STATUS OF 11 T 2-IN-1 Nb_3Sn DIPOLE DEVELOPMENT FOR LHC*

A.V. Zlobin, N. Andreev, G. Apollinari, E. Barzi, R. Bossert, M. Buehler, G. Chlachidze,
J. DiMarco, A. Nobrega, I. Novitski, D. Turrioni, G. Velev, FNAL, Batavia, IL 60510, USA
B. Auchmann, M. Karppinen, L. Rossi, D. Smekens, CERN, CH-1211 Geneva 23, Switzerland

Abstract

The LHC upgrade plans foresee installation of additional collimators in the LHC lattice. To provide the necessary longitudinal space for these collimators, shorter and stronger Nb_3Sn dipoles compatible with the LHC lattice and main systems could be used. This paper describes the design and status of the twin-aperture Nb_3Sn dipole being developed by FNAL and CERN for the LHC, and reports test results of two collared coils to be used in the first 1 m long twin-aperture dipole model.

INTRODUCTION

The LHC luminosity upgrade requires additional collimators to be installed in dispersion suppression areas and high luminosity interaction regions [1, 2]. The ~3.5 m space needed for these collimators can be provided by replacing several 8.33 T LHC main NbTi dipoles with 11 T and 11 m long Nb_3Sn dipoles, which supply the same integrated strength at the nominal LHC current as the main dipoles. To demonstrate feasibility, CERN and FNAL launched an R&D program with the goal to develop a 5.5 m long twin-aperture Nb_3Sn dipole for the LHC. Two such dipoles with a collimator in between will replace one 14.3 m long LHC main dipole.

Design concepts of the twin-aperture 11 T dipole being explored at FNAL and at CERN are described in [3]. The second of two 1 m long collared coils (apertures), to be used in the first 1 m long twin-aperture dipole model, has been fabricated and tested recently at FNAL in a single-aperture configuration. This paper summarizes test results of the two collared coils and reports the status of the twin-aperture 1 m long 11 T Nb_3Sn dipole model being developed at FNAL.

MAGNET DESIGN AND PARAMETERS

The design concepts of the 11 T Nb_3Sn dipole in single-aperture and twin-aperture configurations are described in [2, 3]. The magnet coil was optimized to provide a dipole field above 11 T in a 60 mm aperture at 11.85 kA current with 20% margin, and geometrical field errors below 10^{-4}. The calculated design parameters for long single- and twin-aperture dipoles at I_{nom} of 11.85 kA, T_{op} of 1.9 K, nominal strand J_c(12T,4.2K) of 2750 A/mm^2 and cable I_c degradation of 10% are reported in Table 1. The cross-sections of the 11 T dipole (FNAL design) in both configurations are shown in Fig. 1.

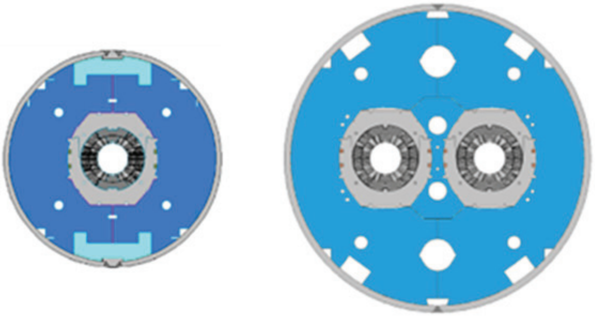

Figure 1: Single-aperture (left) and twin-aperture (right) 11 T dipole cross-sections (FNAL design).

For 1 m long models, the calculated nominal parameters are slightly higher due to some field enhancement in the magnet center from the coil ends. For example, the central field in the single-aperture configuration is 11.07 T at I_{nom}=11.85 kA.

