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Design of self-correction coils in a superferric dipole magnet

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Abstract. Design of self-correction coils in a superferric dipole magnet is carried out. By adopting the self-correction coil (SCC) scheme, we can do online correction of unwanted fields inside the magnet aperture during the whole operating cycle irrespective of their origin. The self-correction coils are short-circuited superconducting coils of required symmetry placed in the useful aperture of the AC dipole magnet. Design and operation mechanism of self-correction coils in a superferric dipole magnet are discussed in this paper.

Keywords. Superferric magnet; self-correction coil; superconducting wire.

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1. Introduction

The fields in normal conducting magnets are dominated by the shape of the iron pole and are excited by coils, usually wound on copper or aluminium conductors, and the field is limited to 2 T. For superconducting magnets, which are mostly intended for operations above 3 T, the field shape is primarily determined by the position of the superconducting coils.

Superferric magnets (SFM) are a hybrid version of superconducting and iron-dominated room-temperature magnets. In the SFM, superconducting coils are used but iron plays an important role in shaping the field. Thus, the ampere turns required to achieve the desired field reduce as compared to the superconducting magnet. SFM are compact due to high current density in the coils when compared to the normal conducting magnet. The construction and operation of the SFM is economical when compared to the normal conducting magnets even if we include of the operation cost of the refrigerator [1]. Energy saving is the key factor even after considering the energy consumption for refrigeration.

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It is impossible to generate a magnet that will not produce an error field in the magnet aperture. These unwanted field harmonics can be eliminated from the useful aperture of the magnet using short-circuited superconducting self-correction coils (SCC) positioned inside the magnet aperture [2–5]. The operation principle of the SCC is based on the following inductive phenomenon: by the magnetic coupling between the error field and the SCC, during excitation of the magnet, the error field present inside the magnet aperture induces current in the SCC. The number of turns in the SCC is so adjusted (in the design stage) that the field due to the induced current in the SCC cancels the error field. By incorporating the SCC in the magnet aperture, large dynamic range (0.1–3.0 T) can be achieved.

In our case, the superferric dipole magnet is an AC magnet where such dynamical self-correction scheme can be implemented. Major advantages of SCC over other mechanisms of correcting the higher-order multipoles are: (1) no additional power supply along with its associated controls are needed and (2) no additional space is required.

The SFM with SCC will allow more choice in producing the field integral, and, hence, give the optics designer more flexibility in choosing the most economical lattice. We are developing SCC with SFM. The main aim of the present research is to check the effectiveness of the self-correction coil mechanism.

In this paper, only the correction of the sextupole component is considered, but this method can be extended to any harmonic order present in the magnet or error field.

2. Mechanism of self-correction coil

We briefly discuss the mechanism of the SCC using a simple model. The principle of the SCC was discussed in detail by Dael *et al* [2] and Hosoyama [3]. Figure 1 shows a model for the SCC, where L_0 is the self-inductance of the main dipole coil, L_1 is the self-inductance of the error coil originated from incorrect coil position or deformation of coil shape or saturation effect of iron yoke, L_2 is the self-inductance of the SCC, M is the mutual inductance between the error coil and the SCC. I_1, I_2, R_1 and R_2 are current and resistance of the main coil and the SCC respectively.

We discuss the case of dipole magnet with sextupole SCC configuration. The aim is to eliminate the sextupole component present inside the dipole magnet aperture.

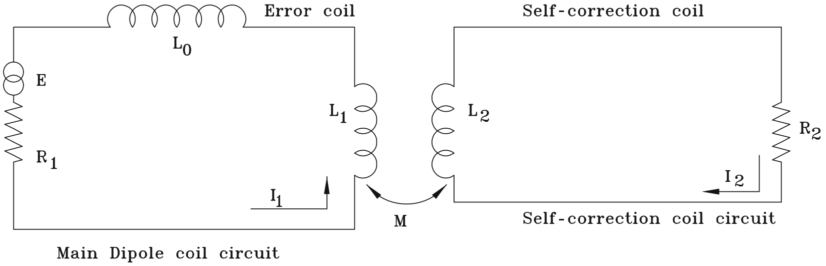

Figure 1. Model for the self-correction coil.

