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Correction of Coil Magnetization Effect in Nb3Sn High Field Dipole Magnet Using Thin Iron Strips

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Abstract - Coil magnetization effects in superconducting accelerator magnets deteriorate the magnetic field quality at low fields and thus reduce the accelerator dynamic aperture, decrease the operation field range for SC magnets and complicate the machine correction system. Analysis shows that this effect becomes more important in high field Nb3Sn magnets being developed for future Very Large Hadron Collider. This note presents the results of calculations of coil magnetization effect and describes a possibility of its correction in the Nb3Sn high field magnet being developed at Fermilab for VLHC.

1. INTRODUCTION

Accelerator magnets must meet quite strong field quality requirements. Typically the low order field harmonics within the 2/3 of the magnet bore must be less than 1-2 units of the magnet main field component (dipole or quadrupole) in the operation field range. However, the results of magnetic measurements in superconducting accelerator magnets show that the field quality deteriorates at low fields. For example, the normalized sextupole component in dipole magnets for the Tevatron, HERA, SSC, LHC usually reaches ~10-20 units at an injection field of ~0.5 T. This effect is known as coil magnetization effect in SC magnets caused by persistent currents in the superconducting filaments. It is large at low fields but it rapidly reduces when the main field increases. The negative results of this effect are the decrease of the dynamic aperture, the reduction of the operation field range, complication and cost growth of the correction system.

The situation becomes even worse for high field accelerator magnets based on the Nb3Sn superconductor which are presently considered for the use in a post-LHC Very Large Hadron Collider. The commercially available Nb3Sn strands provide the critical current density sufficient to increase the magnetic field in accelerator magnets up to 11-13 T. However, they have a quite large effective filament diameter, which together with the high critical current density increases the coil magnetization effect by an order of magnitude with respect to NbTi magnets.

To correct this effect during machine operation, a special field correction system consisting a variety of different multipole corrector magnets is usually used (active correction). Several methods of field quality correction based on superconducting strands and magnetic materials (passive correction) have also been proposed [1-4]. Passive field correction could be very attractive for the use in high field SC accelerator magnets if a reliable and inexpensive technique is developed. This note discuss the possibility of correction of large coil magnetization effect in the Nb3Sn High Field Dipole Magnet developed at Fermilab for VLHC [5] using a simple inexpensive technique based on thin iron strips.

2. COIL MAGNETIZATION EFFECT IN SC DIPOLE WITH Nb3Sn STRANDS

A. *Effect of superconductor magnetization on field harmonics*

The coil magnetization effect was calculated using OPERA 2D code. Details of the calculation procedure and a comparison with the results obtained analytically will be reported separately. To assign the coil magnetic properties for OPERA 2D the magnetization curve for superconducting strand was transformed into the B-H curve. Figure 1 shows the magnetic permeability of the Nb3Sn strand during the field increase in first and second magnetization cycles determined from magnetization curves measured at the Fermilab Short Sample Test Facility [6]. The data correspond to IGC 1 mm Nb3Sn strands with the effective filament diameter of ~120 µm. As it can be seen, in first cycle the superconducting strand is a pure diamagnetic (µ<1) while in second one it shows both paramagnetic (µ>1) and diamagnetic (µ<1) properties.

