STATUS OF A SINGLE-APERTURE 11 T NB$_3$SN DEMONSTRATOR DIPOLE FOR LHC UPGRADES*

A.V. Zlobin#, N. Andreev, G. Apollinari, E. Barzi, R. Bossert, G. Chlachidze, V.V. Kashikhin, F. Nobrega, I. Novitski, D. Turrioni, R. Yamada, Fermilab, Batavia, IL 60510, U.S.A.
B. Auchmann, M. Karppinen, L. Oberli, L. Rossi, D. Smekens, CERN, CH-1211 Geneva 23, Switzerland

Abstract

The planned upgrade of the LHC collimation system includes additional collimators in the LHC lattice. The longitudinal space for the collimators could be obtained by replacing some LHC main dipoles with stronger dipoles compatible with the LHC lattice and main systems. A joint R&D program with the goal of building a 5.5 m long twin-aperture dipole prototype suitable for installation in the LHC is being conducted by FNAL and CERN magnet groups. This paper describes the design and construction experience of the single-aperture 2 m long Nb$_3$Sn demonstrator dipole for the LHC upgrade.

INTRODUCTION

The LHC operation plans include an upgrade of the LHC collimation system [1]. Additional cold collimators will be installed in the dispersion suppression (DS) regions around points 2, 3 and 7, and high luminosity interaction regions at points 1 and 5. The required longitudinal space of ~3.5 m for the additional collimators could be provided by using 11 T dipoles as a replacement for several 8.33 T LHC main dipoles (MB). These dipoles, operating at 1.9 K and powered in series with the MB's, will deliver the same integrated strength at the nominal LHC current. Recent advances in the development of high-field Nb$_3$Sn accelerator magnets suggest that this technology is ready for this application.

To demonstrate feasibility, CERN and FNAL have started a R&D program to build a 5.5 m long twin-aperture Nb$_3$Sn dipole for the LHC upgrade. Two such cold masses with a cold collimator in between will replace one 14.3 m long LHC MB dipole. The program started with the design and construction of a 2 m long single-aperture Nb$_3$Sn demonstrator magnet which will produce an 11 T field in a 60 mm bore at the LHC nominal current of 11.85 kA with 20% margin [2]. This magnet will demonstrate the nominal field and operation margin of the Nb$_3$Sn coils in a single-aperture configuration. Then, two 2 m long twin-aperture demonstrator magnets [3] will be built to optimize the quench performance, field quality and quench protection of Nb$_3$Sn collared coils inside a modified LHC iron yoke. This paper describes the status of the single-aperture Nb$_3$Sn demonstrator dipole R&D.

* Work supported by Fermi Research Alliance, LLC, under contract No. DE-AC02-07CH11359 with the U.S. Department of Energy
# zlobin@fnal.gov

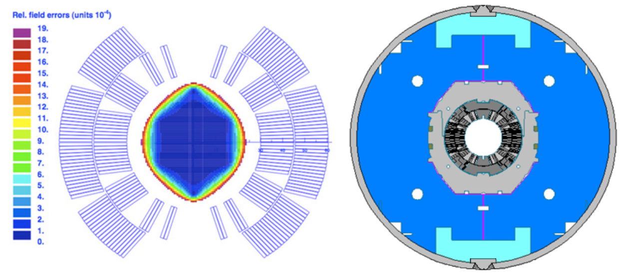

Figure 1: Cross-sections of the coil (left) and the cold mass (right). The dark area in the coil aperture corresponds to relative errors below 10^{-4}.

MAGNET DESIGN

The design concept of the single-aperture 11 T Nb$_3$Sn demonstrator dipole is described in [4]. To accommodate the beam sagitta in the straight 11 m long Nb$_3$Sn magnets, the coil aperture was increased to 60 mm. The coil cross-section was optimized to provide a dipole field above 11 T at the 11.85 kA current with 20% margin, and geometrical field errors below the 10^{-4} level.

Fig. 1 (left) shows the optimized 6-block coil of the demonstrator dipole with relative geometrical field errors in the aperture. The coil cross-section was designed using 15.1 mm wide and 1.29 mm thick Rutherford cable and 0.10 mm thick insulation. The coil consists of 22 turns in the inner layer and 34 turns in the outer layer separated by the 0.506 mm thick interlayer insulation. The mid-plane insulation is 0.125 mm per coil. Coil end blocks were designed to reduce the field level and minimize integrated low-order field harmonics.

The cross-section of the demonstrator dipole cold mass is shown in Fig. 1 (right). Coil pre-stress and support is provided by stainless steel collars, a vertically split iron yoke, Aluminium clamps and a thick stainless steel skin. Two thick stainless steel end plates restrict the axial coil motion from the Lorentz forces applied to the coil ends.

The pre-stress during assembly has to be sufficient to compensate for the differences in the coil and structure thermal contractions during cool-down, and for the Lorentz forces during magnet excitation. The design of the mechanical structure and the coil pre-stress were optimized to maintain the coils under compression up to the ultimate design field of 12 T and keep the coil stress below 165 MPa during magnet assembly and operation.