The current I_1 is controlled by the current feedback system. The current I_2 is determined by solving the following differential equations:

$$E = (L_0 + L_1)\frac{\mathrm{d}I_1}{\mathrm{d}t} + I_1 R_1 + M\frac{\mathrm{d}I_2}{\mathrm{d}t}, \tag{1}$$

$$0 = L_2\frac{\mathrm{d}I_2}{\mathrm{d}t} + I_2 R_2 + M\frac{\mathrm{d}I_1}{\mathrm{d}t}. \tag{2}$$

For simplicity we assume $R_2 = 0$, because the SCC operates under zero resistance superconducting state ($R_2 \sim 10^{-9}\ \Omega$). The decay time constant of the induced current in the SCC is about 10^6 s (the self-inductance L_2 of the SCC $\sim 10^{-3}$ H). Thus, the soldered joint resistance has no important effect. However, it is necessary to make the SCC quench from time to time to cancel the residual currents.

From eq. (2), current I_2 induced in the SCC is calculated using the equation

$$I_2 = -\frac{M}{L_2} I_1, \tag{3}$$

by assuming $I_1 = I_2 = 0$ at $t = 0$.

From eq. (3), the SCC current I_2 and the correction field can be decided. In ideal coil winding of the SCC, the correction field and the error field have the same strength and in opposite directions and thus cancels out the error field inside the SCC [3].

The harmonic components of the error field can be expressed by the error coils. If we assume ideal coil windings for the error field, we can calculate the mutual inductance M. The self-inductance L_2 of the SCC and mutual inductance M between the error coil and SCC are given as

$$L_2 = \frac{\pi\mu_0}{2}\left\{1 + \left(\frac{A_2}{b}\right)^{2n}\right\} n N_2^2, \tag{4}$$

$$M = \frac{\pi\mu_0}{2}\left\{1 + \left(\frac{A_2}{b}\right)^{2n}\right\}\left(\frac{A_2}{A_1}\right)^{n} n N_1 N_2, \tag{5}$$

where n is the multipolarity of the error field considered, b is the inner radius of the iron yoke, N_1, N_2 are the total number of turns per pole, A_1, A_2 are the radius of the error coil and ideal SCC respectively.

3. Design of self-correction coil

In order to compensate for the sextupole error field in the magnet aperture of a superferric magnet, a self-correction coil with sextupole configuration is designed and will be placed inside the aperture of a dipole magnet. Figure 2 shows the cross-section of the SFM with the sextupole SCC. Figure 3a shows the 2D flux pattern when the ampere turns (NI) in the dipole magnet coil is 30,000 and NI in SCC is zero and figure 3b shows the 2D flux pattern when the NI in the dipole magnet coil is zero and NI in the SCC is 588.

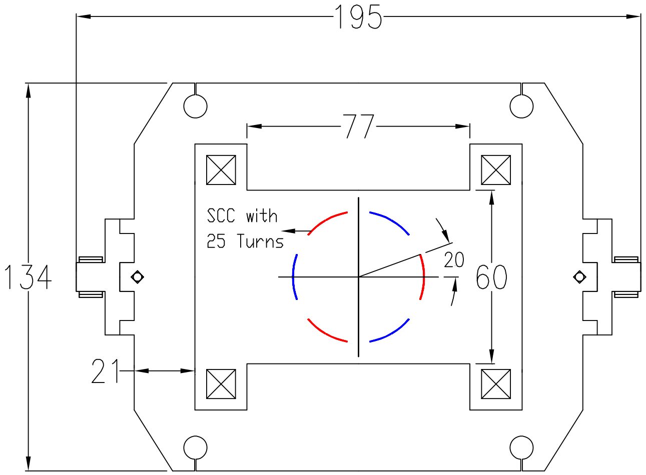

Figure 2. Cross-section of the superferric magnet with sextupole self-correction coil.

For designing single-layer SCC, a sector angle of 20° having 25 turns is chosen. The aperture radius of the SCC is 22.5 mm. The length of the SCC is 80 mm. Detailed design of the proposed SCC is shown in figure 4. A superconductor wire of 0.3 mm in diameter and copper to superconductor ratio of 3.45 will be used for the fabrication of SCC. A filament of 0.1 micrometre diameter is chosen to reduce the hysteresis loss in the SCC during ramp up and down cycle operation. The details of the superconducting wire which will be used to fabricate the SCC are given in table 1. Figure 5 shows the cross-section of tooling parts required for the fabrication of sextupole SCC.