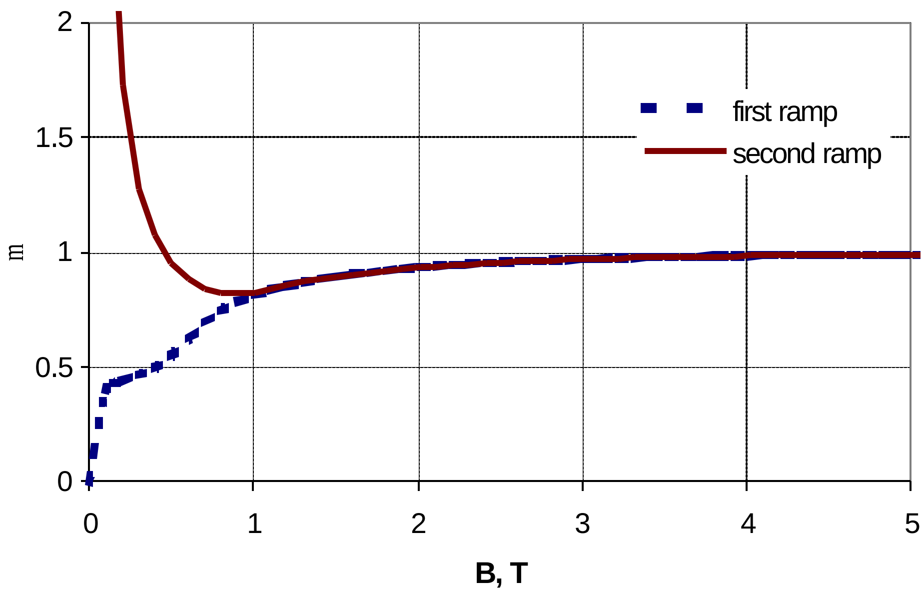

Figure 1: Magnetic permeability of superconducting strand in first and second magnetization cycles.

The magnetic field quality in the magnet central cross-section is described in terms of normalized multipole coefficients defined according to the expression:

$$B_y(x,y)+iB_x(x,y)=B_1\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1},$$

where

$B_x(x,y)$ and $B_y(x,y)$ – horizontal and vertical field components,

B_1 – main dipole component,

Rref - reference radius (*Rref* =1 cm),

b_n and a_n – normal and skew harmonic coefficients.

The absolute values of multipole harmonic coefficients are defined as follows:

$A_n=a_n$´B_1 and $B_n=b_n$´B_1.

Field harmonics were calculated for the Fermilab Nb3Sn high field dipole model [5] in the 0-12 T field range. The calculated multipole coefficients include the geometrical component as well as components related to the coil magnetization and iron saturation effect. Both effects contribute mainly to the low order harmonics. The coil magnetization effect dominates at low fields and the iron saturation effect contributes at high fields. The geometrical low order harmonics were optimized to be small, less than 0.1 unit for the harmonic numbers n<10. The iron saturation effect on the sextupole field component was reduced to 2 units using special correction holes in the iron yoke [7].

The absolute values of the sextupole B3 and decapole B5 components induced by the coil magnetization, vs. the magnet bore field Bo are shown in Figure 2 and 3. The normalized components b3 and b5 vs. the magnet bore field are reported in Figure 4 and 5. The coil magnetization effect for the higher order harmonics is summarized in Table 1.

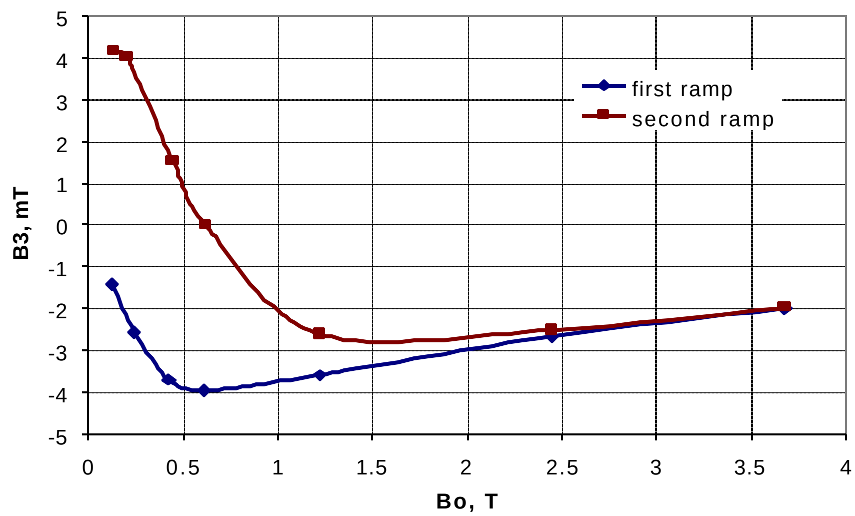

Figure 2: Absolute value of sextupole field component vs. magnet bore field in the first and second cycle.