Magnet quench protection is provided by internal strip heaters installed between the ground insulation layers.

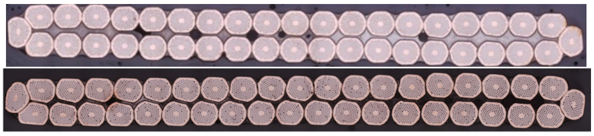

Figure 2: Rectangular (top) and keystoned (bottom) 40-strand cables.

MAGNET CONSTRUCTION

Strand and Cable

The Rutherford cable has 40 Nb_3Sn strands 0.7 mm in diameter, a 15 degree transposition angle and an 85% packing factor [5]. The cable is made of Nb_3Sn RRP-108/127 strand [6] with an effective filament diameter of ~55 µm. The nominal strand $J_c(12T,4.2K)$ is 2750 A/mm^2, the Cu fraction is 0.53 and the matrix RRR is above 60.

A 440 m long piece of cable has been fabricated at FNAL providing two ~200 m long unit lengths for the demonstrator dipole coils and ~25 m piece for short sample studies. The cable was made in two steps, first, with rectangular cross-section and then, after an intermediate anneal, it was re-rolled into the final keystoned cross-section (Fig. 2).

A ~220 m cable piece for a spare coil was fabricated at CERN using a one pass procedure. Tested strand samples extracted from rectangular and keystoned cables show that average I_c degradation after cabling is ~4%.

Coils

Each coil consists of two layers and 56 turns. Both layers are wound from a single 200 m long piece of cable insulated with two layers of E-glass tape 0.075 mm thick and 12.7 mm wide. The coil poles are made of Ti-6Al-4V alloy and wedges are made of stainless steel. 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, i.e. the superconducting Nb_3Sn phase is formed during the coil high-temperature heat treatment. During winding each coil layer is impregnated with CTD1202x liquid ceramic binder and cured under a small pressure at 150ºC for 0.5 hour. During curing the coil layers are shimmed azimuthally to a size ~1 mm smaller than the nominal coil size to prevent turn over-compression due to expansion of the Nb_3Sn cable during reaction [7]. Each coil is reacted separately in an Argon atmosphere using a three-step cycle with T_{max}=640^{o}C for 48 hours. Coil pictures after curing and reaction are shown in Fig.3 (left).

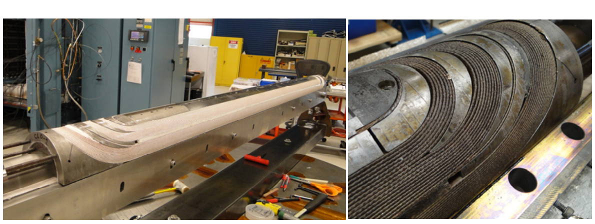

Figure 3: Coil after curing (left) and reaction (right).

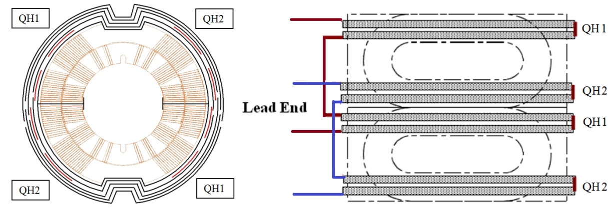

Figure 4: Quench protection heater position (left) and connection scheme (right).

Before impregnation the Nb_3Sn coil leads are spliced to flexible Nb-Ti cables and the coil is wrapped with a 0.125 mm thick layer of E-glass cloth. Each coil is impregnated with CTD101K epoxy and cured at 125°C for 21 hours. The radial and azimuthal coil sizes are controlled in the free condition using a coordinate measuring machine. Two coils, MBH02 and MBH03, with a length of 1965 and 1971 mm were fabricated. The third (spare) coil, MBH04, is being prepared for epoxy impregnation.

Ground Insulation and Protection Heaters

The coil ground insulation consists of 5 layers of 0.125 mm thick Kapton film. Two quench protection heaters composed of 0.025 mm thick stainless steel strips are used on each side of the coil. One heater, QH1, is placed between the 1st and 2nd Kapton layers and the other, QH2, between the 2nd and 3rd layers, covering the outer-layer coil blocks (Fig. 4, left). The resistance of each heater at 300 K is 5.9 Ohm. The corresponding strips on each side of each coil are connected in series forming two independent heaters (Fig. 4, right).

Magnet Assembly

Two coils surrounded by the ground insulation and 316L stainless steel protection shells are placed inside the laminated collars made of Nirosta High-Mn stainless steel. A picture of the collared coil is shown in Fig. 5.

The collared coil is installed inside the vertically split yoke with 400 mm outer diameter made of SAE 1045 iron and fixed with Al clamps. The yoke length is 1950 mm which covers the entire coil and the Nb_3Sn/Nb-Ti lead splices. The 12 mm thick 304L stainless steel shell is pre-tensioned during welding to provide the coil final pre-compression. Two 50 mm thick 304L stainless steel end plates welded to the shell restrict the axial coil motion. A picture of the demonstrator cold mass is shown Fig.6.

