Correction of High Gradient Quadrupole Harmonics with Magnetic Shims

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***Abstract*—Superconducting quadrupole magnets with 70 mm aperture and nominal field gradient of 215 T/m are being developed by the US-LHC Accelerator Project for the Interaction Regions of the Large Hadron Collider. Due to large beam size and orbit displacement in the final focusing triplet, these magnets are subject to stringent field quality requirements. For this reason, a correction scheme based on magnetic shims was investigated. This paper reports design calculations, fabrication issues and tests results involving magnetic shims.**

I. Introduction

The High-Gradient Quadrupole (HGQ) cross-section is shown in Fig. 1. Magnetic shims are located in eight rectangular cavities between the yoke inner surface and the collars. Each shim is a package of magnetic (low-carbon steel) and nonmagnetic (brass or stainless steel) laminations. By adjusting the relative thickness of magnetic and nonmagnetic laminations, it is possible to correct random field errors generated by conductor positioning errors [1]. The maximum allowed standard deviation for HGQ sextupole, octupole and decapole random field errors at collision is specified as 0.8, 0.8 and 0.3 units, respectively [2]. In this paper, magnetic shim design calculations and the field quality correction strategy for the HGQ are presented. Results of tests carried out during the short model R&D program are reported and compared with design calculations. Performance limitations are discussed.

II. Harmonic correction with magnetic shims

A. Definitions

A rectangular coordinate system is defined with the z axis at the center of the magnet aperture and pointing from the return end towards the lead end, the x axis horizontal and pointing to the right of an observer who faces the magnet from the lead end, the y axis vertical and pointing upwards. The field is represented in terms of harmonic coefficients defined by the series expansion:

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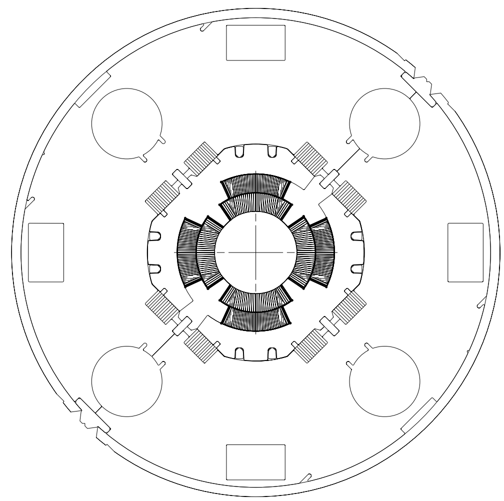

Fig. 1. HGQ cross-section. Magnetic shim laminations are housed in eight rectangular cavities between yoke and collars.

$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty}(B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

The field harmonics can also be expressed in "units" of 10^{-4} of the quadrupole field component: $b_n = B_n/B_2 \cdot 10^4$. A reference radius r_0 of 17 mm is used.

The magnetic shims are labeled by the octant in which they are located. The octants are labeled according to the quadrant in which they are located and the direction of the current flow: octant 1N for quadrant 1, negative (opposite to z-axis orientation) current flow ($0 < \theta < \pi/4$); octant 1P for quadrant 1, positive current flow ($\pi/4 < \theta < \pi/2$); and so forth. In the nominal position, each shim cavity is filled with 1 cm of iron laminations on the midplane side, the remaining part being filled with nonmagnetic laminations. A general position is then given in terms of a filling parameter f, which specifies the thickness [mm] of iron laminations added ($f > 0$) or removed ($f < 0$) with respect to the nominal position. The allowed range of variation for the f parameter is $-10 < f < 10$.

B. Effect of individual shims

The change in sextupole and octupole components at nominal current as function of the position of shim 1N is shown in Figure 2. This calculation has been carried out using the POISOPT optimization routine [4] interfaced to