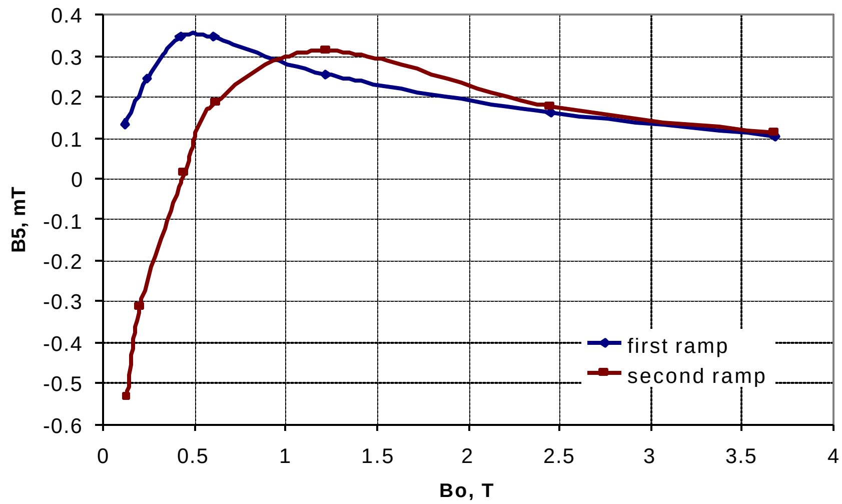

Figure 3: Absolute value of decapole field component vs. magnet bore field in the first and second cycle.

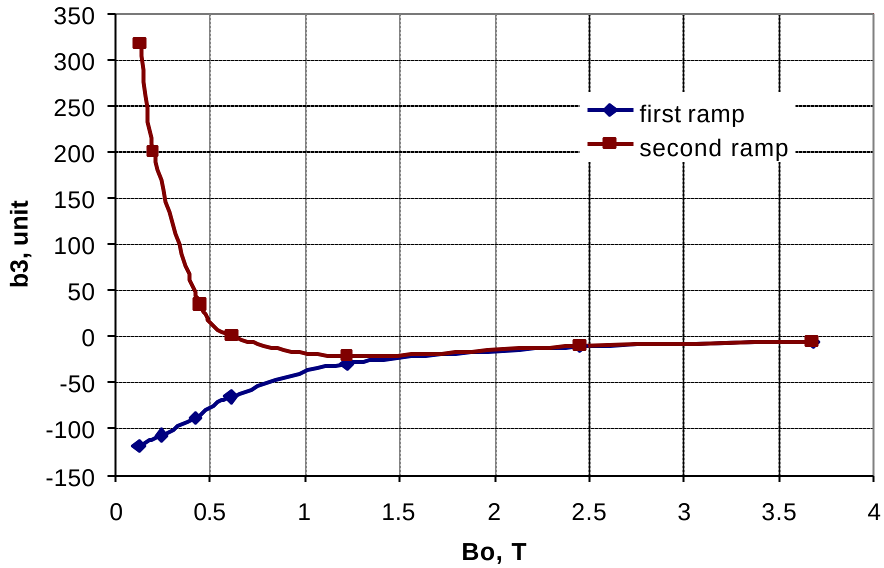

Figure 4: Normalized sextupole field component vs. magnet bore field in the first and second cycle.

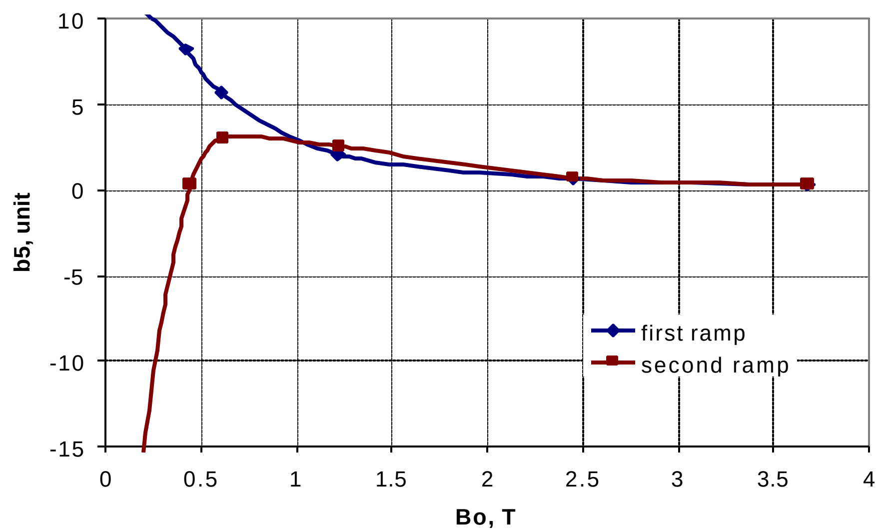

Figure 5: Normalized decapole field component vs. magnet bore field in the first and second cycle.

