

Passive Correction of the Persistent Current Effect in Nb₃Sn Accelerator Magnets

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Abstract—Superconducting accelerator magnets must provide a uniform field during operation. However, the field quality significantly deteriorates due to persistent currents induced in superconducting filaments. This effect is especially large for the Nb₃Sn conductor being implemented in the next generation of accelerator magnets. A simple and inexpensive method of passive correction of the persistent current effect was developed and experimentally verified. This paper describes numerical simulations of the passive correctors and reports the test results.

Index Terms—Hysteresis, magnetic fields, magnetic materials, superconducting magnets.

I. INTRODUCTION

SUPERCONDUCTING accelerator magnets must meet the field quality requirements. In most cases, the low order harmonics at a reference radius must be less than 10^{-4} part of the main field component. However, the field quality significantly deteriorates at low fields due to magnetization of superconducting filaments, caused by the persistent currents.

Magnetization of a superconducting filament is proportional to the critical current density at a given field and the effective filament size. Modern Nb₃Sn strands used in accelerator magnets have large critical current densities and effective filament diameters that increases magnetization by an order of magnitude with respect to the last generation of NbTi strands.

Apart from the type I superconductors, which are purely diamagnetic, hard superconductors of type II exhibit non-linear magnetic properties due to the field penetration inside the filaments. It leads to non-linearity of the magnetic field and generation of large low-order harmonics.

Passive correction of the persistent current effect has been studied in the course of the development of NbTi accelerator magnets. There were considered introduction of passive superconducting strands [1] or nickel tapes [2] inside the coil aperture, nickel powder inside the strands [3] and permanent magnets [4] for the reduction of the persistent current effect. However, due to their complexity and low efficiency none of the proposed techniques found practical implementation in existing accelerators.

A simple and effective method of passive correction of the persistent current effect, based on thin iron strips has also

been proposed [5]. Implications of this method including various corrector configurations, numerical simulations and test results will be discussed.

II. SIMULATION OF THE PERSISTENT CURRENT EFFECT

Magnetic field in a magnet bore will be described in terms of normalized harmonic coefficients according to:

$$B_y(x, y) + iB_x(x, y) = 10^{-4} \times B_{ref} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1},$$

where $B_x(x, y)$ and $B_y(x, y)$ – horizontal and vertical field components; B_{ref} – main field component at the reference radius R_{ref} ; b_n and a_n – normal and skew harmonic coefficients. The reference radius used in this paper is 1 cm.

Simulations of the persistent current effect have been performed using the finite-element code OPERA2D. The simulation method, originally described and experimentally verified in [6], retains high precision of the vector-potential formulation and allows taking into account measured hysteresis curve for any material, including superconductors.

The coil magnetization was characterized by the magnetic properties of 1-mm Nb₃Sn strand with a critical current density of 1600 A/mm² at 12 T and Cu/non-Cu ratio of 0.85, measured at Fermilab [7]. The magnetization curve was adjusted for the cable packing factor and transformed into B(H) curve, suitable for OPERA 2D.

Simulation of the persistent current effect has been performed for the shell type dipole and quadrupole magnets, developed at Fermilab for VLHC. Fig. 1 shows the dipole and quadrupole magnet cross-sections with the flux lines from the persistent currents only (fields from the transport current and iron magnetization were subtracted). Persistent current effect in different block type magnets was analyzed in [5].

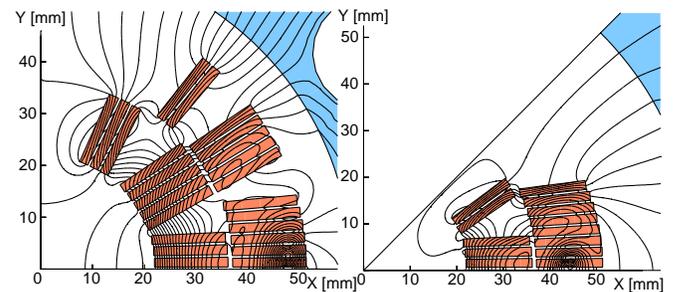


Fig. 1. Magnetization flux in dipole (left) and quadrupole (right) magnets. Flux increment between adjacent lines is constant and equals to 5×10^{-5} Wb/m in all similar plots of this paper.