Table 1: 2 m Long Dipole Parameters at I_{nom}=11.85 kA

Parameter	Single-aperture	Twin-aperture
Yoke outer diameter, mm	400	550
Nominal bore field at I_{nom}, T	10.88	11.23
Short sample field B_{SSL} at T_{op}, T	13.4	13.9
Margin B_{nom}/B_{SSL} at T_{op}, %	81	83
Stored energy at I_{nom}, kJ/m	424	969
F_x/quadrant at I_{nom}, MN/m	2.89	3.16
F_y/quadrant at I_{nom}, MN/m	-1.58	-1.59

MBHSP03 MODEL CONSTRUCTION

11 T dipole coils use a 40-strand Nb_3Sn Rutherford cable with a 0.025 mm thick and 11 mm wide stainless steel core. The cable is made of a 0.7 mm Nb_3Sn composite strand with a Cu/nonCu ratio of 1.0-1.1 and matrix RRR>60. MBHSP03 used RRP108/127 strand whereas MBHSP02 used RRP150/169 strand. The cable is insulated with a 0.075 mm thick and 12.7 mm wide E-glass tape with ~50% overlap. The cross-sections of both strands and the cored insulated cable are shown in Fig. 2.

Figure 2: RRP150/169 and RRP108/127 strands and 40-strand cable with a thin stainless steel core.

The 11 T dipole coil consists of 2 layers and 56 turns. Both layers are wound from a single ~100 m long piece of cable. The coil poles are made of Ti alloy, whereas

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[#] zlobin@fnal.gov

wedges and end parts are made of stainless steel. The coil fabrication process is based on the wind-and-react method. After reaction, coils are impregnated with epoxy resin to improve electrical and mechanical properties of the coil insulation. MBH09 and MBH10 coils used in MBHSP03 employed shorter end parts to improve end part matching with wedges.

The collared coil consists of two coils surrounded by a multilayer Kapton ground insulation and a stainless steel protection shell, and laminated stainless steel collar blocks locked on each side in the midplane by two bronze keys. Two quench protection heaters are mounted on each side of the coil between the 1st and 2nd Kapton layers of the ground insulation. MBHSP03 collared coil used modified collar laminations with larger radius of the inner surface to accommodate a thicker coil protection shell.

In the single-aperture configuration, the collared coil is surrounded by a vertically split 400 mm iron yoke fixed with thick Al clamps. The yoke length covers the entire coil and the Nb_3Sn/NbTi lead splices. The 12 mm thick bolted skin made of stainless steel provides the coil final pre-compression. Two 50 mm thick stainless steel end plates bolted to the skin restrict the axial coil motion. The electrical connection of the two half-coils is placed in a G10 splice box attached to the lead end plate. A picture of MBHSP03 cold mass is shown Fig. 3.

The improved quench performance of dipole mirror MBHSM01 [4], which was assembled with reduced coil pre-stress, suggested using a conservative coil prestress also in MBHSP03. The collar-yoke midplane shims were also optimized to reduce the collared coil bending and thus avoid possible conductor degradation and holding quenches observed in previous dipole models [5].

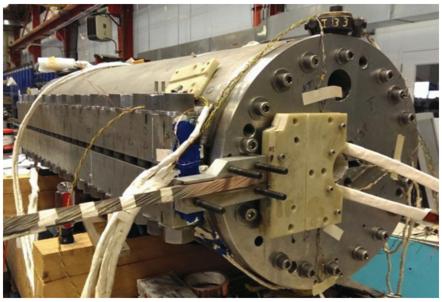

Figure 3: Single-aperture dipole cold mass MBHSP03.

MBHSP03 TEST RESULTS

The MBHSP03 model was tested at FNAL Vertical Magnet Test Facility in April-May 2014. Test results for the previous MBHSP02 model were reported in [5].

Quench current limits for MBHSP03 were estimated using measured witness sample data and calculated magnet load lines. At 4.5 K and 1.9 K, magnet short sample limits are 13.2 kA and 15.1 kA, which correspond to bore fields of 12.0 T and 13.5 T respectively.

The training quenches for MBHSP03 and MBHSP02 are shown in Fig. 4. Training started at 4.5 K with the first quench in both magnets occurring at ~65% of their short sample limit. After 16 quenches at 4.5 K, magnet training was continued at 1.9 K in superfluid helium. The bore field of 11 T in MBHSP03, as in MBHSP02, was reached after ~30 training quenches. MBHSP03 was trained to 11.2 T or 93.3% of the magnet design field. All the training quenches at 1.9 K occurred in the inner-layer high-field blocks. Quench current fluctuations, seen at the field level of 11 T, are likely due to epoxy cracking between the inner-layer pole blocks and coil pole turns caused by the conservative coil pre-stress in this model. To avoid possible conductor degradation the magnet training was interrupted. It will continue in the twin-aperture model after appropriate pre-stress adjustments.

