INFLUENCE OF AZIMUTHAL COIL SIZE ON SKEW MULTIPOLES IN THE LHC DIPOLES

Iouri Vanenkov, Christine Vollinger, CERN, Accelerator Technology Division, Geneva, Switzerland

Abstract

The field quality in superconducting accelerator magnets is strongly influenced by the azimuthal dimension of the superconducting coil. Asymmetries between the upper and lower poles steer skew harmonics that can endanger the beam dynamics stability. We present dimensional measurements of a large number of coils that have been carried out in one of the three manufacturers of the main LHC dipoles. A magneto-static model is then used to work out the influence of coil non-nominalites on field harmonics. Comparison to magnetic measurements carried out at room temperature shows that skew harmonics can be partly traced back to azimuthal coil dimensions. We focus on harmonics, which are more critical with respect to the beam dynamics limits (a_2 and a_4). Finally some strategies are presented, like the sorting of individual coil poles in order to reduce the detrimental effects on these multipoles.

INTRODUCTION

The Large Hadron Collider (LHC), a superconducting proton-proton accelerator, is made of about 8400 superconducting magnet units of different types. Among them, one has 1232 main dipoles, whose 15 m long coils are held in place by austenitic stainless steel collars. The collars are surrounded by an iron yoke, which is contained in a stainless steel shrinking cylinder [1].

The magnetic field components integrated along the dipole length are described through the two-dimensional multipolar expansion at a reference radius R_{ref}:

$$B_y + iB_x = B_1 \sum_n (b_n + ia_n) \frac{(x+iy)^{n-1}}{R_{ref}^{n-1}}, \quad (1)$$

where R_{ref} = 17 mm and the b_n and a_n are the multipolar coefficients. They are usually expressed in 10^{-4} units relative to the main field B_1. Even normal multipoles b_2, b_4, … and skew components a_2, a_3, a_4, … arise due to left-right and top-bottom asymmetries of the coil geometry with respect to the aperture centre. Since an extremely high field quality is needed for the storage of a particle beam for many hours, the relative deviation from the ideal field in the aperture of a magnet should be of the order of 10^{-4} or less [2]. In superconducting magnets, the field quality is determined by the coil arrangement and the position of the conductors. Manufacturing tolerances of the order of 0.05 mm result in a non-nominal azimuthal coil size, thus producing an up/down asymmetry, e.g., a shift and a tilt of the magnet mid-plane. In the warm magnetic measurements, such a mid-plane shift can be seen as a non-zero value of the skew quadrupole a_2 whereas a tilt produces a skew sextupole a_3. While there is a larger margin for a_3, the LHC beam dynamic limits are rather tight for a_2: therefore, we restrict our analysis on this multipole. Measured data on coils sizes show that a shift of the mid-plane of up to 0.15 mm is to be expected. One possibility of reducing the overall spread of the coil sizes is a sorting of the poles to minimize the up/down asymmetry. In this paper we first present the statistical analysis carried out on the mechanical and magnetic measurements data taken on the pre-series dipoles of one manufacturer [3,4]. We then discuss a magneto-static model used to give the dependence of a_2 on the mid-plane shift and the correlations between mechanical and magnetic measurements. Finally, results from optimized coil sizes that could be achieved by applying the sorting algorithm are presented.

AZIMUTHAL COIL SIZE MEASUREMENTS

The measurements of the azimuthal coil sizes and of the equivalent modulus of elasticity give important information for the analysis of the dipole field quality. The size of the coil could vary due to dimensional tolerances of the individual coil components (see for instance [5] for copper wedges analysis) or tolerances in the tooling and they are measured with a precision of ± 0.01 mm. At the dipole manufacturers, coils are measured by means of the so-called Pole Measuring Machines (PMM). Since each one of three dipole contractors is equipped with a different type of PMM, no direct cross-analysis is carried out. However, during the dipole manufacturing each coil layer or pole is measured in several longitudinal positions delivering a large amount of raw data, which is treated in a standard way for all the companies before it is transferred into the CERN database.

In order to standardize the data post-processing and speedup the data exchange between companies and CERN, the Collared Coil Database software package (CCD) was developed at CERN and installed at each dipole manufacturer site. The core of CCD package is a database (MS Access) that includes a facility to exchange the data with CERN via e-mail. For each PMM, the package includes a post-processor application (LabVIEW 6i), which treats the raw data on coil size measurements and does an automated upload of the treated data into the database. The CCD package also includes a data-viewer (LabVIEW 6i) that allows a follow-up to be carried out by the project engineers either at the companies or at CERN. The viewer also includes an optimization tool to do a pairing of the magnet poles for a minimization of the unwanted up/down asymmetry.