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III. METHODS OF PASSIVE CORRECTION

A. Strips in the aperture

Correction of the persistent current effect in the shell type dipole magnets using iron strips in the aperture was considered in [5]. It was demonstrated that thin iron strips placed at certain azimuthal positions within a magnet aperture provide effective correction of the persistent current effect.

The same technique is applicable for the quadrupole magnets. In order to determine the optimum corrector position, a 3 degrees wide and 0.1 mm thick iron strip was installed in the aperture of the quadrupole magnet at 19.75 mm radius. The azimuthal strip position was varied within 0-45 degrees with 3 degrees increment. The strip magnetic properties were taken from [5]. Fig. 2 shows the calculated strip contribution to the low-order harmonics at 44 T/m gradient (3 kA current). Similarly to the dipole magnet, there is a region with positive b_6 and negative b_{10} that allows correction of both harmonics using one strip per octant.

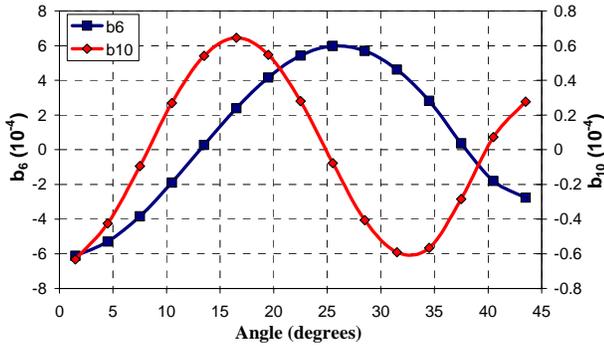


Fig. 2. Harmonics in the quadrupole magnet as function of the strip position.

B. Strips on the wedges

The correcting strips can also be installed on the wedges, separating coil blocks. In this case, however, number of the design parameters is limited by the strip thickness and discrete azimuthal positions. Therefore, in order to eliminate several low-order harmonics without affecting others, one may need to use more correcting strips than in the case with the strips inside the coil aperture.

Passive correctors on the coil wedges were studied for the dipole and quadrupole magnets. In order to find the optimum configurations, a cable-wide iron strip with 0.1 mm thickness was consistently placed on every coil block surface of the inner layer. Fig. 3-4 show calculated strip contribution to the low-order harmonics at 1.2 T field in the dipole and 44 T/m gradient in the quadrupole magnets. Strip numbering starts from the midplane.

Three strips (numbers 3,4,6) with 0.15 mm, 0.27 mm and 0.15 mm thickness are required per quadrant of the dipole coil for correction of b_3 - b_5 harmonics. One strip (number 3) with 0.09 mm thickness is required per octant of the quadrupole coil for correction of b_6 component. Correction of the small b_{10} component can be accomplished by adding ~ 0.05 mm strip (number 4) to the pole surface.

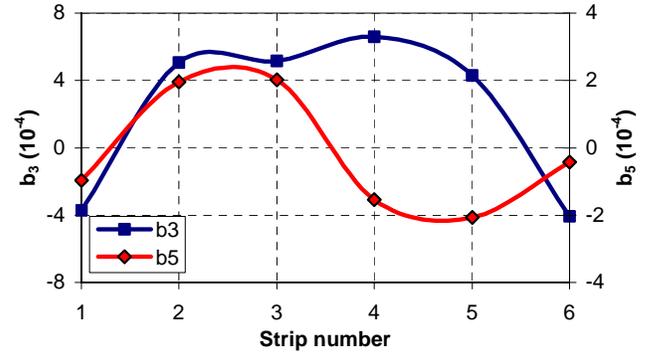


Fig. 3. Harmonics in the dipole magnet as function of the strip number.

