

# MAGNETIC ANALYSIS OF A SINGLE-APERTURE 11 T Nb<sub>3</sub>SN DEMONSTRATOR DIPOLE FOR LHC UPGRADES\*

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## Abstract

Fermilab and CERN are developing a 5.5 m long twin-aperture Nb<sub>3</sub>Sn dipole prototype suitable for installation in the LHC. The first step of this program is the development of a 2 m long single-aperture demonstration dipole with a nominal field of 11 T at the LHC nominal current of 11.85 kA in a 60 mm bore with 20% margin. This paper presents the results of magnetic analysis of the Nb<sub>3</sub>Sn demonstrator dipole for the LHC upgrade.

## INTRODUCTION

The planned upgrade of the LHC collimation system foresees additional collimators to be installed in the dispersion suppressor areas around points 2, 3 and 7 and around high luminosity interaction regions [1]. Replacing some 8.33 T 15 m long Nb-Ti LHC main dipole magnets (MB) with shorter 11 T Nb<sub>3</sub>Sn dipoles compatible with the LHC lattice and main systems could provide the required longitudinal space for the collimators. These twin-aperture dipoles operating at 1.9 K and powered in series with the main dipoles would deliver the same integrated strength of 119 Tm at the nominal current of 11.85 kA.

To demonstrate the feasibility of this approach, CERN and FNAL have started a joint program to build a 5.5 m long twin-aperture Nb<sub>3</sub>Sn dipole for the collimation system upgrade [2]. The first phase of this program is the design, construction and test of a 2 m long single-aperture demonstrator magnet, delivering ~11 T in a 60 mm bore at the LHC nominal current of 11.85 kA with 20% margin.

This paper presents the results of the magnetic analysis of the single-aperture Nb<sub>3</sub>Sn demonstrator including geometrical, coil magnetization and iron saturation effects. Possibilities of field quality correction at low fields using passive correction schemes are explored.

## MAGNET DESIGN

The design details of the single-aperture demonstrator conceptual design are reported in [2, 3]. The coil cross-section was optimized in the double-aperture LHC iron yoke with separate collared coils and a 30-mm coil-yoke gap to provide a dipole field above 11 T at 11.85 kA with ~20% margin on the load line at 1.9 K and the low-order field errors below the 10<sup>-4</sup> level. The coil end spacers were optimized to minimize the integrated low-order field harmonics. The coil consists of 56 turns, 22 in the inner layer and 34 in the outer layer. The cable layer jump is integrated into the first end spacers of the lead end.

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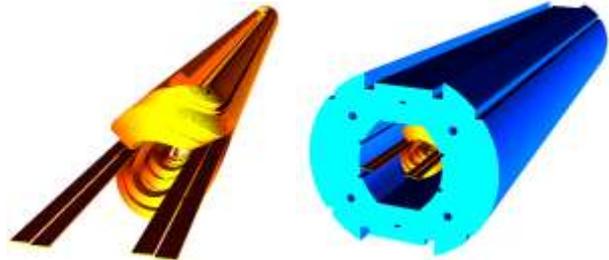


Figure 1: 3D model of the coil with the layer-jump, block transitions and coil leads (left), and the yoke (right).

Both layers are wound from a single length of 40-strand keystoneed 14.7 mm wide and 1.25 mm (average) thick Rutherford cable [4] insulated with two layers of 0.075 mm thick and 12.7 mm wide E-glass tape. The cable is made of Nb<sub>3</sub>Sn RRP-108/127 strand 0.7 mm in diameter [5]. The strand nominal critical current density  $J_c(12\text{ T}, 4.2\text{ K})$  is 2750 A/mm<sup>2</sup>, the effective filament size  $D_{eff}$  is 55  $\mu\text{m}$  and the nominal Cu fraction is 53%.

Two coils surrounded by the multi-layer Kapton insulation and 316L stainless steel protection shells are placed inside the laminated collars made of Nirosta High-Mn stainless steel. The collared coil is installed inside the vertically split 400 mm outer diameter yoke made of soft 1045 iron and fixed with Al clamps. The 12 mm thick 304L stainless steel shell is pre-tensioned to provide final coil pre-compression and support up to the maximum design field of 12 T. Two 50 mm thick 304L stainless steel end plates welded to the shell restrict the longitudinal coil motion. The coil length is 1968 $\pm$ 3 mm. The yoke length is 1950 mm which covers the entire coil and the Nb<sub>3</sub>Sn/Nb-Ti lead splices. The details of magnet fabrication and magnet parameters are reported in [6].

