ANALYSIS OF WARM MAGNETIC MEASUREMENTS OF THE FIRST SERIES-DESIGN PROTOTYPES OF THE LHC MAIN QUADRUPOLES

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Abstract

The room temperature magnetic measurements of the first series-design prototypes of the LHC main quadrupoles are analysed. Data relative to the collared coils and to the assembled cold mass are considered. The averages of the multipoles along the magnet axis are interpreted as the systematic components. The agreement with the nominal design is verified, and possible explanations for discrepancies with regard to the multipole allowed by symmetry are worked out. The standard deviations of the multipoles along the axis are interpreted as the random components. We show that the latter can be interpreted in terms of random movements of up to 25-35 μm of the coil blocks, because of components and assembly tolerances. A good correlation between measurements made on collared coil and the assembled cold mass is found. The influence on field quality of a systematic radial misalignment of the coil conductor is also evaluated.

1 INTRODUCTION

Three LHC quadrupole prototypes 3.25 m long, respectively assembled in the short straight sections called SSS3, SSS4 and SSS5, have been built in Saclay in view of the series production [1-4]. All of them have been measured at room temperature in order to assess their field-shape performance and one of them has been also successfully tested in operational conditions [3]. In this paper we analyse magnetic measurements at room temperature, made at CEA in Saclay. The analysis of these measurements provides relevant information on coil geometry and on its reproducibility, that plays an important role in the determination of both systematic and random components of multipolar errors. Moreover, it allows the determination of correction strategies and an early detection of drifts in the series production. In this paper we assess some of the methods used in this analysis, and we give results for the quadrupole prototypes. A more detailed analysis can be found in [5].

In Section 2 we compute the field shape harmonics expected for the nominal cross-section, distinguishing the different contributions. In Section 3 we present the experimental data. A comparison with nominal values is given in Section 4. In Section 5 we analyse correlation between harmonics of the same order measured in collared coils and in the assembled cold mass. In Section 6 we consider the random components of the field, proposing to interpret them as due to random movements of the coil blocks. Some conclusions and acknowledgements are given in Section 7.

2 CALCULATION OF THE HARMONICS

In Fig. 1 we show the cross section of the quadrupole, with the conventional numbering of the coil blocks. The transport current of the coils induce field-shape harmonics of order n=2(2k+1), with k = integer, due to the four-fold symmetry. Non-allowed normal harmonics induced by the two-in-one design are very small (i.e., less than 0.1 units). Table 1 shows the computed allowed harmonics at a current of 12.5 A. The multipoles are given in 10^{-4} units, at the reference radius R_{ref} = 17 mm, using the standard 2D field expansion:

$$B_y + iB_x = B_2 R_{ref} \sum_{n=1}^{\infty} \left(b_n + ia_n\right) \left(\frac{x+iy}{R_{ref}}\right)^{n-1} .$$

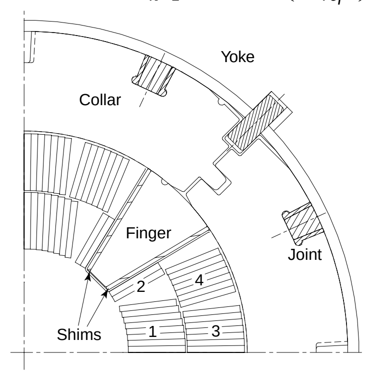

Figure 1: One quarter of the quadrupole cross section

Table 1: Allowed harmonics at room temperature, with I = 12.5 A (R_{ref}=17 mm, 10^{-4} units).

	Coil Geometry	Collared Aperture	Assembled Aperture	Outer Alignment
b_6	4.11	3.46	3.25	6.27
b_{10}	-0.21	-0.16	-0.15	0.31
b_{14}	-0.15	-0.15	-0.14	-0.18
b_{18}	-0.02	-0.02	-0.02	-0.02

We first give the allowed harmonics induced by the coil geometry (Table 1, column 1). In column 2 we compute the harmonics of a collared aperture, including the magnetic effect of stainless steel collars (μ_r=1.0022) and shims (μ_r=1.0048). The harmonics of the assembled aperture, taking into account the yoke contribution, are given in column 3. In column 4 we consider the case of an alignment of the conductors on the two layers outer radii instead than on the winding mandrel as expected in nominal design. In principle, this unwanted situation may happen during the coil production, since the keystone angle of the cable is small and turns of the inner layer could slide towards the interlayer during the magnet energization.

We also evaluated a sensitivity matrix that provides the multipole change due to small rigid movements of the blocks. In Table 2 we give the effect induced on b_6 and b_{10} by four-fold symmetric rigid displacements of 50 µm, using the block coordinates of Fig. 2. Effects on the higher order allowed harmonics are negligible.