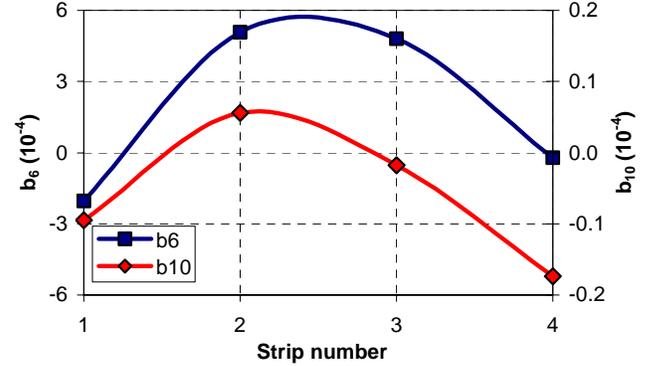


Fig. 4. Harmonics in the quadrupole magnet as function of the strip number.

Fig. 5 shows optimum positions of the passive correctors inside the dipole and quadrupole coils with magnetic flux lines. The passive corrector forces the magnetization flux to coincide with the main field component that reduces distortions of the field quality. Low-order harmonics before and after correction are presented in Fig. 6-7.

Passive correction with the strips on coil wedges has similar performance to the strips inside the aperture. Moreover, in this case the precise strip alignment is automatically achieved during the coil winding. It eliminates additional technological procedures, simplifying construction of long magnets.

Inability to alter the strip position after the Nb_3Sn magnet is made, makes the precise simulation of the persistent current effect and its correction an important issue. Here one can take advantage of experiments with the iron strips inside the aperture during short model R&D and establish the necessary parameters based on feedback from magnetic measurements. Once it is done – the passive corrector can be permanently introduced into the coil design.

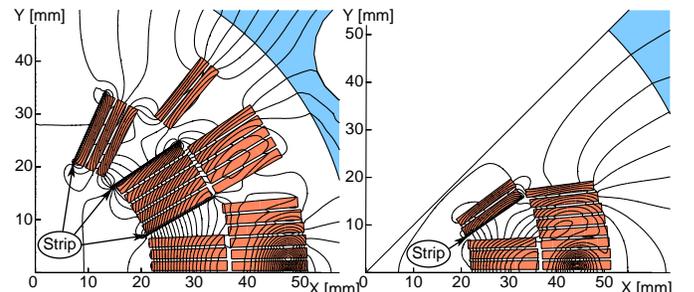


Fig. 5. Magnetization flux in dipole (left) and quadrupole (right) magnets after the passive correction.

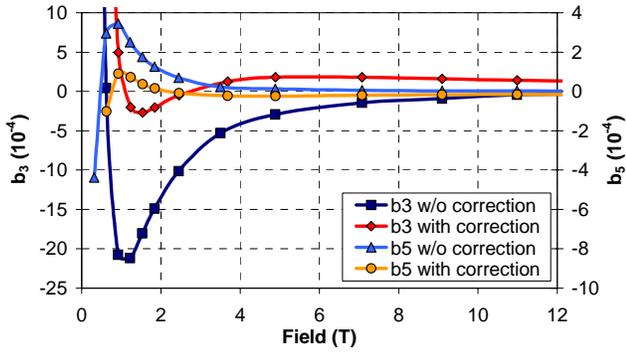


Fig. 6. Low order harmonics in dipole magnet before and after correction.

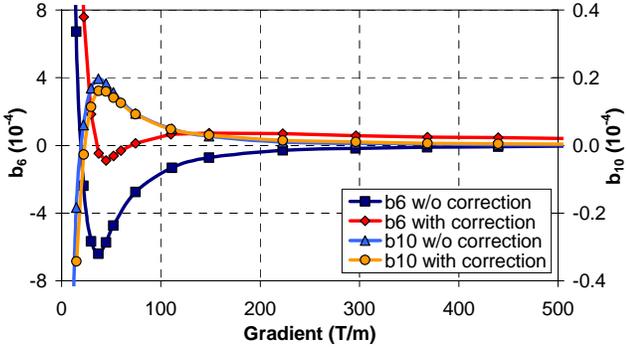


Fig. 7. Low order harmonics in quadrupole magnet before and after correction.

C. Strips inside the cable

A method of passive compensation by the iron core inside a cable [5] allows simultaneous reduction of the persistent current effect and interstrand coupling currents, using magnetic material with a high electrical resistance, e.g. permalloy. Since magnetization curves of superconductor and iron are not symmetrical with respect to the applied field, full compensation can be achieved only at some particular value.