Table 1. High order multipole components (10^{-4}) vs. magnet bore field.

Bo, T	First ramp			Second ramp		
	b7	b9	b11	b7	b9	b11
0.45	-2.31	0.38	0.09	0.16	-0.07	0.15
0.62	-1.71	0.22	0.09	-0.39	0.07	0.13
1.22	-0.65	0.03	0.09	-0.60	0.06	0.09
4.89	-0.05	-0.08	0.10	-0.05	-0.08	0.09
10.97	0.00	-0.10	0.11	0.00	-0.10	0.11

As it can be seen from the above plots and Table 1, the coil magnetization effect gives a significant contribution only to low order harmonics such as b3 and b5. At a bore field of 1 T b3 and b5 reache -40 and +3 units respectively in the first cycle. In the second and subsequent cycles the absolute values of sextupole and decapole are smaller in the field range 0.2<B<2 T and go back to the first cycle values at higher fields. These numbers are too large for accelerator magnets and must be reduced.

3. CORRECTION OF COIL MAGNETIZATION EFFECT WITH IRON STRIPS

A. Method description

To reduce the coil magnetization effect to an acceptable level, a study of passive correction based on iron strips was performed. The idea was to place the iron strips in appropriate places in the magnet in order to compensate the field components generated by the coil magnetization effect. Two magnetic materials were considered for this study: a soft iron with magnetic properties corresponding to the HGQ LHC (or Fermilab MI) iron yoke and Permalloy. The magnetic properties of these materials are reported in Figure 6.

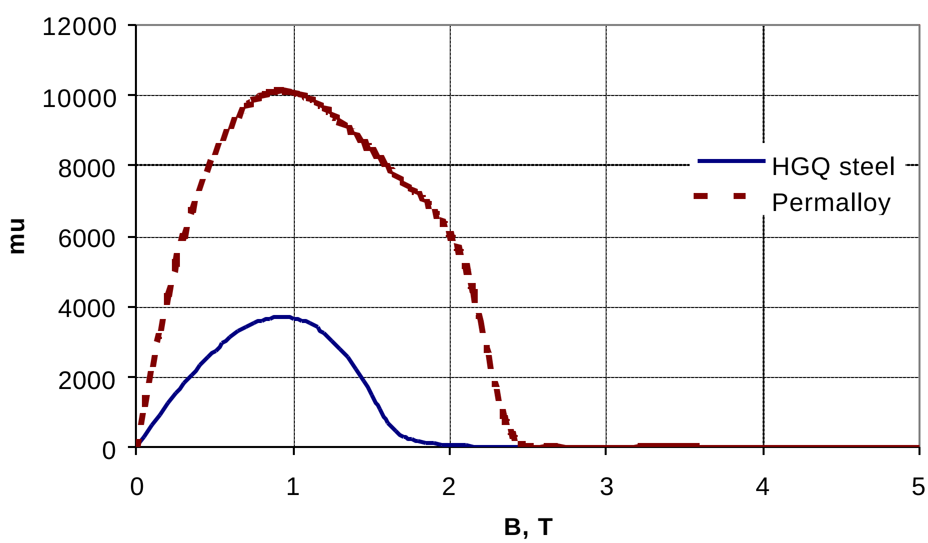

Figure 6: Magnetic permeability μ(B) of the strip materials.

B. Strip size and position optimization

To find the optimal number, size and position of the correction iron strips, a number of calculations were performed. Two strip radial positions in the magnet were analyzed. In the first case, the correction strips were placed in between the coil and the iron yoke on the outer coil surface at a radius of 52 mm. The correction strips were 2mm thick and had an angular dimension of 7.5 deg that corresponds to a strip width of 6.8 mm. Figure 7 shows the sextupole b3 and decapole b5 field components vs. the strip azimuthal position. The higher order multipoles (b7, b9 and b11) are small due to the large distance of strip from the magnet bore.

One can see that to have a positive sextupole b3 and negative decapole b5 the angle range for the strip position has to be between 30 and 60 degrees. The maximum correction effect for b3 is obtained by filling the whole 30-60 degrees range. In this case b3 of +10 units can be generated with 2 mm thick strips. To generate larger b3 and b5, the thickness of the correction strips should be increased. The maximum available space between the coil and the iron yoke in current magnet design allows one to use strips with a thickness of up to 8 mm which can generate b3 of up to +40 units.