The coil size measurements of the pre-series magnets showed that due to the tolerances on the coil components, mostly the insulation of the cable, the coil size varies in the range of +/- 0.2 mm (see fig.1). This coil size variation is random and thus can induce large differences in the azimuthal dimensions of the upper and lower pole within one aperture. As an example, in figure 1 the inner layer coil size in the collared coil no. 15 shows a difference between the size of the upper pole (pole 1) and the lower pole size (pole 2) of 0.15 mm! A similar bad case is observed for the collared coil no. 17. In this graph, each point is the average of coils size measured in 18 positions along the coil, 4 points is a set of poles that belong to one collared coil.

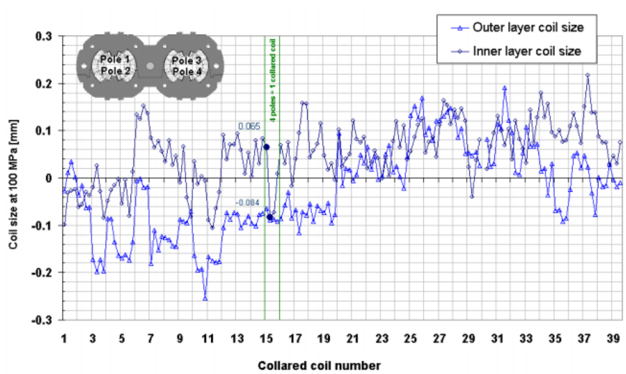

Figure 1: Azimuthal coil size deviation with respect to the nominal size for a set of 40 magnets built by manufacturer 1.

MAGNETIC MEASUREMENTS

All the LHC dipoles will be tested for magnetic field quality at 300 K: a first test is carried out after the collaring and a second one after the yoke assembly is completed and the outer cylinder welded. The magnetic measurement of the collared coils is an essential tool for the control and the steering of the dipole field quality during the mass production [4]. Results are screened to detect assembly errors and are then compared to beam dynamics targets to check if corrective actions are necessary.

Beam dynamics targets are based on the integrated values along the magnet axis, since local variations are negligible for circulating particles. These values are given in terms of systematic (average over 1232 dipoles) and random (standard deviation over 1232 dipoles). The systematic must fit within a range, and the random must be lower than the target. The values are summarized in Table 1.

One can observe that random components are within targets in all cases, a_2 being the case in which we are closer to the tolerance. Moreover, the measured random of a_2 (1.9 units) in the aperture 1 of the pre-series magnets of manufacturer 1 is larger then the random target. Therefore, for this company the analysis of the influence of coil size tolerances on the skew quadrupole are carried out and an improvement is proposed.

Table 1: Measured skew multipoles versus beam dynamics targets.

	a_2	a_3	a_4
Random target	1.6	0.7	0.50
Random measured	1.3	0.4	0.28
Systematic Max	1.3	1.9	0.13
Systematic Min	-0.8	-1.6	-0.16
Systematic Meas.	0.0	-0.1	0.02

MAGNETOSTATIC MODEL

The coils of the LHC main dipole magnet are wound of a Rutherford type cable, containing 28 and 36 wires on the inner and the outer coil layer, respectively. Between the coil blocks, copper wedges are inserted to produce a sufficient field quality in the magnet aperture, since the trapezoidal shape of the cable is not sufficient to build a circular inner alignment, when wound on a mandrel (see fig. 2). Compared to the superconducting cable and the cable insulation, these wedges are rather rigid and define the coil cross-section. At the same time, the outer coil shape is determined by the inner contour of the collars. Although collar deformations take place, since they are up/down symmetric and they do not contribute to skew multipoles, we can neglect them for our analysis.

The influence of different azimuthal coil sizes on skew multipoles has been modelled applying the above quoted approximations using a magneto-static code [6]. Due to the hypothesis on the rigidity of the collars, points 1-4 in fig. 2 are fixed, and the inner and the outer width of the cable (W_i and W_o) are varied to produce a difference between the upper and lower pole azimuthal size. The shape of the copper wedges is also preserved.

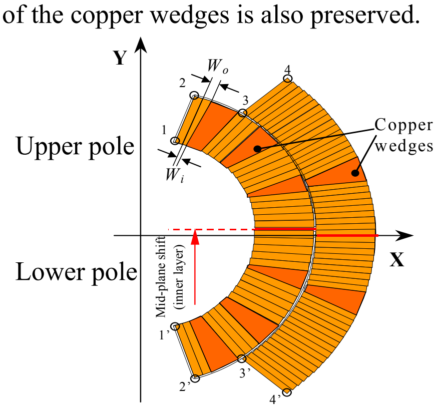

Figure 2: Inner layer mid-plane shift due the coil size difference between upper and lower pole.

Table 2 shows the calculated changes of the skew multipoles a_2 and a_4 due to shifts in the mid-plane of 0.05, 0.10 and 0.15 mm. The values correspond to a smaller upper pole, which means that the mid-plane is shifted upwards. One finds a linear dependence of the multipoles on the mid-plane shift. The inner and the outer layer have been calculated separately: as expected, in general, the multipoles are more sensitive to shifts on the inner layer. The total effect can be obtained by superposition of the contribution of the individual layers.