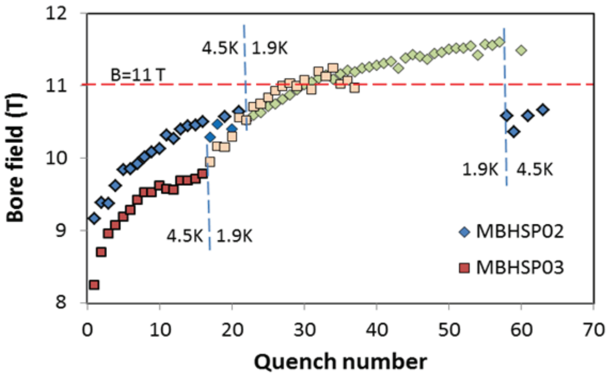

Figure 4: Magnet training.

Fig. 5 shows the holding time to quench vs. current at 4.5 K and 1.9 K for MBHSP02 and MBHSP03. Vertical lines at 9.9 kA (4.5 K) and 11.5 kA (1.9 K) show that unlike in MBHSP02 no quenches were detected in MBHSP03 after ~30 minutes at steady current.

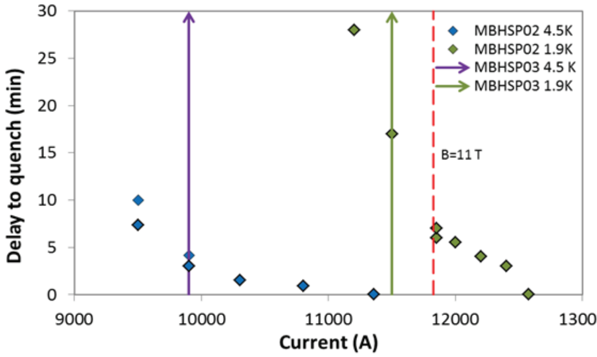

Figure 5: Holding time to quench vs. plateau current.

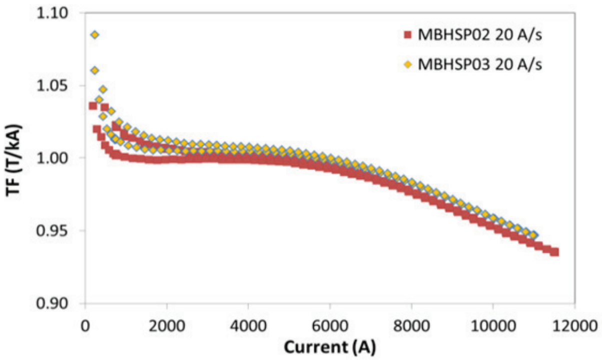

Figure 6: Transfer function *TF* vs. magnet current.

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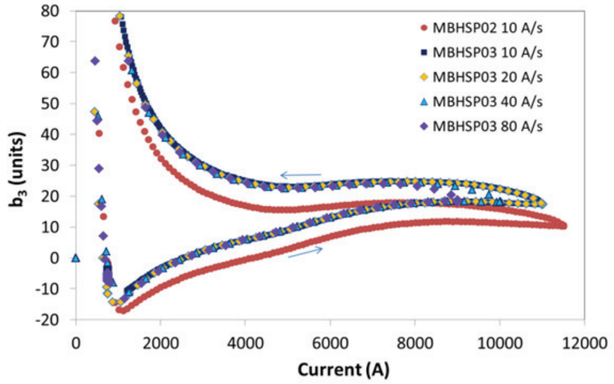

Figure 7: Sextupole b_3 vs. magnet current.

