PERSISTENT CURRENT EFFECT IN 15 - 16 T Nb_3Sn ACCELERATOR DIPOLES AND ITS CORRECTION*

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Abstract

Nb_3Sn magnets with operating fields of 15-16 T are considered for the LHC Energy Doubler and a future Very High Energy pp Collider. Due to large coil volume, high critical current density and large superconducting (SC) filament size the persistent current effect is very large in Nb_3Sn dipoles al low fields. This paper presents the results of analysis of the persistent current effect in the 15 T Nb_3Sn dipole demonstrator being developed at FNAL, and describes different possibilities of its correction including passive SC wires, iron shims and coil geometry.

INTRODUCTION

Commercially produced Nb_3Sn composite wires provide high critical current density J_c which is sufficient to increase the operation field in accelerator magnets up to 15-16 T. Magnets with this level of nominal field are considered for the LHC Energy Doubler and a future Very High Energy pp Collider [1].

The persistent current effect in superconducting (SC) accelerator magnets degrades the magnet field quality and, thus, reduces the accelerator dynamic aperture and the operation field range which complicates the field correction system. In a new generation of accelerator magnets based on Nb_3Sn superconductor the persistent current effect is considerably larger than in traditional NbTi magnets due to higher J_c and larger SC filament size d_{eff} [2]. Due to the large coil volume the persistent current effect becomes even larger and, therefore, more important in 15-16 T Nb_3Sn dipoles. This paper presents the results of analysis of the coil magnetization effect in the 15 T Nb_3Sn dipole demonstrator being developed at FNAL and describes different correction options including coil geometry, iron shims and passive SC wires.

MAGNET DESIGN AND PARAMETERS

The design of the 15 T dipole demonstrator being developed at FNAL is described in [3], [4]. It consists of a 4-layer graded coil with 60-mm aperture and a cold iron yoke with 587 mm outer diameter separated from the coil by a 2 mm spacer. The coil cross-section is shown in Fig. 1. The coil is based on two 15 mm wide cables. The 28-strand inner and 40-strand outer cables use 1.0 mm and 0.7 mm Nb_3Sn strands respectively. The strand and cable parameters are reported in [5]. The magnet maximum design bore field is 15.61 T at 4.2 K and 17.04 T at 1.9 K.

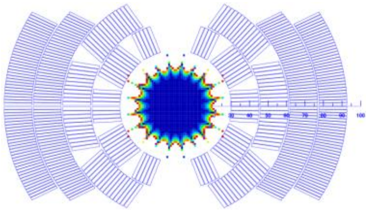

Figure 1: Coil cross-section. The dark colored zone in the aperture represents a field uniformity better than 2×10^{-4}.

COIL MAGNETIZATION EFFECT

The allowed "normal" B_n^Y and "skew" B_n^X field harmonics (n=1, 3, 5, …) produced by the coil magnetization M are represented as follows

$$B_n^{\,Y} + iB_n^{\,X} = -\frac{nR_{ref}^{\;n-1}}{2\pi}\int_S M(z)\left(\frac{e^{i\alpha(z)}}{z^{n+1}} - \frac{z^{*n-1}e^{-i\alpha(z)}}{R_{Fe}^{2n}}\right)dS\,, \quad (1)$$

where $z=x+iy$, $z^*=x-iy$, $\alpha(z)$ is the angle between the vector M and axis Y, S is the coil cross-section, R_{Fe} is the iron yoke ID, and R_{ref} is the reference radius in the magnet aperture.

The coil magnetization related to the persistent currents in SC filaments is represented as follows

$$M(B,T) = -\mu_0\frac{2}{3\pi}\lambda_{coil}\varepsilon(B)J_c(B,T)d_{sc}\,, \quad (2)$$

where λ_{coil} is the coil filling factor with superconductor, $J_c(B)$ is the superconductor critical current density, d_{sc} is the effective SC filament diameter, and $\varepsilon(B)$ is the function describing the field profile inside the SC filaments.

Formulas (1) and (2) show correlations of the field harmonics related to the coil magnetization with the magnet design and superconductor parameters.

