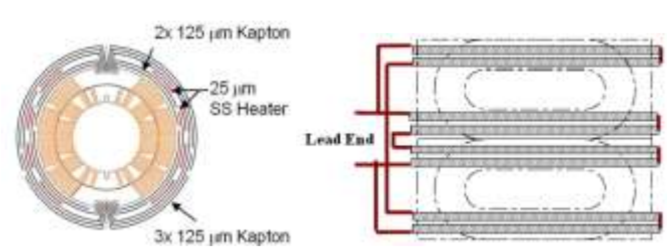

Fig.5. Quench protection heater position (left) and connection scheme (right).

III. Technology and Model Fabrication Status

A. Cable

A Rutherford cable for the 11 T Nb_3Sn demonstrator dipole magnet has been developed [8]. The cable has 40 RRP-108/127 0.7 mm strands, 15 degree transposition angle and 85% packing factor. The cable fabrication procedure consists of two steps. First, the cable with rectangular cross-section is made. Then, after an intermediate anneal it is re-rolled into the final keystoned cross-section. The experimental data collected for Nb_3Sn cables indicate that the cable cross-section expands anisotropically during reaction due to the superconducting phase transformation [11]. An additional thickness and width of 3% and 1%, respectevely, relative to the unreacted cable was included in the cable dimensions for the magnetic design optimization. The coil dimensions in winding and curing tooling are determined by the un-reacted cable cross-section, whereas the coil dimensions in reaction and impregnation tooling are based on the reacted cable cross-section. Cable geometrical parameters are listed in Table 7.

TABLE 7 Nominal Cable Parameters

Parameter	Rectangular	Keystoned	
	Un-reacted	Un-reacted	Reacted
Mid-thickness, mm	1.300	1.269	1.307
Width, mm	14.50	14.70	14.85
Keystone angle, deg	0.0	0.79	0.81

Cable samples with rectangular and keystone cross sections, with and without a stainless steel core were fabricated and successfully tested [8, 12]. The I_c degradation from cabling is less than 3.5%.

A single 440 m long piece of cable has been fabricated providing two ~200 m long unit lengths for demonstrator dipole coils and ~25 meters of cable for short sample studies.

B. Coil

Each two-layer coil consists of 56 turns and has a length of 1.75 m. Both layers are wound from a single 200 m long piece of cable insulated with two layers of 0.075 mm thick and 12.7 mm wide E-glass tape. The thickness of the insulation between the coil layers is 0.506 mm. The mid-plane insulation thickness is 0.125 mm per coil. The ground insulation of the coils consists of a 0.125-mm-thick layer of epoxy-impregnated E-glass cloth, and 5-layers of 0.125-mm-thick Kapton film.

The coil poles are made of Ti alloy. The end spacers are made of stainless steel using the selective laser sintering (SLS) process. The cable layer jump is integrated into the first end spacers of the lead end.

Coils are fabricated using the wind-and-react method when superconducting Nb_3Sn phase is formed during high-temperature heat treatment of wound coils. During winding each coil layer is impregnated with CTD1008x liquid ceramic binder and cured at 150ºC for half an hour. During curing the coil layers are shimmed azimuthally to a size ~1 mm smaller than the nominal coil size to prevent coil over-compression due to expansion of Nb_3Sn during reaction.

Each coil is reacted separately using a three-step cycle with T_{max}=640°C for 48 hours. Several round and extracted from the cable witness samples are reacted along with each coil to estimate the coil short sample limit. Before impregnation the Nb_3Sn coil leads are spliced to flexible Nb-Ti cables. Each coil is impregnated with CTD101K epoxy and cured at 125°C for 21 hours. The design size of the coil is achieved during the coil impregnation.

Two 2-m-long practice coils, one made of copper cable, and another one made of RRP-114/127-strand, were fabricated and examined prior starting the real coil production in order to test tooling and tune procedures.

C. Coil collaring and cold mass assembly

Assembly and pre-load procedures for brittle Nb_3Sn coils using round collars were developed and successfully demonstrated [13]. The details of these procedures as well as the coil final pre-load during cold mass assembly for the demonstrator will be optimized using a 0.6-m-long mechanical model with the Nb_3Sn practice coil. The collar laminations and yoke block for the mechanical model are being procured.

IV. Conclusion

An 11 T Nb_3Sn twin-aperture dipole magnet for the LHC collimation system upgrade is being developed by a Fermilab-CERN collaboration. To demonstrate the coil technology, a 2 m long, single-aperture demonstrator magnet has been developed. The engineering design of the magnet and fabrication tooling is complete. Two cable unit lengths were fabricated and coil winding has started. The magnet assembly and cold tests are planned at the beginning of 2012.

Acknowledgment

The authors thank technical staff of Fermilab's Technical Division for contributions to magnet design and fabrication.

References

[1] L. Rossi et al., "Advanced Accelerator Magnets for Upgrading the LHC", *this conference*.

[2] A.V. Zlobin et al., "Development of Nb_3Sn 11T Single Aperture Demonstrator Dipole for LHC Upgrades", Fermilab-Conf-11-126-TD, PAC'2011, NYC, March 2011.

[3] M. Karppinen et al., "Design of 11 T Twin-Aperture Nb_3Sn Dipole Demonstrator Magnet for LHC Upgrades", *this conference*.

[4] 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,January 2011.

[5] J. Ahlbäck et al., "Electromagnetic and Mechanical Design of a 56 mm Aperture Model Dipole for the LHC", IEEE Trans. on Magnetics, July 1994, vol 30, No. IV, pp. 1746-1749

[6] G. Ambrosio et al., "Magnetic Design of the Fermilab 11 T Nb_3Sn Short Dipole Model", IEEE Trans. on Applied Supercond., v. 10, No. 1, March 2000, p.322.

[7] ROXIE 10.2, http://cern.ch/roxie.

[8] E. Barzi et al., "Nb_3Sn Cable Development for the 11 T Dipole Demonstration Model", CEC/ICMC'2011, Spokane, WA, June 2011.

[9] M.B. Field et al., "Internal tin Nb_3Sn conductors for particle accelerator and fusion applications," *Adv. Cryo. Engr.*, vol. 54, pp. 237–243, 2008.

[10] G. Chlachidze et al., "The study of single Nb_3Sn quadrupole coils using a magnetic mirror structure," IEEE Trans. on Applied Supercond., Volume 21, Issue 3, June 2011 Page(s): 1692-1695.

[11] N. Andreev et al., "Volume expansion of Nb_3Sn strands and cables during heat treatment", CEC/ICMC'01, Madison, WI, July 2001.

[12] E. Barzi et al., "Development and Fabrication of Nb_3Sn Rutherford Cable for the 11 T DS Dipole Demonstration Model", *this conference*.

[13] R. Bossert et al., "Fabrication and Test of 90-mm Nb_3Sn Quadrupole Model Based on Dipole-Type Collar", IEEE Trans. on Applied Supercond., Volume 21, Issue 3, June 2011 Page(s):1777-1780.