Table 2: Sensitivity matrix for 50 µm rigid displacements of the blocks. (R_{ref}=17 mm, 10^{-4} units)

	δr_1	δr_2	δr_3	δr_4
δb_6	-0.25	0.87	-0.12	0.15
δb_{10}	0.11	-0.10	0.00	0.00
	$\delta \varphi_1$	$\delta \varphi_2$	$\delta \varphi_3$	$\delta \varphi_4$
δb_6	-2.13	0.18	-0.15	-0.15
δb_{10}	-0.14	0.06	0.00	0.00
	$\delta \alpha_1$	$\delta \alpha_2$	$\delta \alpha_3$	$\delta \alpha_4$
δb_6	-1.22	0.06	-0.07	-0.09
δb_{10}	-0.09	0.04	0.00	0.00

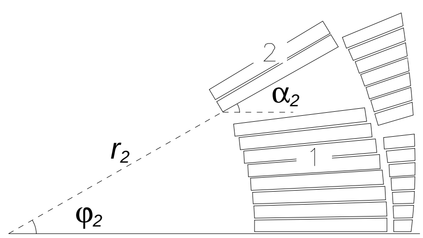

Figure 2: Parameters defining the block position.

3 EXPERIMENTAL DATA

The field-shape was measured at room temperature with I = 12.5 A, using a 0.75 m long rotating coil, at five positions along the quadrupole axis. We considered only the three central positions to characterise the harmonics, since fringe field effects affect the first and the last positions. In Table 3 we give the averages and the standard deviations measured for the left aperture of SSS4, both for the collared coil and for the assembled cold mass. In Table 4 we analyse the average of each aperture and we compute their global average and standard deviation for the six available apertures.

4 COMPARISON TO NOMINAL VALUES AND INVERSE PROBLEM

One observes a systematic discrepancy of around 3 positive units in b_6, whilst higher order allowed multipoles are very close to the nominal values. The discrepancy in b_6 could be explained by a shift of the inner layer turns towards the outer layer (see Table 1), but in this case one would have a b_{10} with an offset of around –0.5 units, that seems unlikely. Using the sensitivity matrix (see Table 2) we worked out two rigid block displacements that give rise to the observed b_6 and b_{10}. They can be explained by an azimuthal shrinkage of the inner layer of about 100 µm or an azimuthal shrinkage of block 1 combined with a radial shift of block 2 towards the outside, both of about 60 µm. Both solutions feature an azimuthal length of block 1 shorter than the nominal one. This is confirmed by mechanical measurements in Saclay showing that pole pieces are 50 µm larger then the nominal design. The observed discrepancy is reproducible in all magnets, and therefore a correction, if needed, should be feasible.

Table 3: Harmonics in the left aperture of SSS4. Collared and assembled cases (R_{ref}=17 mm, 10^{-4} units).

	SSS4 Collared		SSS4 Assembled	
	Avg	σ	Avg	σ
b_3	-1.28	0.34	-0.92	0.36
a_3	1.15	0.43	1.02	0.47
b_4	-0.09	0.14	-0.04	0.14
a_4	-0.38	0.64	-0.37	0.61
b_5	0.19	0.04	0.17	0.04
a_5	-0.01	0.28	-0.01	0.28
b_6	**6.32**	**0.23**	**5.95**	**0.23**
a_6	0.05	0.56	0.04	0.53
b_{10}	**-0.13**	**0.02**	**-0.12**	**0.02**
b_{14}	**-0.18**	**0.00**	**-0.17**	**0.00**

Table 4: Harmonics in the three quadrupole prototypes. Collared and assembled cases (R_{ref}=17 mm, 10^{-4} units).

	Collared Apert.		Assembled Apert.	
	Avg	σ	Avg	σ
b_3	0.54	1.76	0.50	1.62
a_3	0.46	2.02	0.41	1.83
b_4	0.03	0.15	0.09	0.16
a_4	-1.17	2.20	-1.10	2.06
b_5	-0.27	0.34	-0.25	0.33
a_5	0.28	0.47	0.27	0.42
b_6	**6.06**	**0.72**	**5.68**	**0.69**
a_6	-0.04	0.07	0.11	0.28
b_{10}	**-0.11**	**0.03**	**-0.10**	**0.03**
b_{14}	**-0.18**	**0.00**	**-0.17**	**0.00**

For the non-allowed harmonics b_3, a_3 and a_4 we have somewhat relevant values that randomly vary from aperture to aperture. This gives rise to a sigma of the averages of the about two unit (see Table 4). Indeed, for all apertures, we find inverse solutions corresponding to block displacements not exceeding 30 to 40 µm. This means that it is very difficult to correct these effects, since they are within the design tolerances (see also Section 6). We also notice the unexplained feature that b_4 is always much smaller than b_3, a_3, and a_4.

5 CORRELATION

There is an excellent correlation between the average harmonics measured for each aperture in the collared coils and in the assembled cold masses. The correlation coefficient is always close to one, the slope of the interpolating straight is close to one and the offset close to zero. The only exception is b_6 (see Fig. 3) which has an offset of 0.4 units; our model predicted an offset of 0.2 units due to iron yoke effect (see Table 2). The same correlation holds in each magnet for single measurements along the axis.