A disadvantage of this position for the correction strips is that they become a part of the magnet design. To adjust the strip size and position one needs to disassemble the magnet. There are additional contradictions with the current mechanical design that should also be resolved. Nevertheless, this correction scheme will be further studied as a possible candidate for the use in high field accelerator magnets.

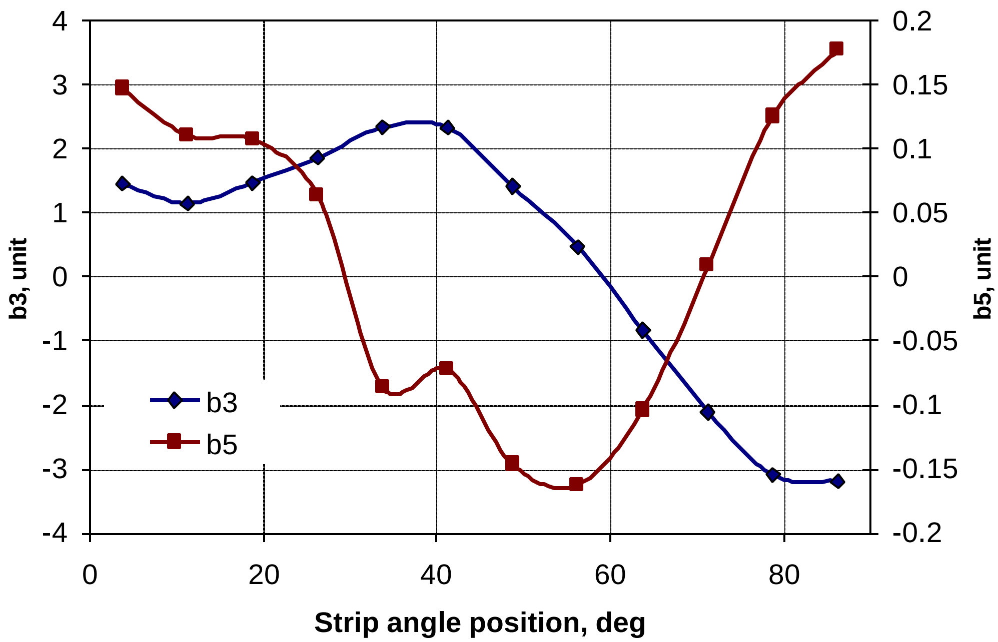

Figure 7: b3 and b5 vs. strip azimuthal position for the correction strips installed between the coil and the iron yoke.

In the second case the strips were installed on the beam pipe at the outer radius of 19.75 mm. Due to the closer distance to the magnet bore, they had a considerably smaller thickness of 0.2 mm and the same angular width of 7.5 degrees corresponding to a strip width of 2.58 mm. Figures 8 and 9 show the dependence of the multipole components generated by the correction strips versus their azimuthal position in the magnet bore. In this case all low order multipole components are presented, although the high order harmonics b7, b9 and b11 are relatively small. One can see that these relatively small correction strips produce large low order field harmonics that can be used for compensation of the coil magnetization effect.