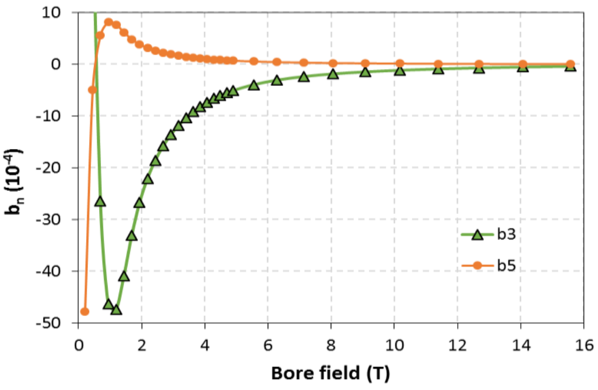

Figure 2: Calculated normal sextupole b_3 and decapole b_5 vs. the bore field in FNAL 15 T Nb_3Sn dipole.

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Figure 2 shows the dependence of the normal sextupole b_3 and decapole b_5 in the aperture of FNAL 15 T Nb_3Sn dipole at R_{ref} of 17 mm vs. the bore field calculated using ROXIE [6]. For the selected conductor parameters and the coil geometry the peak values of b_3 and b_5 are -48 and 8 units respectively. Both values correspond to a bore field of ~1.4 T and are a factor of two larger than in the 11 T Nb_3Sn dipole models for LHC upgrades [7], and an order of magnitude larger than in the Nb-Ti LHC main dipoles. Large b_3 values were also reported for the high-field Nb_3Sn dipoles of other designs [2], [8].

COIL MAGNETIZATION CORRECTION

Several passive correction schemes were proposed to compensate the coil magnetization effect in SC accelerator magnets. In this paper correction schemes based on passive SC wires and iron shims in magnet aperture, and on the optimization of the coil geometry are discussed. The magnetization curves of SC wires and iron strips used for sextupole passive correction are shown in Fig. 3. The wire has 1 mm diameter, d_{eff}=57 µm and J_c=2.7 kA/mm^2 at 12 T and 4.2 K, and *Cu:nonCu* ratio of 1.13. The wire parameters J_c *and* d_{eff} were selected to avoid magnetization fluctuations due to flux jumps at low fields.

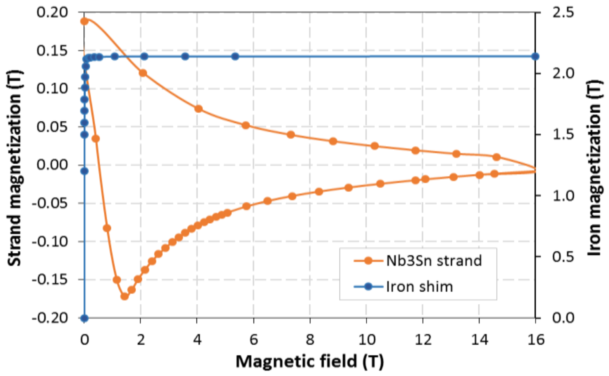

Figure 3: Magnetization of Nb_3Sn wire and iron strip.

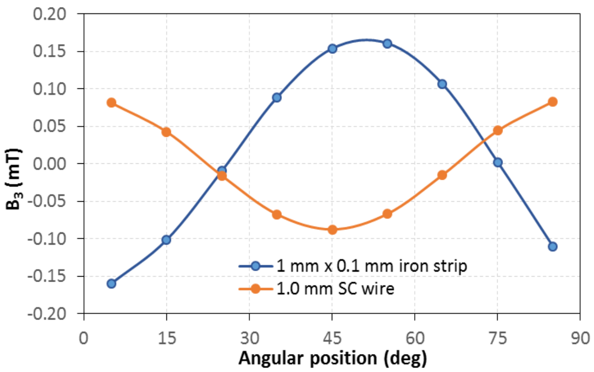

Figure 4: B_3 produced by the iron strip or the Nb_3Sn wire vs. their azimuthal position in aperture at B_0=1.93 T.