Figure 5: Collared coil.

ISBN 978-3-95450-115-1

Figure 6: Demonstrator dipole cold mass.

MAGNET PARAMETERS

Calculated design parameters of the demonstrator magnet at I_{nom}=11.85 kA are shown in Table 1. The calculations considered nominal strand parameters, a 10% cable critical current degradation and peak-field enhancement in the magnet ends. In the single-aperture demonstrator magnet the calculated central field at 11.85 kA is 10.88 T [8], whereas in the twin-aperture magnet it increases to 11.23 T due to field enhancement in the twin-aperture configuration [3].

Table 1: Demonstrator Dipole Design Parameters at I_{nom}.

Parameter	Value
Bore field	10.88 T
Short-sample current/field at	14.72 kA / 13.5
Differential inductance	5.51 mH/m
Stored energy	424 kJ/m
Horizontal Lorentz force	2.89 MN/m
Vertical Lorentz force	-1.58 MN/m

The quench current limit for the demonstrator dipole was also estimated based on measured witness sample data and the calculated magnet load line (Fig. 7). At 4.2 K it is 13.3 kA and at 1.9 K it is 15.0 kA which corresponds to the maximum bore field of 12.67 and 13.39 T respectively. The magnet margin to quench on the load line is 21%.

Table 2 summarizes the results of 2D and 3D simulations for the magnet transfer function *TF* and low order field harmonics at injection and nominal currents after an LHC pre-cycle with a reset current of I_{min}=100 A.

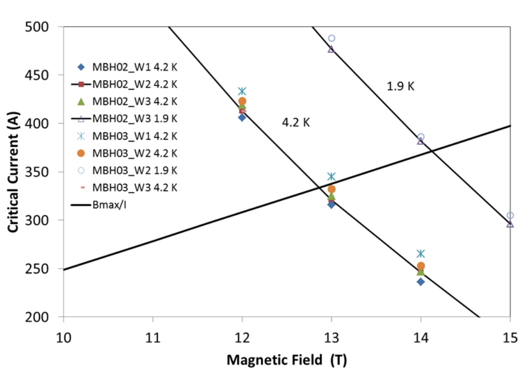

Figure 7: Witness sample $I_c(B)$ and magnet load line.

Differences between 2D and 3D results are due to contributions from the block transition cables, layer jumps and coil leads on the magnet lead end [8].

Table 2: 2D and 3D *TF* and Low-Order Field Harmonics.

Parameter	Value		
Model	3D	2D	2D
Coil Current	I_{nom}	I_{inj}	I_{nom}
Persist. Currents	no	yes	yes
B_1/I, T/kA	-0.92	-1.01	-0.92
b_3	5.7	36.5	-1.4
b_5	1.2	7.9	0.5
b_7	0.0	-0.4	-0.1
b_9	0.8	1.4	1.0
a_1	3.3	0.0	0.0

CONCLUSION

A 5.5 m long, 11 T Nb_3Sn twin-aperture dipole prototype for the LHC collimation system upgrade is being developed by a FNAL-CERN collaboration. To demonstrate the feasibility and magnet performance, a 2 m long, single-aperture demonstrator magnet has been built and is being tested at FNAL.

ACKNOWLEDGMENT

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

REFERENCES

[1] L. Bottura et al., "Advanced Accelerator Magnets for Upgrading the LHC", *IEEE Trans. on Applied Supercond., accepted for publication, 2012.*

[2] A.V. Zlobin et al., "Development of Nb_3Sn 11 T Single Aperture Demonstrator Dipole for LHC Upgrades", *Proc. of PAC'2011*, NYC, 2011, p. 1460.

[3] M. Karppinen et al., "Design of 11 T Twin-Aperture Nb_3Sn Dipole Demonstrator Magnet for LHC Upgrades", *IEEE Trans. on Applied Supercond.*, *accepted for publication,* 2012.

[4] A.V. Zlobin et al., "Design and Fabrication of a Single-Aperture 11 T Nb_3Sn Dipole Model for LHC Upgrades", *IEEE Trans. on Applied Supercond.*, *accepted for publication,* 2012.

[5] E. Barzi et al., "Studies of Nb_3Sn Strands Based on the Restacked-Rod Process for High-field Accelerator Magnets", *IEEE Trans. on Applied Supercond.*, *accepted for publication,* 2012.

[6] M.B. Field et al., "Internal Tin Nb_3Sn Conductors for Particle Accelerator and Fusion Applications," *Adv. Cryo. Engr.*, vol. 54, 2008, p. 237.

[7] N. Andreev *et al.*, "Volume expansion of Nb_3Sn strands and cables during heat treatment", *Adv. in Cryo. Engineer.*, V. 48, AIP, 2002, p. 941.

[8] B. Auchmann et al., "Magnetic Analysis of a Single-Aperture 11 T Nb_3Sn Demonstrator Dipole for LHC Upgrades", *this conference*.