2D simulations are carried out using Poisson code [6] to simulate the ampere turns needed in the SCC to eliminate the sextupole component present within the aperture of the SCC. Table 2 gives the comparison of ampere turns in the dipole magnet coil, dipole field A_1, sextupole field A_3, ampere turns in the SCC needed to eliminate the A_3 component and ratio of the sextupole field with respect to the dipole field (A_3/A_1) at a normalization radius of 15 mm. Table 3 gives the generation of the sextupole field as a function of ampere turns in the SCC when the magnetic field due to the dipole magnet is 8570 G. It is evident from table 3 that 588 ampere turns in the SCC is needed to eliminate the sextupole component present in the magnet. As the SCC consists of 25 turns, the error field will generate 23.5 A current in the SCC to eliminate the sextupole component. Figure 6 shows the magnetic field pattern along the radial direction with SCC and without SCC.

4. Test magnet system

In order to check the effectiveness of SCC mechanism, an H-type dipole magnet is designed and fabricated using 1.5 mm thick iron laminations. The design of the magnet is carried out using 2D Poisson Code. The designed field is 8570 G which is governed by the available power supply (6 V and 160 A) and size of cryostat ($\Phi = 200$ mm) which are readily available.

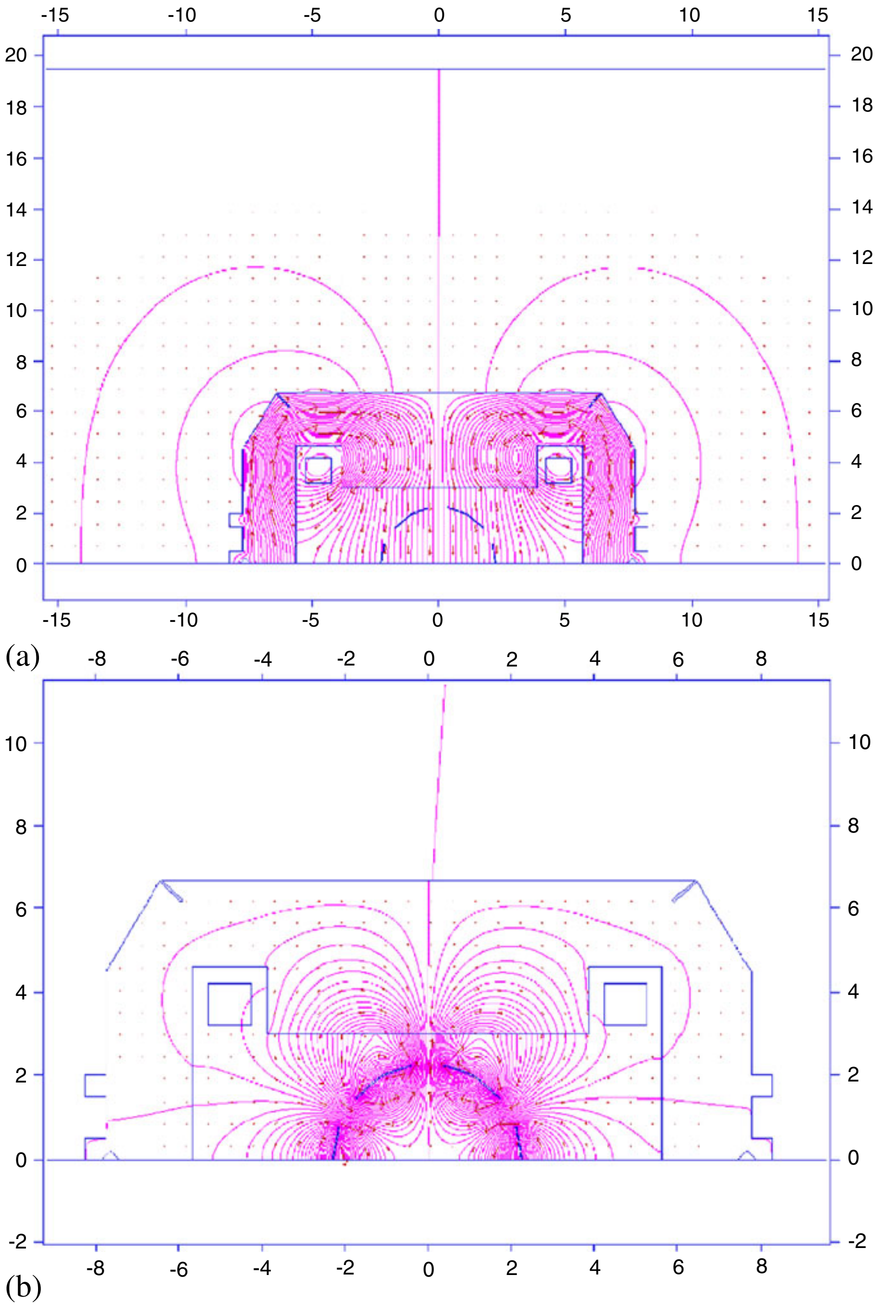

Figure 3. (**a**) 2D Flux pattern of SFM. (**b**) 2D Flux pattern of SCC.

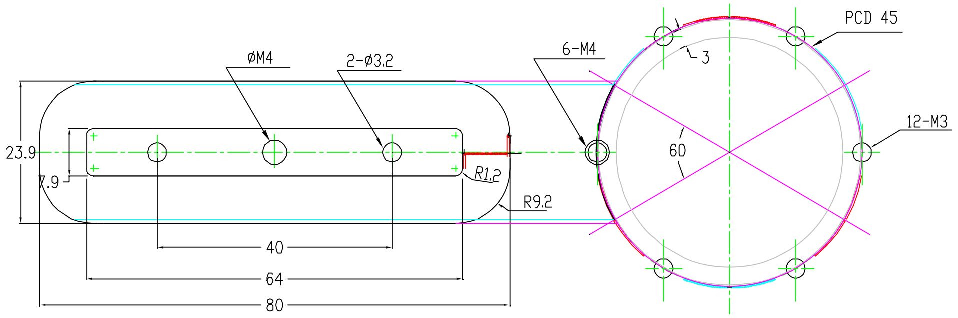

Figure 4. Cross-section of the sextupole self-correction coil.

Table 1. Specification of the superconducting wire.

Parameter	Value	
	Dipole magnet coil	Self-correction coil
Wire diameter	0.68 mm	0.3 mm
Filament diameter	6 μm	0.1 μm
NbTi/Cu	1:1.8	1:3.45
I_c	383 A @ 4 T	75 A @ 1 T
	100 A @ 8.57 T	32 A @ 2 T
Pitch length	30 mm	2 mm

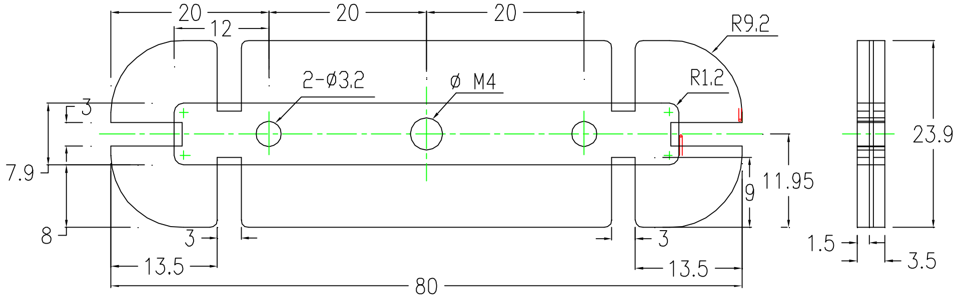

Figure 5. Cross-section of sextupole self-correction coil tooling.

Table 2. Dependence of ampere turns needed in the SCC to eliminate the sextupole component as a function of ampere turns in the main coil.

NI/Coil (Main/SCC)	A_1 (G)	A_3 (without SCC) (G)	A_3 (with SCC) (G)	A_3/A_1 (with SCC)
1000/24	4.08E+02	−0.10E+02	−14.9E−02	−3.65E−04
10000/243	4.07E+03	−1.02E+02	−7.58E−01	−1.86E−04
30000/588	8.57E+03	−2.44E+02	−8.53E−02	−9.96E−06

Table 3. Sextupole field as a function of ampere turns in the SCC when the field due to main dipole magnet is 8570 G.