Figure 4 shows the calculated absolute normal sextupole B_3 produced by a 1 mm Nb_3Sn wire, and by a 1 mm wide and 0.1 mm thick iron strip placed on the coil inner surface at a bore field of 1.93 T vs. their azimuthal position in the magnet aperture. For the wire calculations were done using formulas (1) and (2), and for the iron strip using ROXIE.

Since B_3 from the coil magnetization is negative, by placing the SC wires at the angles of 0-22.5 and 67.5-90 degrees (22 wires per quadrant) allows compensating 1.57 mT (~30%) out of coil B_3 = -5.17 mT at the main field of 1.93 T at R_{ref}=17 mm. Similarly, filling the angular positions of 25-75 degrees in each quadrant with the iron strips allows compensating 2.56 mT (~50%) of the coil B_3. Notice, that the SC wire corrector will add 0.4 mT (~60%) to the coil B_5=0.75 mT at 1.93 T whereas the iron corrector will reduce it by -0.35 mT. To minimize the impact of SC corrector on B_5 the angular corrector length of each sector has to be increased to ~30 degrees. The correction strength of B_3 in this case reduces to 1.36 mT or by ~13%.

Passive SC Wires

Figure 5 shows the normal sextupole B_3 at R_{ref}=17 mm produced by the magnet coil magnetization, 3 layers of passive 1 mm SC wires in the magnet aperture placed at 0-22.5 and 67.5-90 degrees in each quadrant, and their combined effect vs. the magnet bore field. The described corrector limits the total B_3 variations from -0.4 to 0 mT at the bore fields above 0.7 T. This corrector reduces the range of B_3 variations by a factor of 13.

A disadvantage of this corrector type is its relatively large radial size of 3 mm. The corrector thickness can be reduced by using SC wires with smaller *Cu:nonCu* ratio and better wire compaction in the corrector.

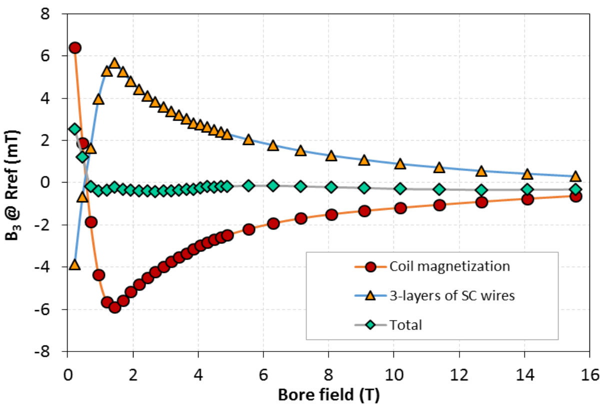

Figure 5: B_3 at R_{ref}=17 mm produced by the coil magnetization and its correction using passive SC wires in magnet aperture.

Iron Strips

Figure 6 shows the normal sextupole B_3 produced by the coil magnetization, by the 0.15 mm thick iron strips placed at 25-75 degrees per quadrant (top) and by the 0.375 mm thick iron strips at 50-75 degrees per quadrant as well as the small negative geometrical component b_3 of -0.8 units (bottom), and their total effect vs. the bore field. In the first case the iron strip corrector limits the total B_3 variations to ±2 mT for a bore field range of 0.7-15 T. In the second case the total B_3 varies from -0.13 to 1.25 mT for the bore fields increasing from 1.2 to 15 T. In the latter case the B_3 variation range reduced by a factor of 3.8. The small negative geometrical component and 0.375 mm thick iron strips reduce the B_3 variations by a factor of 11.