## MAGNETIC ANALYSIS

The demonstrator magnet was modeled with ROXIE [7] using properties of key structural materials. The 3D models of the 11 T demonstrator dipole coil and the iron yoke are shown in Fig. 1. Relative harmonic coefficients are given in units 10<sup>-4</sup> for a reference radius of  $R_{ref}=17\text{ mm}$ .

### Magnet Geometry and Iron Saturation Effect

Fig. 2 shows a 2D simulation of the transfer function  $TF=B/I$  and the sextupole  $b_3$  and decapole  $b_5$  field harmonics in the current cycle due to iron yoke saturation for the 1045 iron. The persistent current effect is not considered. In the current cycle from injection to the nominal current  $TF$  reduces by 8%,  $b_3$  reaches its maximum of 1.4 units at ~5 kA, and  $b_5$  reduces by 30%.

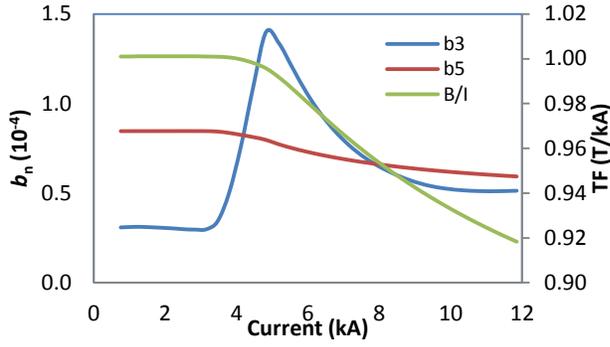


Figure 2: 2D simulation of the  $b_3$  and  $b_5$  (left axis) and  $TF$  (right axis) variations due to iron saturation.

The  $TF$ ,  $b_3$  and  $b_5$  variations along the magnet are shown in Fig. 3. The  $b_3$  and  $b_5$  amplitude in magnet ends is quite large, reaching 300 and 250 units respectively. Nevertheless, due to the end block position optimization both return and lead ends are rather well balanced. The impact of the current leads, block connections and layer jump are visible on the lead end side.

Due to the extension of the iron yoke over the entire length of the coil including Nb<sub>3</sub>Sn/Nb-Ti splices, peak field enhancement in the coil ends reaches 0.3 T and, hence, reduces the margin on the load line by 1.9%. It also increases the magnetic length by 3.5 cm, and the  $b_3$  component by 1.6 units.

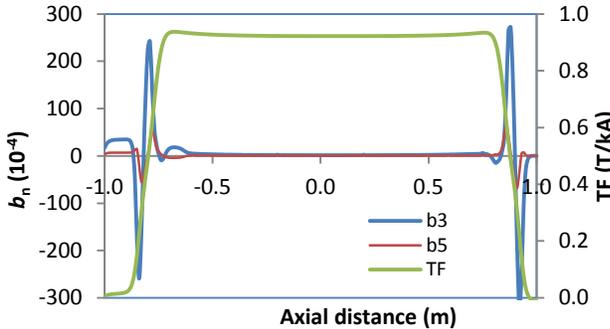


Figure 3:  $TF$ ,  $b_3$  and  $b_5$  variations along the magnet.

### Persistent Current Effect

The strand magnetization data were parameterized using the experimental  $J_c(B)$  dependence and  $D_{eff}=55 \mu\text{m}$  for the nominal RRP-108/127 strand used in the demonstrator dipole and  $D_{eff}=45 \mu\text{m}$  for the R&D RRP-150/169 strand being developed for accelerator magnets [8].

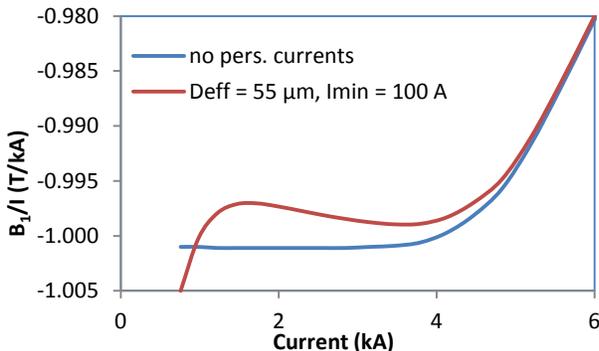


Figure 4: 2D simulation of the transfer function with and without persistent current effects.

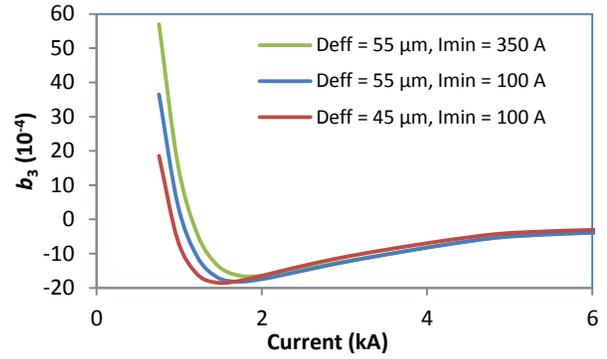


Figure 5:  $b_3$  variation vs. magnet current for different  $D_{eff}$  and pre-cycle reset currents.