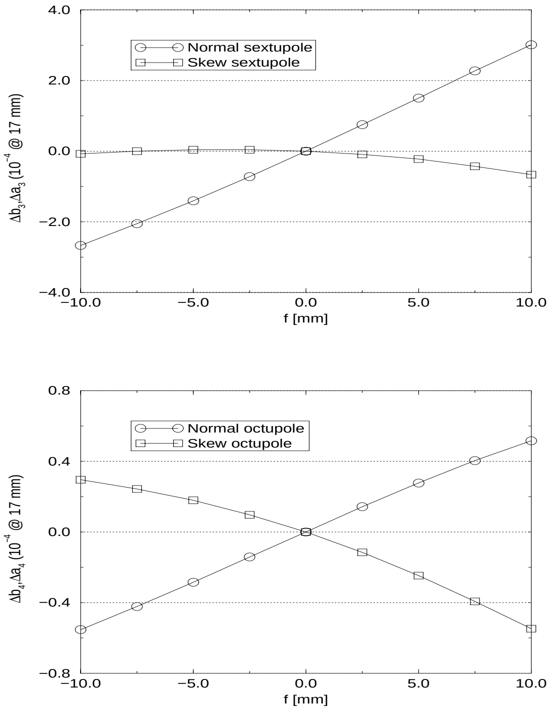

Fig. 2. Variation of normal/skew sextupole, octupole and decapole as function of position of shim 1N at 11.1 kA.

the POISSON package [5]. Due to iron saturation, the magnetic shim effect is strongly current-dependent. In order to obtain the desired correction at nominal current (collision), overcompensation by about a factor 2 at injection is necessary.

If the harmonics generated by shim 1N are known, the harmonics generated by other shims can be obtained based on symmetry operations. Table I shows the symmetry relations between the harmonics generated by different shims [6]. B'_n, A'_n indicate the multipole components computed for each shim. B_n, A_n indicate the multipole components computed for shim 1N (Fig. 2). Since the main field component B_2 is invariant (B'_2=B_2 for all cases), the same relations hold for multipole coefficients expressed in "units".

TABLE I

Symmetries in the harmonics generated by magnetic shims.

Shim	$n = 2k-1$		$n = 2k$	
	B'_n	A'_n	B'_n	A'_n
1N	B_n	A_n	B_n	A_n
1P	$(-1)^{k+1} A_n$	$(-1)^{k+1} B_n$	$(-1)^{k+1} B_n$	$(-1)^{k} A_n$
2P	$(-1)^{k} A_n$	$(-1)^{k+1} B_n$	$(-1)^{k+1} B_n$	$(-1)^{k+1} A_n$
2N	$-B_n$	A_n	B_n	$-A_n$
3N	$-B_n$	$-A_n$	B_n	A_n
3P	$(-1)^{k} A_n$	$(-1)^{k} B_n$	$(-1)^{k+1} B_n$	$(-1)^{k} A_n$
4P	$(-1)^{k+1} A_n$	$(-1)^{k} B_n$	$(-1)^{k+1} B_n$	$(-1)^{k+1} A_n$
4N	B_n	$-A_n$	B_n	$-A_n$

TABLE II

Shimming configurations (sign of the f parameter at each location) for correction of the sextupole and octupole components.

MS	$f[b_3]$		$f[a_3]$		$f[b_4]$	$f[a_4]$
	RM	DM	RM	DM		
1N	+	+	+	-	+	-
1P	-	+	-	-	-	-
2P	+	-	-	-	-	+
2N	-	-	+	-	+	+
3N	-	-	-	+	+	-
3P	+	-	+	+	-	-
4P	-	+	+	+	-	+
4N	+	+	-	+	+	+

C. Correction schemes

The symmetries in the harmonics generated by different shims can be exploited to generate correction schemes for a single sextupole or octupole component, without affecting the others. Table II shows a set of correction schemes which can be used to correct individual sextupole and octupole field errors [6]. Each column defines the sign of the filling factor at each location with respect to a reference filling factor f. All schemes are designed so as to generate a positive correction for positive values of f.

Although the effect of a single shim is not symmetric with respect to the f=0 position, the required cancellations are provided separately for the subset of shims operating at positive and negative f values. As a result, the overall correction applied to the targeted component is symmetric with respect to the f=0 position.

The fact that the symmetry relations exchange the normal and skew sextupole harmonics generated by different shims (Table I) opens the possibility of defining two correction schemes for each sextupole component, with complementary properties. The two schemes use the same f values at the N locations, but opposite values at the P locations. In the first case, the contribution of the normal and skew terms has the same sign, while in the second configuration the sign is opposite. For this reason, the first mode is labeled as "direct" (DM), the second as "reverse" (RM). In the first case, a larger correction can be achieved, while in the second case, finer adjustments are possible for a given lamination thickness. Another difference between the 2 modes is that they have opposite effects on the b_1 and b_5. Depending on the particular set of errors in a magnet, it will be more convenient to use either one or the other in order to achieve the best overall field quality.

