FIELD-SHAPE IMPERFECTIONS OF THE CERN-LHC DIPOLE ARISING FROM MECHANICAL DEFORMATIONS AND COMPONENT TOLERANCES

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Abstract

The stability of the geometry of the superconducting coils is essential to the field homogeneity of the LHC dipole magnets. Mechanical stresses during coil assembly, thermal stresses during cool-down and electromagnetic stresses during operation are the sources of deformations of the coil geometry. Additional sources of field-shape errors are the dimensional tolerances of the magnet components and of the manifacturing and assembling tooling. To provide a realistic evaluation of the field-shape imperfections of the LHC dipoles arising from the above effects, appropriate finite-element computations were carried out to model the dipole cross-section in presence of stresses and a preliminary insight of the effect of the manifacturing tolerances was achieved as well.

1 INTRODUCTION

In superconducting hadron colliders, the stability of the single-particle motion is dominated by nonlinear errors in the main magnets. This phenomenon is particularly harmful at injection, when the beam size is maximum.

There are three main sources of field imperfections in a superconducting magnet, the non-ideal geometry of the coils, the persistent currents and the iron saturation. The iron saturation is almost irrelevant at the excitation level of the injection plateau. The persistent currents, mostly determined by the size of the superconducting filament adopted, produce multipolar errors that are eventually minimised by an appropriate design of the cross-section. In this paper, we concentrate our attention on the detrimental effects of a non-ideal shape of coils in the LHC dipole and suggest a possible cure to reduce them. The nominal shape of the coils already introduce significant systematic harmonics in the magnetic field. In addition, the mechanical tolerances of the magnet components produce random deviations of multipolar harmonics from magnet to magnet. Coil deformations resulting from the assembly prestress and to the thermal shrinkage during the cool-down are another source of field errors which must be known and possibly controlled. We first evaluate the magnetic errors induced by geometrical imperfections, then we suggest possible corrective actions based on the use of an appropriate set of shims to be inserted during the assembly of the coils.

Note that the multipolar harmonics will be given at the reference radius $R_{ref} = 17$ mm, which is the new standard adopted for LHC.

2 ERRORS DUE TO COIL GEOMETRY

Let us consider the LHC dipole with the 6-block and 40-turns coil design described in Ref. [1]. The nominal shape of the coils allows to minimise the odd harmonics b_3, b_5, b_7 and b_9, taking into account the expected effect of persistent currents. The various contributions to the systematic field-shape imperfections are given in Table 1.

Table 1: Systematic errors expected in the LHC dipoles. Unit 10^{-4} at the reference radius of 17 mm.

	nominal	geometric	pers. current
b_3	-6.50	4.14	-10.61
b_5	0.37	-0.88	-1.25
b_7	0.08	0.62	-0.53
b_9	0.34	0.10	0.24
b_{11}	0.58	0.58	-

Errors in coil positioning within mechanical tolerances induce field-shape imperfections randomly varying from dipole to dipole. It is usual to estimate them in a rough approximation, by varying the position of each superconducting block in an independent manner along the radial and the azimuthal direction with a Gaussian distribution. We also used this procedure paying attention to avoid, in our computer simulation, interferences between the displaced blocks. All our random diplacements are centered around the nominal positions, have an r.m.s. value of 50 μm and a distribution cut at $\pm$ 1 σ. With 500 random realisations, we obtain the results shown in Table 2. They are consistent with similar results reported in Ref. [1]. In Table 3 there are the random errors obtained by extrapolating to the LHC dipoles the harmonics measured in the HERA dipoles and the estimated variations of the average field errors from vendor to vendor [5]. This last information give an indication of how different can be the systematic field-shape imperfections in the various production lines. Indeed, our simple estimate of the random errors in Table 2 is consistent with the data of Table 3, except for high order components. This is likely to be due to the moderate precision of the magnetic measurements amplified by our extrapolation rather than to a not yet understood structural reason. The distributions of some random multipoles are shown in Fig. 1. Looser mechanical tolerances generate larger random field errors. Indeed, the multipoles increase quasi-linearly for r.m.s. displacements up to $200\mu m$.