NI/pole main coil (=30,000) NI/coil (SCC)	A_1(G)	A_3(G)	A_3/A_1
0	8.57E+03	−2.44E+02	−2.85E−02
100	8.56E+03	−2.02E+02	−2.36E−02
400	8.56E+03	−7.75E+01	−9.06E−03
588	8.56E+03	−8.53E−02	−9.96E−06
600	8.55E+03	+5.53E+00	6.47E−04

The aperture gap of the dipole magnet is 60 mm and the core length is 160 mm. Pole shape of the dipole magnet is not optimized to minimize the sextupole component. Since the aim of present work is to check the effectiveness of SCC, laminations are cut using wire cutting technique to obtain the designed core profile.

Race track coil design is chosen for the dipole magnet coil. The coil consists of 196 turns (14 × 14 turns). After winding each layer, thin coating/layer of Araldite ® adhesive (50% epoxy resin and 50% hardener) is applied. The physical length of the coil is 220 mm and the cross-section area of the coil is 9.8 mm × 9.8 mm. The superconducting wire used to fabricate the coil is made of NbTi filaments in a Cu matrix with formvar insulation. The copper-to-superconductor area ratio is 1.8 and the filament diameter is 6 μm. Major parameters of the superconducting wire are given in table 1.

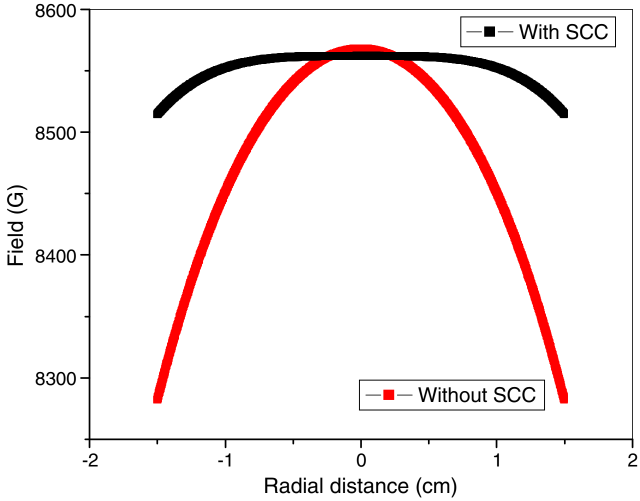

Figure 6. Magnetic field pattern with and without SCC simulated using Poisson code.

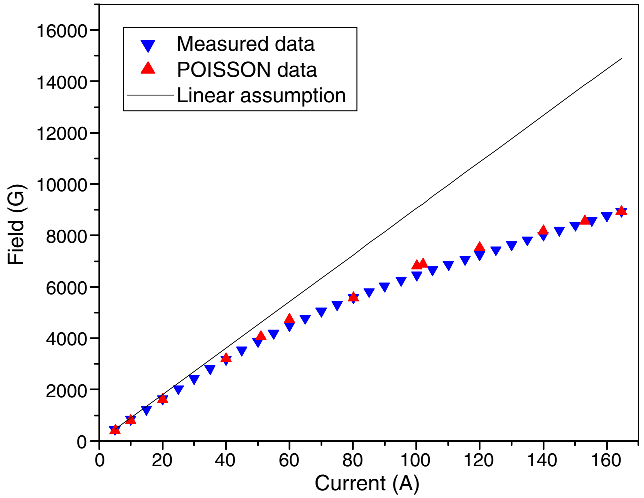

Figure 7. Calculated and measured magnetic fields at the centre of the magnet.

5. Test result and future plan

Superferric magnet was cold tested at 4.2 K and the magnetic field was measured at the centre using Hall probe. The measured non-linearity in the magnetic field is 33% and it matches with the theoretical simulations as shown in figure 7.

We are planning to finish the fabrication of self-correction coil with sextupole configuration and set it in the superferric magnet for the harmonic measurement to check the effectiveness of self-correction coil.

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