Figure 3 shows the calculated differential changes in the harmonics as function of f when the corresponding correction scheme is applied. These results have been calculated using POISOPT, so they take into account coupling effects between different shims. However the effect of coupling is small, as expected since the magnetic shim correction is small compared to the main field. For example, the change in b_3 for I=11.1 kA, f=10 mm is 10.0(RM)/12.6(DM), to be compared with the values 10.2(RM)/12.5(DM) obtained under the assumption of uncoupled effects.

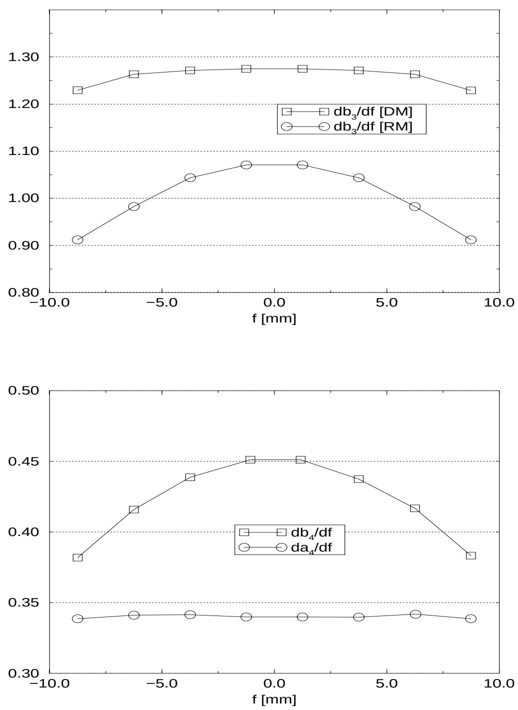

Fig. 3. Differential change of the sextupole and octupole components (the skew sextupole has the same dependence as the normal sextupole).

TABLE IV

Variation in normal and skew harmonics of order 1-6 for a magnetic shim configuration designed to provide a $+1.5\sigma$ correction of all sextupole and octupole components.

Harmonic	Low current		Nominal current	
order	Normal	Skew	Normal	Skew
1	-6.1	13.9	-3.5	7.7
2	6.4	2.2	1.7	0.8
3	2.6	2.7	1.3	1.3
4	2.5	1.9	1.3	1.3
5	0.1	-0.3	<0.1	-0.1
6	<0.1	<0.1	<0.1	<0.1

The effect of changes in magnetic shim configuration on the quadrupole can reach 5 units (0.05% change of the transfer function). For the dipole component, 20 units correspond to a misalignment of 10^{-3} of the reference radius (17μm). The maximum observed effect is 35 units or 30μm displacement. For the decapole component, the maximum effect is 0.19 units in “reverse” mode. This may be used to provide small corrections. If no correction is needed, the “direct” mode shall be used, which has no significant effect on the decapole.

The maximum corrections that can be applied to a single (normal or skew) harmonic component are about 10 units for the sextupole and about 3 units for the octupole. By superimposing the filling parameters computed at each location for each multipole component, a combined correction of several harmonics can be obtained.

In order to take into account the effect of nonlinearities in magnetic shim response (Fig. 3), the shimming parameters computed using the central coefficients can be refined, based on the observed deviations, by doing a second iteration (again using the central coefficients to compute the correction). Table III shows an example of this method. It is supposed that a correction of 1.3 units at nominal current (I=11.1 kA) in all four harmonics needs to be generated. The sextupole correction is implemented operating in “reverse” mode.

As can be seen, two steps are sufficient to ensure that all the required corrections are met with good accuracy. In practice, assuming for example a minimum lamination thickness of 0.5 mm, the final solution for implementation will be: f=1.0/1.5/3.0/4.0. Table IV shows the corresponding calculated changes in the harmonics (up to n=6) both at low current and at nominal current. As can be seen, the desired correction of sextupole and octupole components can be provided without significant changes of the other harmonics.

D. Tests results

The calculated effect of individual shims on the harmonics was tested in HGQ01 by extracting shim 1P between the first and the second thermal cycle. Table V shows good agreement between calculated and measured change in the harmonics. Both the calculated and the measured effects on harmonics of order 5 and above are negligible.

The magnetic shim correction has to be computed based on warm magnetic measurements carried out using typical excitation currents of 10-20 A. To study the impact of signal size on measurement quality, the harmonics were measured at I=10, 20, 30, 40 A. The variations for low order harmonics was within 0.1 units.

The effect of mechanical variations was investigated with a series of measurements inserting one shim at a time in the same cavity. The distribution of measured field has a width of less than 0.1 units.