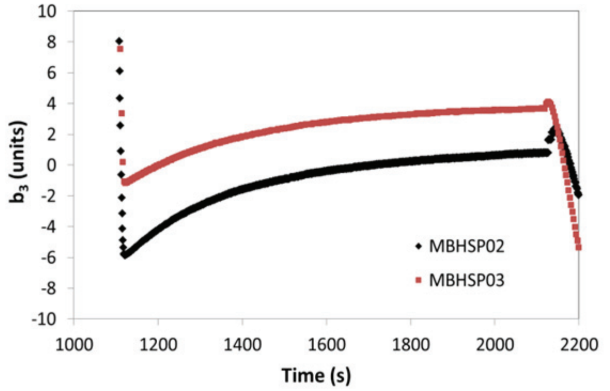

Figure 8: Transfer function TF vs. magnet current.

Magnet Transfer Function (TF) and sextupole (b_3) loops vs. current at 1.9 K with various current ramp rates for MBHSP03 and MBHSP02 are shown in Figs. 6 and 7. The persistent current effect, seen at low currents in the *TF* and b_3, is significant due to large D_{eff} and J_c of the Nb_3Sn strand used in both models. The ramp rate effect is small as expected for a cored cable. The iron saturation effect in *TF* and b_3 starts at ~4 kA and is consistent with expectations.

The measured b_3 decay at the LHC injection porch in MBHSP03 and MBHSP02 is shown in Fig. 8. In both models the b_3 decay is large (4-7 units) and reproducible.

Table 2 presents the geometrical harmonics at 3.5 kA in the magnet body for the both models. All the higher order harmonics (n>3) are small. The values and variation of low order harmonics is large due to variations of the coil size and shims used for coil pre-stress.

Table 2: Field Harmonics at I=3.5 kA

n	MBHSP02		MBHSP03	
	a_n	b_n	a_n	b_n
2	0.14	-4.93	-4.63	1.43
3	-1.44	8.44	2.0	16.1
4	0.24	-0.17	-0.09	0.05
5	0.15	1.02	-0.1	0.81
6	0.00	-0.23	-0.25	-0.2
7	-0.05	0.03	0.02	0.26
8	0.00	0.00	0.06	0.01
9	0.12	0.18	0.21	1.29

TWIN-APERTURE MODEL ASSEMBLY

The assembly scheme of the twin-aperture 11 T dipole model is shown in Fig. 9 (left). Two collared coils are installed inside a vertically split iron yoke 550 mm in diameter with an iron spacer separating the collared coils horizontally. The yoke length covers the entire length of the collared coils. The 12 mm thick welded skin made of stainless steel supports the yoke and provides the coil final pre-compression. Two 50 mm thick stainless steel end plates welded to the skin restrict coil axial motion. The mechanical model of the twin-aperture cold mass with instrumented collared coil blocks is shown Fig. 9 (right).

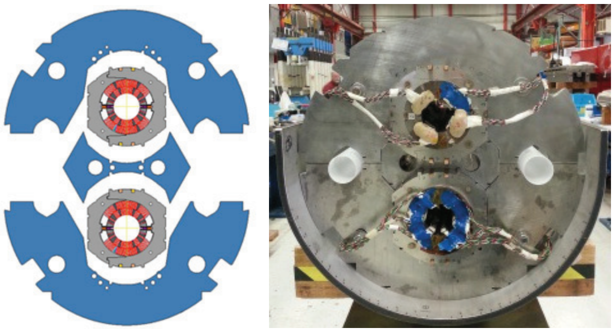

Figure 9: Assembly scheme of twin-aperture 11 T dipole model (left) and magnet mechanical model (right).

Two 1 m long collared coils to be used in the first twin-aperture 11 T Nb_3Sn dipole models have been built and tested in single-aperture configurations MBHSP02 and MBHSP03. Both collared coils were trained above the nominal operation field of 11 T to 11.7 T and 11.2 T respectively at 1.9 K, or 97.5% and 93.3% of the dipole design field of 12 T. The collared coil of MBHSP03 will be re-collared with slightly larger radial shim to increase the coil pre-stress before using it in the twin-aperture model. The training of both collared coils will continue in the twin-aperture configuration. The assembly of the first twin-aperture dipole model is in progress. Model test is planned in September 2014.

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