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

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Abstract
Fermilab and CERN are developing a 5.5 m long twin-aperture Nb$_3$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$_3$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 8.35 T 15 m long Nb-Ti LHC main dipole magnets (MB) with shorter 11 T Nb$_3$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$_3$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$_3$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$^{-4}$ 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.

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$^{-4}$ for a reference radius of $R_{ref}$=17 mm.

Magnet Geometry and Iron Saturation Effect
Fig. 2 shows a 2D simulation of the transfer function $TF=B_l/l$ 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$_3$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 $I_s(B)$ dependence and $D_{eff}=55$ µm for the nominal RRP-108/127 strand used in the demonstrator dipole and $D_{eff}=45$ for the R&D RRP-150/169 strand being developed for accelerator magnets [8].

![Graph showing transfer function and strand magnetization data](image)

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

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![Graph showing TF variation vs. magnet current for different $D_{eff}$ and pre-cycle reset currents](image)

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$_3$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 (2nd and 3rd 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](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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**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 ±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$_3$Sn strands with $D_{eff}$=75 μm 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 $b_3$ for the baseline conductor RRP-108/127 are shown in Fig. 7. The effect on $b_3$ 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.

**REFERENCES**