The transfer functions calculated with and without the persistent current effect for the nominal RRP-108/127 strand are compared in Fig. 4. It is clearly visible that the re-magnetization is not complete at injection level. The coil magnetization effect is smaller than the iron saturation and is visible only up to 6 kA or half of the  $I_{nom}$ .

Fig. 5 shows the dependence of  $b_3$  induced by persistent currents in Nb<sub>3</sub>Sn sub-elements for the RRP-108/127 and RRP-50/169 strands on magnet current with the pre-cycle reset current of 350 and 100 A. The smaller  $D_{eff}$  by a factor of 1.22 reduces  $b_3$  at injection from 37 to 19 units or by a factor of 1.95. Between 1 kA and 1.7 kA the smaller filament size even produces larger  $|b_3|$ . Only at currents above 4.5 kA does  $b_3$  scale linearly with the sub-element size. This behavior is related to the coil re-magnetization process after previous current cycle which is completed at 4.5 kA. It is also shown in Fig. 5 that the present LHC pre-cycle with  $I_{min}=100$  A significantly reduces the  $b_3$  at injection with respect to the nominal  $I_{min}=350$  A [9].

### Magnetic Calculation Summary

Table 1 summarizes the results of 2D and 3D simulation for the magnet transfer function  $TF$  and low order field harmonics including  $a_1$ ,  $b_3$ ,  $b_5$ ,  $b_7$  and  $b_9$  at the injection and nominal currents after an LHC pre-cycle with a reset current of  $I_{min}=100$  A. Differences between 2D and 3D results (2<sup>nd</sup> and 3<sup>rd</sup> columns) are essentially due to asymmetries on the coil lead end side.

Due to large iron saturation in the single-aperture magnet with 400 mm yoke outer diameter, the bore field  $B_1$  at  $I_{nom}=11.85$  kA is 10.88 T for the 1045 iron yoke. However, in the twin-aperture dipole with the iron used in MB dipoles,  $B_1$  is 11.21 T due to the field enhancement in the twin-aperture configuration [10].

Table 1: 2D and 3D  $TF$  and low-order field harmonics.

Parameter	Values				
Model	2D	2D	3D	2D	2D
Current	$I_{inj}$	$I_{nom}$	$I_{nom}$	$I_{inj}$	$I_{nom}$
Iron satur.	yes	yes	yes	yes	yes
Pers. Curr.	no	no	no	yes	yes
$B_1/I$ , T/kA	-1.00	-0.92	-0.92	-1.01	-0.92
$b_3$	0.3	0.5	5.7	36.5	-1.4
$b_5$	0.8	0.6	1.2	7.9	0.5
$b_7$	-0.1	-0.1	0.0	-0.4	-0.1
$b_9$	0.9	1.0	0.8	1.4	1.0
$a_1$	0.0	0.0	3.3	0.0	0.0

## Field Quality Correction

The quantitative prediction of field harmonics at injection is affected by a large level of uncertainty. Nevertheless, we can explore measures to compensate field errors at injection, knowing that the model will need to be gauged to measurements at a later stage. The goal of the correction, according to beam dynamics simulations, is to keep the value of  $b_3$  within  $\pm 20$  units at low currents.

A reduction of the coil magnetization effect could be achieved by a passive correction based on superconducting strands [11] or magnetic shims [12] or their combination. An example of a passive correction scheme based on two rows of 0.8 mm Nb<sub>3</sub>Sn strands with  $D_{\text{eff}}=75 \mu\text{m}$  in four sectors of 45 degrees and four 0.5 mm thick iron strips placed near the magnet midplane is shown in Fig. 6. The uncorrected and corrected  $b_6$  for the baseline conductor RRP-108/127 are shown in Fig. 7. The effect on  $b_5$  and higher order harmonics is small. The ferromagnetic shims are modeled using the coupling of finite elements and boundary elements. The coupled effect of ferromagnetic shims and passive strands was computed by weak coupling via iteration.

At injection current the strand magnetization in the passive strands is near zero, thus, an effective compensation is only achieved beyond the injection level. The ferromagnetic shims are used to reduce the sextupole field at injection. The described passive corrector reduces  $b_3$  at injection from +37 to +7 units or by a factor of 5. At high currents, both the strand and shim-based compensation are diminished. The price that is paid for this compensation is a 4 mm reduction of the magnet aperture.