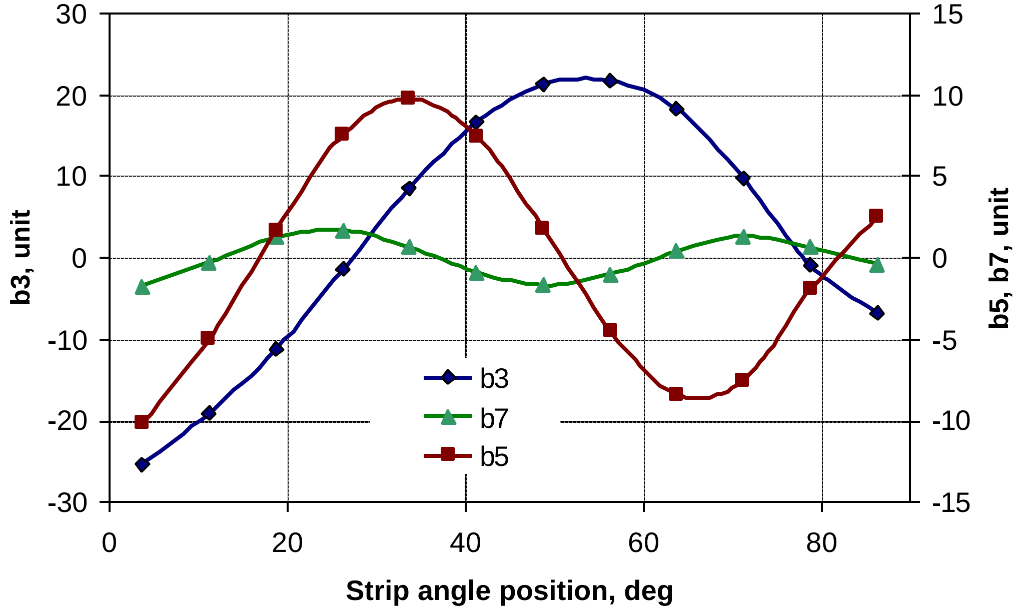

Figure 8: b3, b5 and b7 vs. strip azimuthal position on the beam pipe.

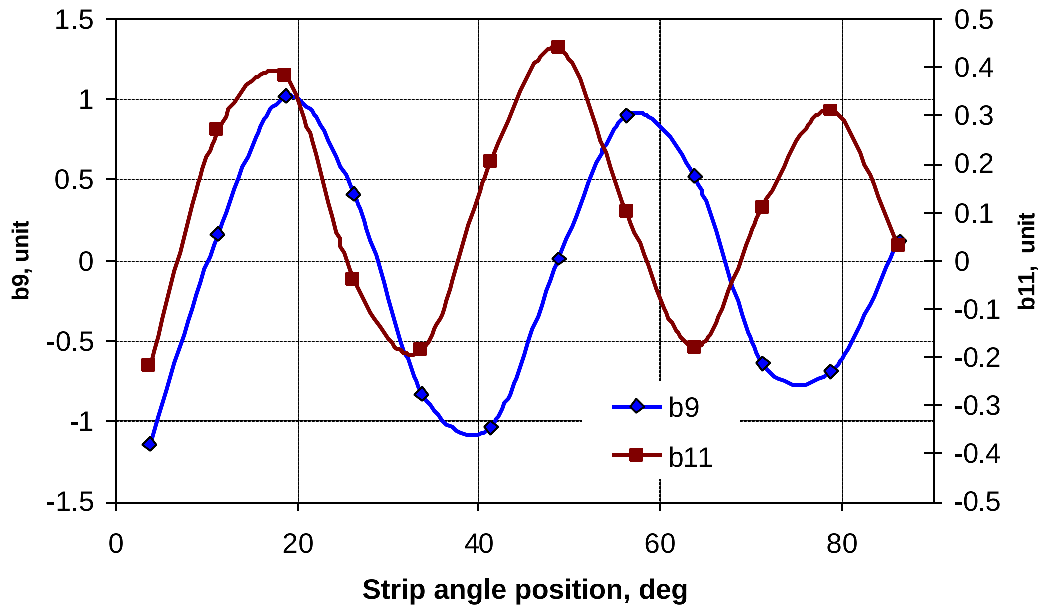

Figure 9: b9 and b11 vs. strip azimuthal position on the beam pipe.

Based on the analysis of curves presented in Figures 8 and 9, the optimal number of strips - 2, strip thickness - 0.23 mm, strip widths - 3.79 mm (11 degrees) and 5.17 mm (15 degrees), and the azimuthal positions of the strip center - 39 and 65 degrees were chosen. The position of the correction strips and the field distribution within the magnet bore are shown in Figure 10.