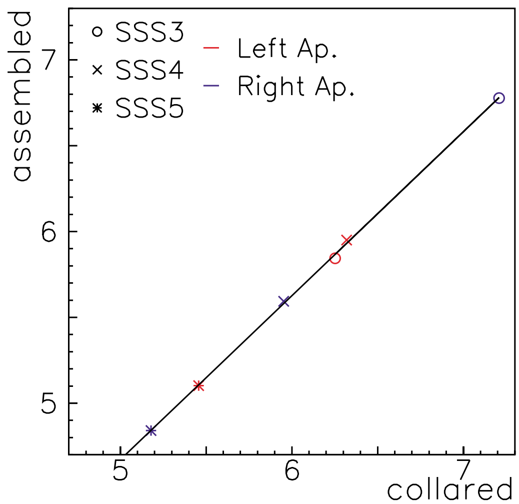

Figure 3: Collared-assembled correlation for the average values of b_6 for the six apertures.

6 RANDOM EFFECTS

It has been shown [6] that random block displacements induce random harmonics of order *n*, the standard deviations σ_n of which are given by the following scaling law:

$$\sigma_n(d) = dAB^n ,$$

where *d* is the r.m.s. of the random displacement, and *A* and *B* are fit constants that depend on the coil design.

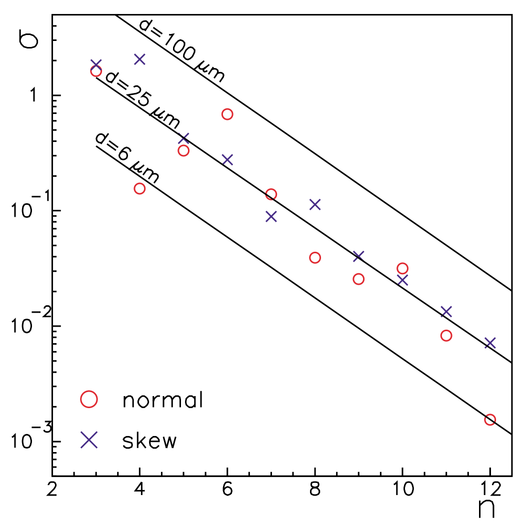

Figure 4: R.m.s. multipole variation versus the order *n* for assembled prototypes, (R_{ref}=17 mm, 10^{-4} units)

We can work out the value of *d* by comparing the sigmas of the experimental data to the previous law. Using the longitudinal variation of the harmonics for a single magnet, we deduce a value of *d* of the order of 25-35μm, see Ref. [5,6]. We have a similar situation for the r.m.s. of the harmonics from aperture to aperture, with the exception of the values relative to a_4 and b_6 (Fig. 4). This means that for these multipoles the longitudinal variation along an aperture is smaller than the variation of the averages from aperture to aperture. These results are the same for the collared and the assembled cases.

7 CONCLUSIONS

We have analysed warm magnetic measurements of three quadrupole prototypes built in CEA Saclay in view of the series production for the LHC. The agreement between systematic components and the design values has been considered. Some offset in the b_6 is systematically observed in all magnets and apertures, and should be corrected easily through a change of the azimuthal length of the coil of the order of 0.1 mm. Higher order allowed harmonics are in good agreement with nominal design.

Non-allowed low order harmonics feature relevant values that randomly vary from magnet to magnet, and from aperture to aperture. They give rise to a random component in a_3, b_3, and a_4 of about two units r.m.s. We show that such harmonics can be due to block movements of about 30-40 μm: this means that a tighter control of these harmonics seems not feasible. Indeed, the impact of these random components on beam dynamics should be evaluated.

In general random variations from magnet to magnet can be interpreted as due to uncorrelated block movements with a r.m.s. of 25-35 μm, i.e. the components tolerances. Correlation between the collared coils and the assembled cold mass measurements are very good, with slope one; the offset is different from zero only in the case of the b_6, as expected from simulations.

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REFERENCES

[1] T. Tortschanoff et al., "The short straight section for the LHC", PAC'97, Canada, 1997.

[2] M. Peyrot, J. M. Rifflet, F. Simon, T. Tortschanoff, P. Védrine, *IEEE Trans. Appl. Sup.*, **10** (2000) 170-2.

[3] T. Tortschanoff et al. "Performance of the Series-design prototype main Quadrupole for the LHC", these proceedings.

[4] P. Rohmig et al., "A modular design for the 56 Variants of the Short Straight Section in the Arcs of the Large Hadron Collider, these proceedings.

[5] S. Redaelli, W. Scandale, E, Todesco, LHC Project Note, to be published.

[6] S. Gleis, W. Scandale, E. Todesco, LHC Project Note 209.