Table 2: Calculated effect of a mid-plane shift on skew multipoles.

Mid-plane shift	Inner layer		Outer layer	
	δa_2	δa_4	δa_2	δa_4
0.05 mm	-2.67	-0.38	-1.56	-0.11
0.1 mm	-5.30	-0.77	-3.16	-0.20
0.15 mm	-7.95	-1.07	-4.69	-0.36

CORRELATIONS

From cross-analysis of data on magnetic and coil size measurements, some correlation between the expected a_2 due to coil mid-plane shift and the measured values can be observed (see fig. 3).

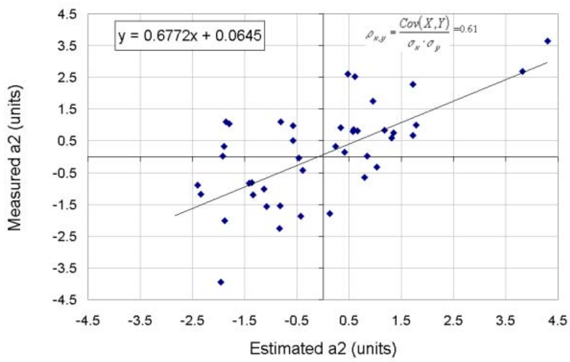

Figure 3: Measured and estimated a_2 resulting from the expected coil mid-plane shifts in the magnets of manufacturer 1.

In this graph the data belongs to the magnets, which are collared without sorting of their poles. The fact that the correlation factor is only 0.61 indicates that not only the difference in coil sizes but also other factors (such as a re-distribution of the current density within a coil arc due to tolerances of coil components) is contributing to these harmonics. For the last 9 magnets the manufacturer 1 has applied the sorting of poles within one set of poles and this already reduced the sigma on a_2 from 1.9 to 1.5 (see fig. 4). This was sufficient to reach the target value of 1.6. At the time of writing this paper, more magnets were assembled following coils sorting procedure and the sigma on a_2 was decreased even more. It is clear that if a bigger stock of poles is used, a safety margin could be added. In case of a stock with 12 poles, which becomes realistic when the companies move into series production scale, the effect on sorting becomes even more efficient (see fig.5). It should be noticed, that the sorting of the poles might be limited in some cases due to constraints in the mix of the cables produced by different manufacturers. This could limit the pole pairing only if the stock of poles is small.

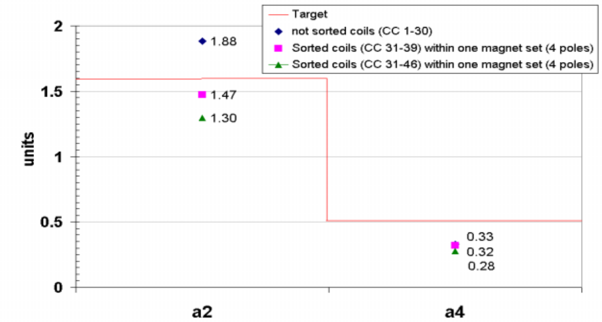

Figure 4: Effect of poles sorting on random of a_2 and a_4 .

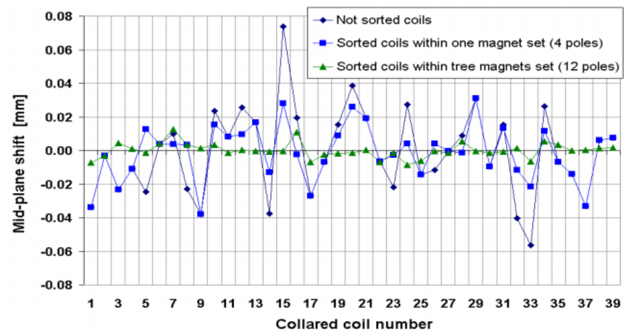

Figure 5: Effect of poles sorting on mid-plane shift value.

CONCLUSIONS

A model was developed to compute the effect of azimuthal coil size variation on the skew qudrupole and skew octupole of superconducting LHC dipole. The model was applied to the data on coil sizes of one dipole manufacturer. Some correlation was observed between measured and expected multipole coefficients.

A sorting of coils procedure, introduced at one of the dipole manufacturer, shown that it is a good method to reduce the random of a_2 mutipole. Dedicated software was developed and introduced to the dipole manufacturer to follow the coil size trends and simplify the procedure of sorting the poles.

ACKNOWLEDGEMENTS

We wish to thank L. Rossi for support, discussions and help given in this work. We thank the project engineers of the AT-MAS group for the constant support in the analysis and for providing assembly data.

REFERENCES

[1] L.Rossi, these proceedings.
[2] S. Fartoukh et al, *LHC Project Report* 501 (2002).
[3] M. Modena et al, these proceedings.
[4] W. Scandale et al, these proceedings.
[5] B. Bellesia, *LHC Project Report* 630 (2003).
[6] S. Russenschuck, ROXIE: Routine…, CERN 99-01, Geneva, 1999