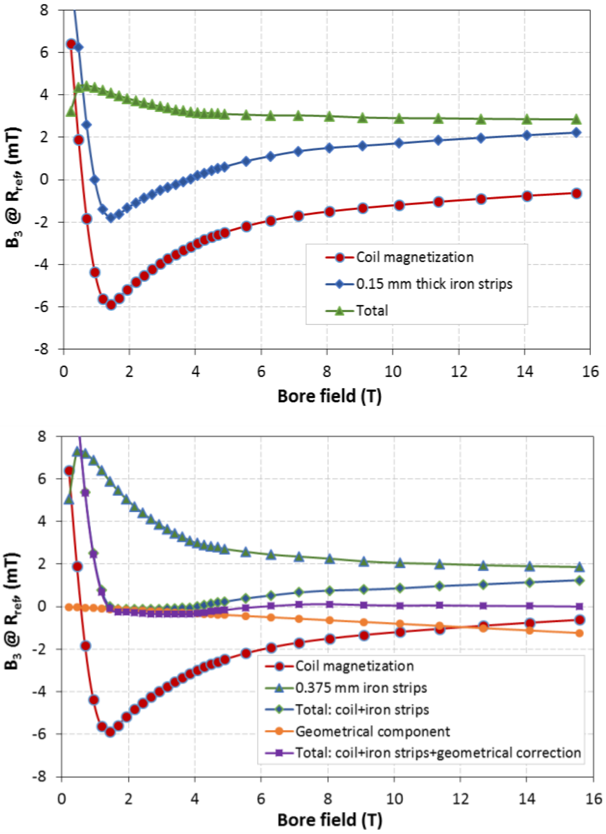

Figure 6: B_3 at R_{ref}=17 mm produced by the coil magnetization and its correction by using the 0.15 mm thick iron strips at 25-75 degrees per quadrant (top) or by the 0.375 mm thick iron strips at 50-75 degrees per quadrant and the small geometrical component (bottom).

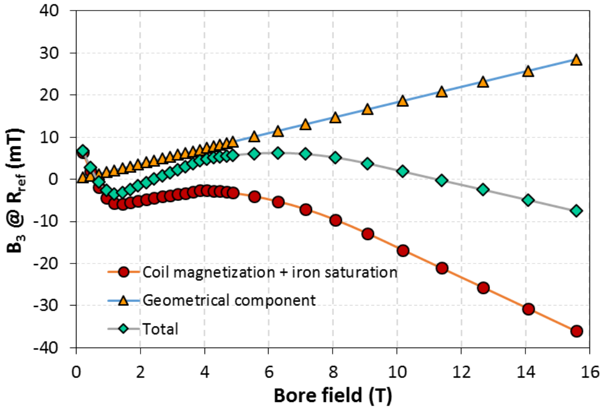

Figure 7: B_3 at R_{ref}=17 mm produced by the coil magnetization and iron saturation effects and its correction with a positive geometrical sextupole component.

COIL MAGNETIZATION AND IRON SATURATION CORRECTION

The FNAL 15 T dipole demonstrator has also a large iron saturation effect due to the small distance between the iron and the coil and a large maximum design field [4]. The calculated B_3 produced by the coil magnetization and the iron saturation effects at R_{ref}=17 mm is shown in Fig. 7. At a bore field of 15 T B_3 reaches -35 mT which is almost an order of magnitude larger than the maximum coil magnetization effect. The preliminary analysis shows that correction holes in the iron yoke do not suppress the iron saturation effect up to the nominal design field of 15 T.

Figure 7 shows the effect of introducing a correcting geometrical sextupole error (b_3=+18 units) by optimizing the coil geometry. This geometrical correction allows reducing the total B_3 variations range by a factor of 2.5 to approximately ±7 mT.

CONCLUSION

The analysis of the coil magnetization effect on the field quality of the FNAL 15 T Nb_3Sn dipole demonstrator shows that for the present magnet design and superconductor parameters the normal sextupole and decapole field components are relatively large at low fields. It was shown that 3 layers of 1 mm diameter Nb_3Sn wires or 0.375 mm thick iron strips (combined with small geometrical component) in the magnet bore provide an effective reduction of the coil magnetization effect by a factor of 13 and 11 respectively.

The FNAL 15 T dipole demonstrator has also a large iron saturation effect. It was shown that the geometrical correction of +18 units allows reducing the total range of B_3 variations to approximately ±7 mT.

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