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

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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.

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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 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.
MAGNET CONSTRUCTION

Strand and Cable

The Rutherford cable has 40 Nb\textsubscript{3}Sn strands 0.7 mm in diameter, a 15 degree transposition angle and an 85% packing factor [5]. The cable is made of Nb\textsubscript{3}Sn RRP-108/127 strand [6] with an effective filament diameter of \( \sim 55 \mu m \). 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 \( \sim 200 \) m long unit lengths for the demonstrator dipole coils and \( \sim 25 \) 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 \( \sim 220 \) 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 \( \sim 4\% \).

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\textsubscript{3}Sn 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 \( \sim 1 \) mm smaller than the nominal coil size to prevent turn over-compression due to expansion of the Nb\textsubscript{3}Sn cable during reaction [7]. Each coil is reacted separately in an Argon atmosphere using a three-step cycle with \( T_{max}=640\)ºC for 48 hours. Coil pictures after curing and reaction are shown in Fig.3 (left).

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 1\textsuperscript{st} and 2\textsuperscript{nd} Kapton layers and the other, QH2, between the 2\textsuperscript{nd} and 3\textsuperscript{rd} 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\textsubscript{3}Sn/Nb-Ti lead splices. The 12 mm thick 304L stainless steel shell is pretensioned 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.
MAGNET PARAMETERS

Calculated design parameters of the demonstrator magnet at \( I_{\text{nom}} = 11.85 \) 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 \( I_{\text{nom}} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore field</td>
<td>10.88 T</td>
</tr>
<tr>
<td>Short-sample current/field at</td>
<td>14.72 kA / 13.5</td>
</tr>
<tr>
<td>Differential inductance</td>
<td>5.51 mH/m</td>
</tr>
<tr>
<td>Stored energy</td>
<td>424 kJ/m</td>
</tr>
<tr>
<td>Horizontal Lorentz force</td>
<td>2.89 MN/m</td>
</tr>
<tr>
<td>Vertical Lorentz force</td>
<td>-1.58 MN/m</td>
</tr>
</tbody>
</table>

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 \( I_{\text{min}} = 100 \) A.

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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3D 2D 2D</td>
</tr>
<tr>
<td>Coil Current ( I_{\text{nom}} )</td>
<td>( I_{\text{ini}} ) ( I_{\text{nom}} )</td>
</tr>
<tr>
<td>Persist. Currents</td>
<td>no yes yes</td>
</tr>
<tr>
<td>( B_{1}/I, ) T/kA</td>
<td>-0.92 -1.01 -0.92</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>5.7 36.5 -1.4</td>
</tr>
<tr>
<td>( b_5 )</td>
<td>1.2 7.9 0.5</td>
</tr>
<tr>
<td>( b_{y} )</td>
<td>0.0 -0.4 -0.1</td>
</tr>
<tr>
<td>( b_{o} )</td>
<td>0.8 1.4 1.0</td>
</tr>
<tr>
<td>( a_1 )</td>
<td>3.3 0.0 0.0</td>
</tr>
</tbody>
</table>

CONCLUSION

A 5.5 m long, 11 T Nb\(_3\)Sn 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

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REFERENCES