Another source of magnetic errors varying from dipole

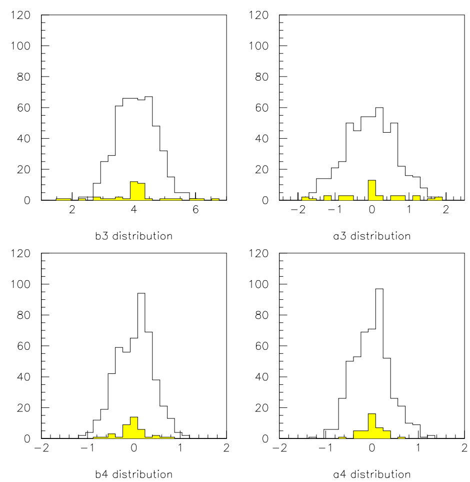

Figure 1: b_3 and b_4 errors distribution for 500 realization of random blocks displacements (white background) and for collar deformations (dark background).

Table 2: Random errors expected in the LHC dipoles. Unit 10^{-4} at the reference radius of 17 mm.

	statistical model	
n	σ_{b_n}	σ_{a_n}
3	0.87	0.90
4	0.53	0.55
5	0.31	0.34
6	0.18	0.20
7	0.11	0.12
8	0.07	0.06
9	0.04	0.03
10	0.02	0.02
11	0.02	0.02

to dipole is related to the imperfect shape of the collars. To estimate this effect in a proper manner we need a statistical model of the possible mechanical defects of the collars, which is not yet available. With a simplified model, however, we can estimate the expected errors at least in a crude approximation. We assume, somehow arbitrarely, that all the collars of a given dipole have the same shape with some deformation localised in a precise azimuthal sector of the cross-section. For instace, we assume that the upper external quadrant of one aperture is too large or too inclined and so on. We also assume that the deviation from the nominal position is as large as the allowed mechanical tolerance, i.e. 50 μm.

The magnetic errors induced by the considered modes of collar deformations are shown in dashed in Fig. 1. Our analysis is by far non-exhaustive. However, it is already sufficient to show that the magnetic errors due to collar tolerances have the same order of magnitude as the random errors of Table 1. It is intersting to note however that for low order harmonics, i.e. below n=4, the effect of the collar

Table 3: Random errors extrapolated from Hera and uncertainty from vendor to vendor. Unit 10^{-4} at the reference radius of 17 mm.

	extrapolations from Hera		uncertainty	
n	σ_{b_n}	σ_{a_n}	σ_{b_n}	σ_{a_n}
3	1.44	0.43	0.87	0.84
4	0.49	0.49	0.34	0.49
5	0.65	0.33	0.42	0.42
6	0.28	0.14	0.57	0.57
7	0.25	0.25	-	-
8	0.21	0.22	-	-
9	0.22	0.29	-	-
10	0.24	0.24	-	-
11	0.20	0.20	-	-

deformations seems to be the leading source of random errors; for high order harmonics, instead, this effect becomes smaller and smaller and can be neglected above n=7.

3 ERRORS INDUCED BY STRESSES

Collaring, assembling and thermal stresses induce a non-negligible deformation of the coil conductors. The deformations can be computed by a finite element code like ANSYS [3], and a program like ROXIE [4] can be used to evaluate the induced multipolar errors.

We computed the magnetic errors at three successive stages of the magnet production, namely for a collared coil, for a yoked warm magnet, and finally for a cold magnet at low excitation (B=0.5 Tesla). In Tab. 4 we give the new

Table 4: Multipoles with deformed coils. Unit 10^{-4} at the reference radius of 17 mm.

	COLLARED	ASSEMB.	COOLED
b_2	$+2.98$	$+4.31$	$+4.03$
b_3	$+7.24$	$+8.01$	$+7.87$
b_4	$+0.53$	$+0.65$	$+0.38$
b_5	-1.18	-1.17	-1.18
b_6	-0.01	$+0.02$	$+0.13$
b_7	$+0.80$	$+0.81$	$+0.82$
b_8	-0.01	-	$+0.02$
b_9	$+0.08$	$+0.09$	$+0.09$
b_{10}	-0.01	$+0.02$	$+0.15$
b_{11}	$+0.59$	$+0.59$	$+0.62$

values of the multipoles at the three stages considered. The mechanical deformations are always quite large,i.e. a few tenth of mm, and the deformed shapes are different from one situation to an other. However, the resulting multipoles are similar in size, at least for the allowed odd harmonics. The even harmonics, instead, vary quite considerably. This result is qualitatively confirmed by the available magnetic measurements of a few 10 m long prototype dipoles [6].