The capability to correct a single harmonic component

TABLE III

Calculation of shim parameters for combined correction of sextupole and octupole components.

Harmonic component	Required Δ	f_1 [mm]	Δ_1	f_2 [mm]	Δ_2
b_3	1.3	1.3	1.6	1.0	1.2
a_3	1.3	1.3	1.2	1.4	1.3
b_4	1.3	3.1	1.3	3.0	1.3
a_4	1.3	3.8	1.3	3.9	1.3

TABLE V

Comparison of calculated and measured harmonics generated by individual shim (1P).

Harmonic	I=10 A		I=10 kA	
change	Calc.	Meas.	Calc.	Meas.
Δb_3	0.7	0.3	0.1	0.0
Δa_3	4.5	4.7	2.9	2.6
Δb_4	1.1	1.3	0.6	0.5
Δa_4	0.3	0.4	0.3	0.2

TABLE VI
Comparison of calculated vs measured correction

Correction	Calculated	Measured
Δb_3	0.0	0.3
Δa_3	0.0	-0.2
Δb_4	0.0	0.0
Δa_4	-2.9	-3.1

without affecting the others was also tested. The desired correction was Δa_4=-2.0 units in cold conditions, at nominal current (this value was chosen based on magnetic measurements of HGQ01, which showed 2 units of a_4). Using the calculated coefficient a_4/f=0.34, we find f=-5.9. The corresponding expected change at low current is -2.9 units. A set of shims was fabricated and warm magnetic measurements were carried out. Table VI shows the results of this test. The measured values agree with calculations within a few tenths of a unit.

E. Performance limitations

In the HGQ, the iron yoke is located at a large distance from the bore due to the thick coil and collar, and gives a relatively small contribution to the central field (about 10%). For this reason, the magnetic shim effect decays rapidly with harmonic number. Only low order harmonics can be effectively corrected.

The cavity dimension restricts the filling parameter for all shims to the range [-10,10] mm. A sufficient condition is that the sum of the four shimming parameters must be less than 10. With this criterion, the maximum correction which can be achieved simultaneously for the four harmonics is 1.5 units. In cases when the desired corrections for all four harmonics could not be obtained, priority would be given to full correction of the sextupole components, with only partial correction of the octupole components.

Due to saturation effects, a given correction at nominal current results in overcompensation of about a factor 2 at injection. For this reason, the magnetic shim correction scheme does not allow a reduction of random field errors at injection, and causes variations of harmonic components during magnet excitation.

Inductive voltages generated by displacements of magnetic shims by about 25 μm during excitation have been observed during magnet testing. These spurious effects are dangerous as they can interfere with proper operation of the protection system. It should be noted however that the tests performed so far used solid bars rather than laminated shims. Solid bars are more difficult to fit precisely in the shim cavity, and have larger spring constants. This problem may not appear using a precisely fit laminated shim package with smaller spring constant.

In magnet production, the magnetic shim correction must be determined based on warm measurements of the collared coil. Inserting the magnetic shims after yoking is made difficult by the presence of end cans for mechanical support. Taking into account these fabrication constraints, the accuracy of field quality correction with magnetic shims is limited by uncertainty in determining the final magnet field quality based on warm measurments of the collared coil. Comparison between the harmonics measured during magnet fabrication using the SSC system (mole), before cooldown and training quenches in the vertical test facility, and after training shows differences of half a unit to one unit which are not reproducible from magnet to magnet. These may be due to either accuracy of the warm measurements or changes in the harmonic content during the later stages of production and the first series of training quenches. However, no significant changes of the harmonics have been observed after the first series of training quenches at 4.5 K. Taking these effects into account, the magnetic shim method would only be effective in correcting magnets which show errors above 1 unit at the collared coil production stage. A minimum lamination thickness of 2 mm is sufficient to achieve this accuracy.

III. Conclusions

A method for correction of low order harmonics using magnetic shims has been investigated as part of the HGQ short model program.

Correction of individual sextupole and octupole components at nominal current up to several units are possible, with small effect on all other harmonics. Simultaneous corrections of all four sextupole and octupole components up to ± 1.5 units are also possible. The effect on other harmonics is small.

Uncertainty in determining the final magnet harmonics based on warm magnetic measurements of the collared coil limit the accuracy of the magnetic shim correction to about one unit.

Results from the HGQ short model program indicate that magnetic shim correction is not required to achieve the specified field quality. For this reason, in order to simplify magnet fabrication it is not presently planned to implement the magnetic shim correction scheme during HGQ production.

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