Assuming the compensation field of 2.5 T (to have a correcting effect as in the case with the strips on the dipole wedges), one gets magnetizations $M_{sc} = -0.12$ T and $M_{fe} = 2.13$ T [5]. For an average strand packing factor $\lambda_{sc} = 0.88$, the core packing factor is $\lambda_{fe} = 0.048$. If the core takes 2/3 of the cable width – its thickness should take 7.2 % of the cable thickness or 0.13 mm for 1.8 mm thick cable.

It is a factor of 5 larger than the thickness of a stainless steel core, being routinely used for the reduction of interstrand coupling currents. Such a thick core would increase the cable rigidity, making difficulties during the coil winding. Thus, it is possible to achieve only a partial compensation of Nb_3Sn magnetization using the iron core of a reasonable thickness.

Nevertheless, the compensating iron core can be successfully (and most naturally) implemented in $NbTi$ magnets. According to [8], at the compensation field of 1 T, the $NbTi$ strand magnetization is $M_{sc} = -0.011$ T. For the same strand packing factor, core magnetization and width as in the considered Nb_3Sn cable, the core thickness should be 0.6-0.9% of the cable thickness or 10-15 μm for 1.8 mm thick cable, which is safe for the coil winding.

IV. COMBINATION OF PASSIVE CORRECTION WITH COIL OPTIMIZATION

The passive correction of the persistent current effect is effective at low fields. However, due to the reason mentioned earlier, it creates a positive overcompensation at high fields that may need a correction itself. To understand efficiency of the passive correction within the operating field range, it is convenient to represent harmonics in the absolute units, where the maximum active corrector contribution is a straight line, parallel to the horizontal axis.

Fig. 8. illustrates the sextupole curves with and without the passive correction. The active corrector should have the maximum strength of $B_3 = 1$ mT/cm² in order to eliminate the sextupole component remaining after the passive correction within 1-11 T field range. Apart from that, it has to reverse the current, which is not a well-suited regime for a superconducting magnet.

Nevertheless, just the passive correction itself reduces the necessary active corrector strength by a factor of 2.8 with respect to the non-corrected case. Furthermore, as follows from Fig. 8., positive part of the corrected sextupole curve can be approximated quite well by a straight line. Since geometrical (generated by the coil geometry) harmonics in absolute units are the straight lines proportional to the field - a cancellation of the linear sextupole part at high fields can be accomplished by introduction of the opposite geometrical harmonic.

Fig. 8. shows the influence of the geometrical sextupole ($b_3 = -0.86 \cdot 10^{-4}$), which virtually eliminates the magnetization sextupole at the fields above 6 T. Then the necessary active corrector strength drops to $B_3 = 0.6$ mT/cm². In addition, the active corrector does not need to reverse the polarity and can be switched off after the field reaches 6 T.

The geometrical correction was also considered for the case without the passive correction. It is necessary to introduce a positive geometrical harmonic ($b_3 = 0.66 \cdot 10^{-4}$) to cancel the non-corrected sextupole at 11 T field. However, the minimum on the sextupole curve at 1.5 T field virtually does not change due to a small effect of the geometrical component at low fields. It shows that just the coil optimization itself is ineffective for the reduction of the persistent current effect.

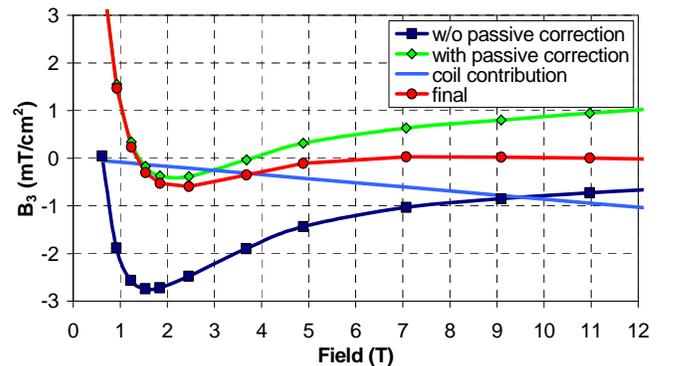


Fig. 8. Cancellation of positive passive overcompensation at high fields by a geometrical harmonic.

