DEVELOPMENT OF NB_3SN 11 T SINGLE APERTURE DEMONSTRATOR DIPOLE FOR LHC UPGRADES*

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Abstract

The LHC collimation upgrade foresees additional collimators installed in dispersion suppressor regions. To obtain the necessary space for the collimators, a solution based on the substitution of LHC main dipoles for stronger dipoles is being considered. CERN and FNAL have started a joint program to demonstrate the feasibility of Nb_3Sn technology for this purpose. The goal of the first phase is the design and construction of a 2-m long single-aperture demonstrator magnet with a nominal field of 11 T at 11.85 kA with 20% margin. This paper describes the magnetic and mechanical design of the demonstrator magnet and summarizes its design parameters.

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 shall be powered in series with the main dipoles and deliver the same integrated strength of 119 T·m 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. 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. The goal of this model is to demonstrate the quench performance, nominal field, and operation margin of the Nb_3Sn coils in a single aperture structure.

The design and technology of the demonstrator magnet relies on results of Nb_3Sn magnet R&D programs at FNAL [2]-[3], and Nb-Ti LHC magnet development at CERN [4]. 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.

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MAGNET DESIGN AND PARAMETERS

General Concept

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 outer shell. 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 chosen to be 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 exisiting yoke from Fermilab's dipole models of HFDA series [5] with an outer diameter of 400 mm and the inner contour adapted to the collared coil design.

Magnetic Design

The coil cross-section for the demonstrator magnet was optimized using the ROXIE code [6] for the preliminary twin-aperture configuration, based on separate collared coils and 30-mm thick collar. The measured magnetization data of the MB steel were used for field computations. The goal was to provide a dipole field above 11 T at 11.85 kA, 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.

The coil consists of 56 turns, 21 turns in the inner layer and 35 turns in the outer layer. Both layers are wound from a single length of keystoned Rutherford-type cable insulated with two layers of 0.075-mm thick and 12.7-mm wide E-glass tape.

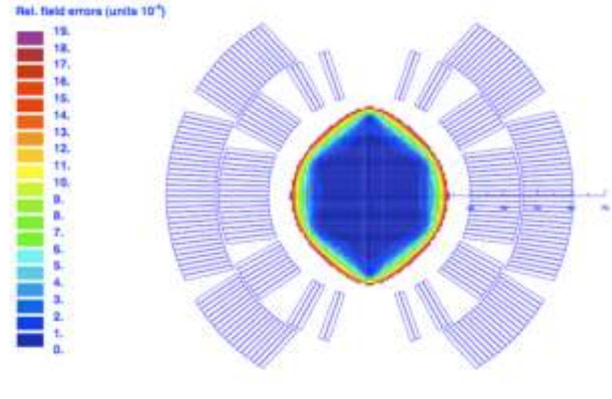

Figure 1: Coil cross-section with geometrical field errors.

Table 1: Cable parameters

Parameter	Value	
	Un-reacted	Reacted
Number of strands	40	
Transposition angle, deg	15	
Mid-thickness, mm	1.269	1.307
Width, mm	14.70	14.85
Keystone angle, deg	0.79	0.81

Cable geometrical parameters are listed in Table 1. The cable is made of 0.700 mm Nb_3Sn RRP-108/127 strand produced by Oxford SC Technologies (OST) using the Restack Rod Process [7]. The strand nominal critical current density J_c(12T,4.2K) is 2750 A/mm^2 and the nominal Cu fraction is 0.53.

During reaction, the Nb_3Sn strands expand due to the phase transformation. Experimental data [8] collected for Nb_3Sn cables suggest an expansion factor of 3% in thickness and 1% in width. The dimensions of the coil winding and curing tooling are determined by the un-reacted cable cross-section, whereas the dimensions of the coil reaction and impregnation tooling are based on the reacted cable dimensions. The latter ones were also used for the coil electromagnetic optimization and analysis.

The thickness of the insulation between the coil inner and outer layers is 0.506 mm. The mid-plane insulation thickness is 0.20-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 stainless steel end spacers were optimized for low strain in the winding blocks, and for minimal integrated low-order field harmonics. The layer jump is integrated in the first end spacers of the lead end.

Mechanical Structure

The cold mass cross-section of the 11T demonstrator dipole is shown in Figure 2. The two epoxy-impregnated coils surrounded by ground insulation and the stainless steel protection shells are assembled inside the laminated stainless steel collars.

The minimal thickness of slightly elliptical collar is 25 mm. The expected azimuthal pre-compression of the coils after collaring is ~70 MPa. The collared coil assembly is then placed in between the two half-yokes and clamped with Al clamps. The stainless steel bolt-on outer shell is pre-tensioned under the yoking press to obtain a maximum azimuthal coil pre-stress of 100 MPa at room temperature. Based on ANSYS analysis, the pre-stress is sufficient to keep coil under compression up to the maximum design field of 12 T.

The mechanical structure is optimized to maintain the coil stress below 160 MPa at all times, which is considered a safe level for brittle Nb_3Sn coils [9]. Two 50-mm thick end plates bolted to the outer shell restrict the longitudinal coil motion under axial Lorentz forces.