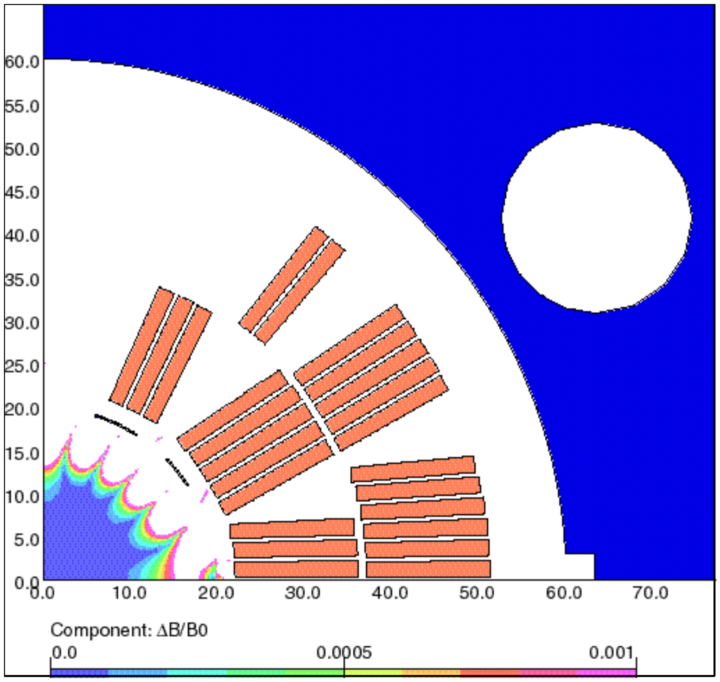

Figure 10: Optimized position of the correction strips and field distribution in the magnet bore.

C. Calculation results

The calculation results of the normalized sextupole b3 and decapole b5 field harmonics before and after correction with the optimized iron strips on the beam pipe for the first and second cycle are shown in Figures 11 and 12.

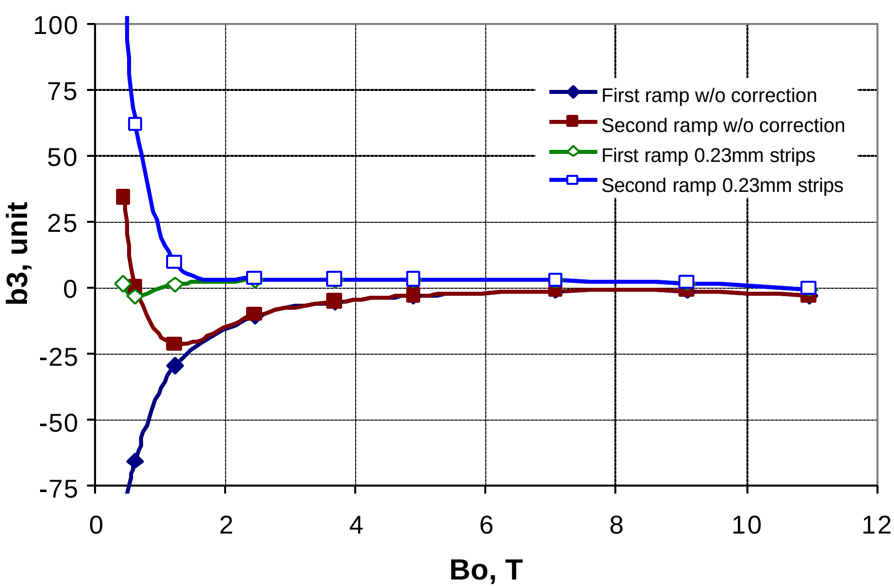

Figure 11: Sextupole field component b3 before and after correction vs. magnet bore field in the first and second cycle.

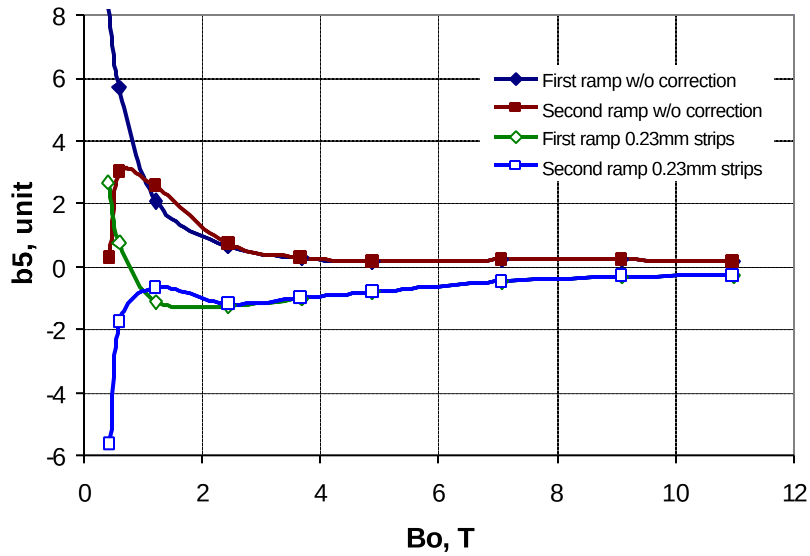

Figure 12: Decapole field component b5 before and after correction vs. magnet bore field in the first and second cycle.