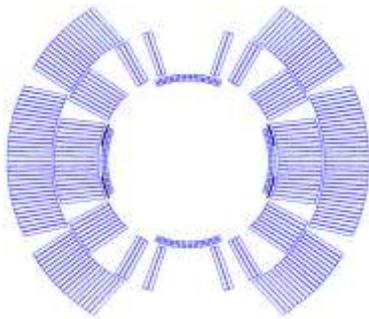


Figure 6: Passive compensation by four sectors of passive strands and 0.5 mm thick ferromagnetic shims covering 15 degrees each.

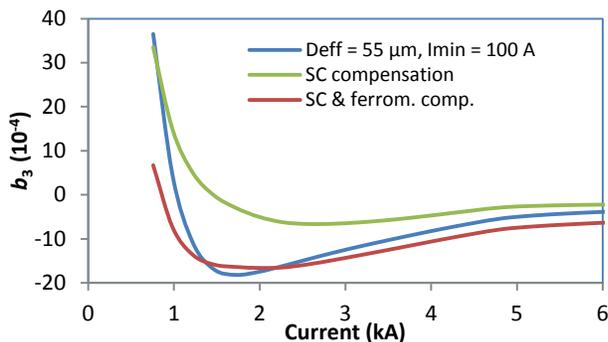


Figure 7: Sextupole compensation using superconducting strands and ferromagnetic shims.

## CONCLUSIONS

2D and 3D magnetic analysis has been performed for the 2 m long single-aperture demonstrator dipole including geometrical, coil magnetization and iron saturation effects. Geometrical field errors in the coil body are small due to coil cross-section optimization. The coil leads and the layer jump increase the integrated  $b_3$  to 6 units. The iron saturation effect reduces the TF by 8%. The effect on low-order field harmonics is small.

The coil magnetization effect is relatively large at the LHC injection level due to the high  $J_c$  and large  $D_{\text{eff}}$  of the state-of-the-art Nb<sub>3</sub>Sn strands used in the demonstrator magnet. This effect could be reduced by using strands with smaller  $D_{\text{eff}}$  and by the use of passive correction schemes. Passive correctors will be fabricated and tested with the 11 T demonstrator magnet. A short model magnet with RRP-150/169 strand and passive corrector models will be tested later this year.

## 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<sub>3</sub>Sn 11T Single Aperture Demonstrator Dipole for LHC Upgrades", *Proc. of PAC'2011*, NYC, 2011, p. 1460.
- [3] A.V. Zlobin et al., "Design and Fabrication of a Single-Aperture 11T Nb<sub>3</sub>Sn Dipole Model for LHC Upgrades", *IEEE Trans. on Applied Supercond.*, accepted for publication, 2012.
- [4] E. Barzi et al., "Development and Fabrication of Nb<sub>3</sub>Sn Rutherford Cable for the 11 T DS Dipole Demonstration Model", *IEEE Trans. on Applied Supercond.*, accepted for publication, 2012.
- [5] M.B. Field et al., "Internal Tin Nb<sub>3</sub>Sn Conductors for Particle Accelerator and Fusion Applications," *Adv. Cryo. Engr.*, vol. 54, 2008, p. 237.
- [6] A.V. Zlobin et al., "Status of a Single-Aperture 11 T Nb<sub>3</sub>Sn Demonstrator Dipole for LHC Upgrades", *this conference*.
- [7] ROXIE, <http://cern.ch/roxie>
- [8] E. Barzi et al., "Studies of Nb<sub>3</sub>Sn Strands Based on the Restacked-Rod Process for High-field Accelerator Magnets", *IEEE Trans. on Applied Supercond.*, accepted for publication, 2012.
- [9] N. Sammut et al., "Mathematical formulation to predict the harmonics of the superconducting large hadron collider magnets: III. precycle ramp rate effects and magnet characterization." *Phys. Rev. Spec. Top. Accel. Beams* 12, 2009.
- [10] M. Karppinen et al., "Design of 11 T Twin-Aperture Nb<sub>3</sub>Sn Dipole Demonstrator Magnet for LHC Upgrades", *IEEE Trans. on Applied Supercond.*, accepted for publication, 2012.
- [11] M.A. Green, "Control of the Fields Due to Superconductor Magnetization in the SSC Magnets", *IEEE Trans. on Magnetics*, v. 23, No.2, 1987, p.506.
- [12] V.V. Kashikhin and A.V. Zlobin, "Correction of the Persistent Current Effect in Nb<sub>3</sub>Sn Dipole Magnets", *IEEE Trans. on Applied Supercond.*, v. 11, No. 1, March 2001, p. 2058.