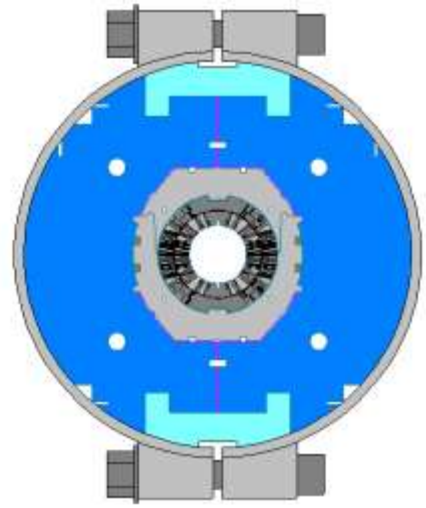

Figure 2: Cold mass cross-section.

Design Parameters

The calculated design parameters of the 11 T demonstrator magnet are summarized in Table 2. This calculation assumes a 10% critical current degradation in cable with respect to the nominal strand parameters. In the single-aperture configuration with 400 mm iron yoke the central field at the nominal current of 11.85 kA is 10.86 T, whereas in the twin-aperture configuration it reaches 11.21 T. The demonstrator magnet margin to quench on the load line is 21%. The iron yoke length is 1.8 m covering the entire coil, which results the conductor peak field being 1.5% higher in the end region than in the straight section. The magnetic length of the demonstrator magnet is 1.690 m.

Table 2: Magnet design parameters

Parameter	Value
Nominal current I_{nom}, A	11850
Nominal bore field, T	10.86 (11.21*)
Short-sample current I_c, A	15030
Maximum 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

* double-aperture configuration

Table 3 shows the transfer function and the expected field harmonics at injection and at nominal current with standard LHC pre-cycle. The data include coil magnetization effect due to persistent currents in the Nb_3Sn filaments and the iron saturation effect. Although the yoke of the demonstrator magnet was not optimized to suppress the iron saturation effect, the comparison of the magnetic model with measurements will help to understand and optimize the field quality in the twin-aperture 11 T dipole magnet.

Table 3: Transfer function and field harmonics (in units 10^{-4}) in the straight section at R_{ref}=17 mm

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

Figure 3 shows b_3 and b_5 (in units 10^{-4} at a reference radius of 17 mm) as a function of excitation current after the standard LHC pre-cycle from I_{inj}=757 A to I_{nom}=11850 A and back. The Nb_3Sn RRP-108/127 strand used in the demonstrator magnet has a relatively large effective filament diameter of ~50 μm as compared to 6-7 μm in the Nb-Ti strands of the LHC main dipole cable. As a consequence, the persistent current effect in the 11 T Nb_3Sn dipole is significantly larger than in the LHC main dipoles and may require additional multipole correctors. Note that the presented persistent current analysis using ROXIE code [5] is based on an idealized $J_c(B)$ fit that does not account for the possible reduction of filament magnetization due to instabilities at low fields. Measurements on the demonstrator magnet will serve to adjust the parameters of this numerical model to study the 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. The results of these studies will define the effective filament diameter and twist pitch of Nb_3Sn strand, necessity of a stainless steel core in the cable [9] as well as parameters of passive field correction [10], and LHC powering pre-cycle to reduce the coil magnetization effects in the twin aperture 11T dipole.

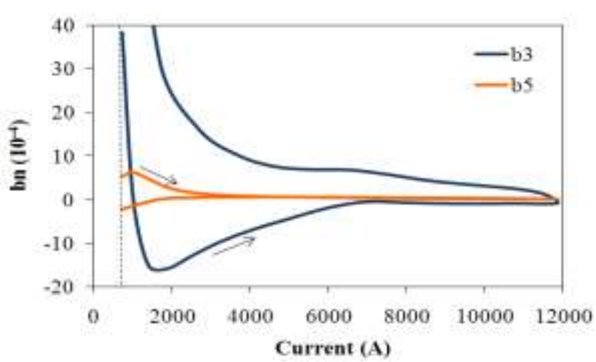

Figure 3: b_3 and b_5 (in units 10^{-4} at a reference radius of 17 mm) vs. excitation current after the standard LHC pre-cycle from I_{inj}=757 A to I_{nom}=11850 A and back.

Quench Protection

Magnet protection in case of a quench is provided by the quench heaters. Quench protection heaters composed of stainless steel strips are placed between the 2^{nd} and 3^{rd} Kapton layers of ground insulation, covering the outer-layer coil blocks. The heater strips on each side of each coil are connected in series forming two heater circuits connected in parallel. In the case of a magnet quench at the maximum operating current of 11.85 kA, the expected coil outer-layer temperature under heaters is less than 140 K for operation of both heater circuits, and less than 200 K in case of one heater circuit failure. The maximum hot spot temperature calculated for a 50 ms protection system delay does not exceed 240 K and 340 K respectively. These results of the preliminary quench analysis suggest that the quench protection scheme with outer-layer heaters provides adequate magnet protection. Experimental studies and optimization of DS dipole quench protection is an important part of demonstration magnet test program.

CONCLUSIONS

An 11 T Nb_3Sn twin-aperture dipole magnet for the LHC collimation system upgrade is being developed in 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 nearly complete and first winding trials are in progress. The cold tests are planned towards the end of 2011. The conceptual design of the twin-aperture 11 T dipole magnet has been started.

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