In the first cycle the correction strips provide a full compensation of b3 and b5 for a bore field higher than 0.5 T. In the second and further cycles the compensation is effective only at fields higher than 1 T. Thus far the correction strips increase the magnet dynamic range from 4 to 12 (by factor of 3). It is also easy to see that a further increase of the magnet dynamic range with a help of this method is not possible because of a sharp change of the harmonics at low fields. The situation would be improved by reducing the effective filament diameter in Nb3Sn strands.

Data presented in Figure 13 show the sensitivity of the sextupole component to strip magnetic permeability and their thickness at different fields.

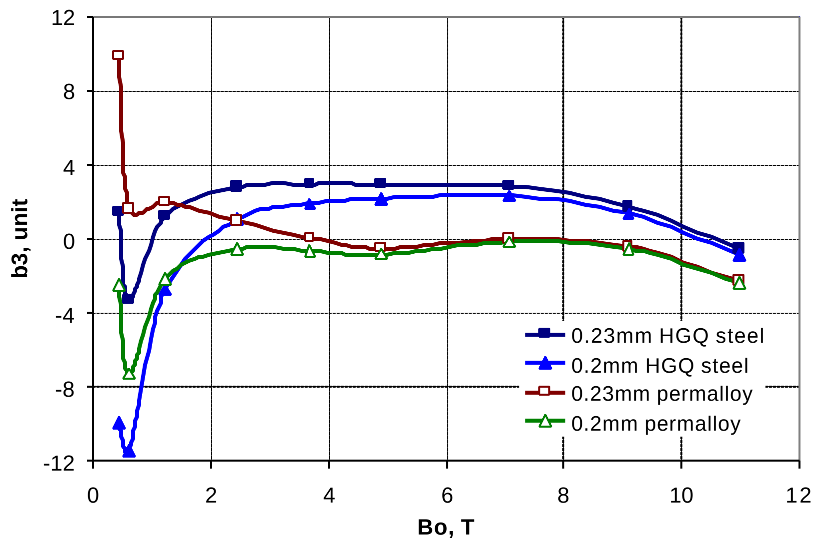

Figure 13. Corrected sextupole field component b3 vs. the magnet central field for different strip materials and thicknesses in the first excitation cycle.

CONCLUSIONS

The analysis of the coil magnetization effect on the field quality of the Fermilab Nb3Sn high field dipole model shows that at present effective filament size of ~100-120 microns the sextupole and decapole field components are quite large at low fields. It was shown that thin iron strips placed in the magnet bore on the outer surface of the beam pipe provide an effective correction of the coil magnetization effect in Nb3Sn magnets with a large effective filament diameter. Using the proposed correction technique, the injection field in this magnet could be reduced to 1 T, which significantly increases the magnet operation field range. By reducing the effective filament diameter and using the proposed correction technique one could further decrease the injection field of Nb3Sn accelerator magnets and thus increase their dynamic range. In this case the requirements on minimal effective filament size in Nb3Sn strands would be driven by the conductor stability and cost considerations. The variation of the magnetic properties of iron strip and their anizothropy will be experimentally studied in order to optimize further their position and geometry in the magnet.

REFERENCES

[1] B.C. Brown, H.E. Fisk and R. Hanft, IEEE Trans. on Magnetics, MAG-21, No. 12, 1985, p.979.

[2] M.A. Green, IEEE Transaction on Magnetics, MAG-23, No.2, 1987, p.506.

[3] M.A. Green, “Passive Superconductor a Viable Method of Controlling Magnetization Multipoles in the SSC Dipole”, IISSC Supercollider 1, Plenum Press, New York, 1989, p.351.

[4] E.W. Collings et al., “Design of Multifilamentary Strands for SSC Dipole Magnets”, IISSC Supercollider 2`, Plenum Press, New York, 1990, p.581.

[5] G. Ambrosio, et.al, "Development of the 11 T Nb_3Sn Dipole Model at Fermilab", *MT-16*, Tallahassee, FL, 1999.

[6] C. Boffo, “Magnetization Measurements at 4.2 K of Multifilamentary Superconducting Strands”, thesis of University of Udine (Italy), December 1999.

[7] G. Ambrosio et al., “Magnetic Design of the Fermilab 11 T Nb_3Sn Short Dipole Model”, *MT-16*, Tallahassee, FL, 1999.