V. FABRICATION AND TEST OF PASSIVE CORRECTORS

Two persistent current correctors based on the proposed earlier strips in the aperture geometry were fabricated and tested with the Fermilab Nb₃Sn short dipole models. For simplicity of construction, the correctors were built with one iron strip per coil quadrant, optimized for reduction of both sextupole and decapole components. The iron strip width was 15.85 mm and the thickness varied from 0.1 mm in the single strength corrector to 0.2 mm in the double strength one. The strips were installed between several layers of epoxy-impregnated fiberglass tape at 21.4 mm radius and 55.2 degrees angle from the coil midplane to the strip center. Afterwards, the corrector was cured at ~120 °C that formed a rigid fiberglass pipe with the iron strips embedded inside.

The persistent current effect was measured and calculated in the Fermilab Nb₃Sn short dipole models HFDA02, HFDA03. During the simulations, magnetization curves measured for the relevant Nb₃Sn strands [9] were used. The persistent current correctors were introduced in the magnet apertures between the thermal cycles. Measurements of the field harmonics were performed in the magnet body in cases with and without the passive correctors under otherwise identical conditions [10].

The measured and calculated values of sextupole and decapole components before and after correction by the single and double strength correctors are shown in Fig. 9-10. It can be seen that the persistent current effect was gradually reduced. In the case with the double strength corrector, the sextupole curve is virtually flat for the fields above 2 T. Table I summarises the field harmonic variations between 1.5 T and 4 T field, measured and calculated with and without correction.

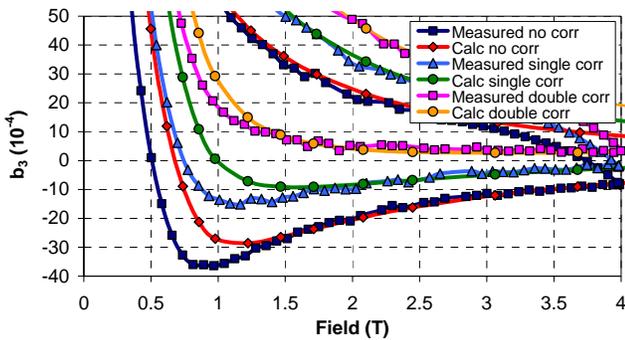


Fig. 9. Normal sextupole before and after correction.

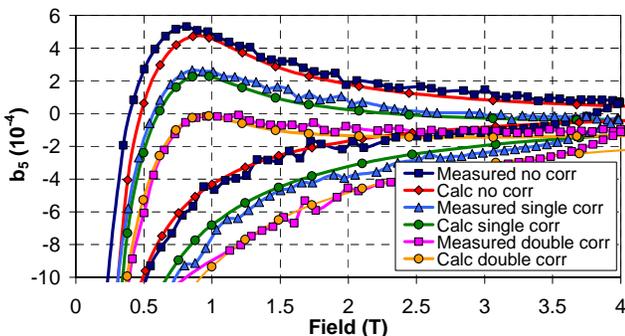


Fig. 10. Normal decapole before and after correction.

TABLE I
HARMONIC VARIATIONS IN 1.5-4 T RANGE

Correction type	$\Delta b_3, 10^{-4}$		$\Delta b_5, 10^{-4}$	
	Calc.	Meas.	Calc.	Meas.
No correction	18.9	19.4	2.4	2.4
Single strength	7.3	11.0	1.4	1.7
Double strength	4.4	3.7	0.4	0.3

Reasonable correlation between calculations and measurements validates the possibility of precise prediction and correction of the persistent current effect in Nb₃Sn accelerator magnets using thin iron strips.

VI. CONCLUSION

The persistent current effect was calculated in dipole and quadrupole magnets based on Nb₃Sn superconductor. The field quality distortions were unacceptably large and needed correction. A simple and effective passive correction of the persistent current effect using thin iron strips was developed. An approach to eliminate the passive overcompensation at high fields and enhance the effect of passive correctors based on small adjustments of the coil geometry was proposed.

Two passive correctors of the persistent current effect were manufactured and tested with Nb₃Sn models. High corrector efficiency for the reduction of the persistent current effect was experimentally confirmed. Good correlation between calculations and measurements verifies the numerical simulations of the persistent current effect and the passive correction based on iron strips.

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