4 SHIMING AS CORRECTIVE ACTION

A possible way to reduce the field-shape imperfection consists in changing the coil geometry by an appropriate set of shims [2]. We investigate this possibility in the LHC dipole using a computer model based on ROXIE. Our aims are twofold: find the range of tunability of the multipoles and verify their dependence on the shim size.

We assume that shims up to 200 μm thickness can be inserted at the mid-plane and at the pole of both the inner and the outer coils. We also assume that we can vary in the same range the size of the four copper wedges. With these hypothesis, the multipolar components vary almost linearly with the thickness of both the shims and the wedges. As an example, in Table 6 we give the change of multipoles due to various changes of coil dimentions. In the first four cases we add shims of 100 μm at the inner midplane, at the inner pole, in the outer midplane and in the outer pole respectively. In the last four cases, instead we increase by 100 μm the size of the four wedges between the blocks. In all the considered cases we assume that the change of the coil geometry is uniform along the azimuth. The shims have a

Table 5: Effect of shims on multipolar errors. ROXIE calculations v6-1. Unit 10^{-4} at the reference radius of 17 mm.

	b_3	b_5	b_7	b_9	b_{11}
i_{mid}	$+1.41$	-0.06	-0.02	-	-
i_{pol}	-1.31	-0.17	-0.01	-	-
o_{mid}	$+1.94$	-0.36	$+0.01$	-0.05	-
o_{pol}	-3.43	-0.95	-0.27	-0.01	-0.02
wed_1	-0.63	$+0.01$	$+0.02$	-	-
wed_2	-1.61	$+0.13$	$+0.20$	$+0.09$	$+0.02$
wed_3	$+1.97$	$+0.67$	-0.08	-0.07	$+0.02$
wed_4	-2.72	-0.28	-	$+0.04$	-

Table 6: Effect of left-right asymmetric shims on multipolar errors. ROXIE calculations v6-1. Unit 10^{-4} at the reference radius of 17 mm.

	inner coil	outer coil
b_2	$+1.75$	$+2.94$
b_3	$+0.71$	$+0.97$
b_4	$+0.13$	-0.18
b_5	-0.03	-0.18
b_6	-0.03	$+0.04$
b_7	-0.01	$+0.06$
b_8	-	-
b_9	-	-0.02
b_{10}	-	-0.01
b_{11}	-	-

significant effects on all the allowed harmonics at the same time. However one can act on a single harmonic by an appropriate set of shims. Indeed, we may have to introduce the shims already in the nominal coil design in order make possible positive or negative changes of the coil and block size. To act on even multipolar errors a left-right asymmetric set of shimms is to be used. The corresponding variation of the multipolar errors is given in Table 7. The effect on low order harmonics, like the normal quadrupole and octupole is significant but unfortunately not independent. A independent control of the harmonics requires again more than one shim in appropriate locations.

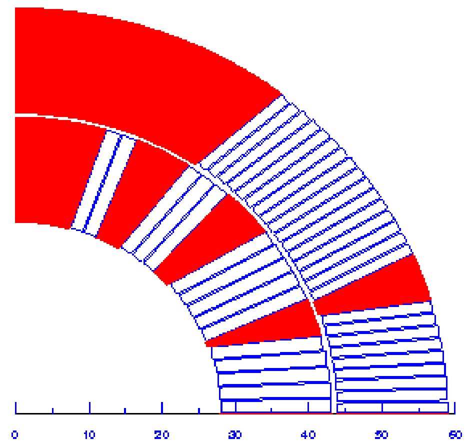

Figure 2: 6 blocks coil cross section

5 CONCLUSIONS

The geometrical coil imperfections of the LHC dipole play an essential role in the determination of random and systematic field-shape impefections. Random multipoles are due to the variation of the coils and collars geometry within the allowed tolerances. We pointed out that low order multipoles may be more affected by the collar imperfectons; instead, high order multipole may be more affected by the positionning errors of the individual blocks. Systematic multipoles already present in the nominal design vary substantially due to the deformation of the conductor resulting from mechanical and thermal stresses. Methods to reduce the multipoles can be based on the use of set of shims by which one can vary the coil geometry. Shims of one or two hundred of μm size are already adequate for our needs. However, we would like to suggest in the near future slight changes of the collar geometry so to prevent at least the increase of the systematic field-shape errors.

6 REFERENCES

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