OPTIMIZATION OF THE EVEN NORMAL MULTIPOLE COMPONENTS IN THE MAIN DIPOLE OF THE LARGE HADRON COLLIDER

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Abstract

In this paper we discuss even multipolar components of the Large Hadron Collider dipole in relation to the manufacturing features and target values required by beam dynamics. Due to the two-in-one collar geometry, systematic components are induced by the mutual influence of the two apertures and are strongly affected by the shape of the magnetic iron yoke. In order to optimize the normal quadrupole and octupole harmonics, a new design was chosen for the ferromagnetic insert between the iron yoke and the collars. Three different insert shapes were selected and installed in a full scale prototype. The measured dependence of the even multipoles on the insert shape shows a good agreement with simulations based on a magnetostatic code. A final design of the insert has been worked out and implemented in pre-series magnets. Data relative to even multipoles in pre-series magnets are presented, both at room temperature and at the operational temperature of 1.9 K. Comparison with target values required by beam dynamics is discussed.

1 INTRODUCTION

The LHC main dipole features two-in-one austenitic steel collars that break the left-right symmetry of the iron laminations around each aperture (see Fig. 1). This induces unwanted systematic even multipoles that must be minimized through a careful shaping of the ferromagnetic material around the collars. In this paper we present measurements and simulations that have been carried out to optimize this shape and the final design. We also give the status of the even multipoles in the measured pre-series dipoles both at 300 K and under operational conditions. Due to the left-right symmmetry of the whole dipole, the two apertures have opposite left-right asymmetry, and even systematic components are expected to have opposite signs in the two apertures. Therefore the signs of data relative to the second aperture have been changed to make them homogeneous to those of the first aperture.

2 b_2 AND b_4 OPTIMIZATION IN PROTOTYPES

The measured values of b_2 and b_4 at room temperature in the first three assembled LHC dipole prototypes are shown in Table 1. Values are expressed in 10^{-4} units of the main dipole field. A systematic non-zero average of the even multipoles was found: b_2 is around 4 units, and b_4 around -0.3 units. This was due to a mismatch between magnetic and mechanical design, and it is well beyond tolerances on systematics per arc of ± 1.9 for b_2 [1].

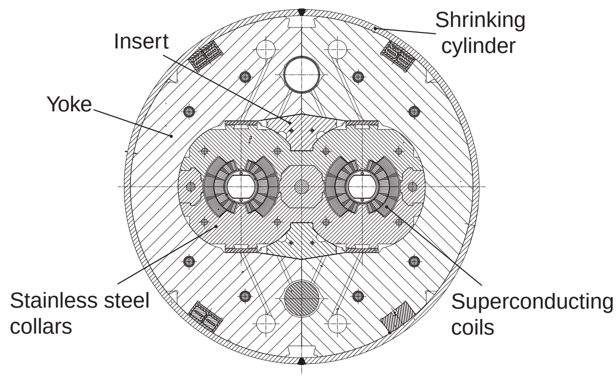

Figure 1: Cross-section of the main LHC dipole

Table 1: b_2 and b_4 multipoles at room temperature for the first three LHC dipole prototypes, with their average and standard deviation ($R_{ref} = 17$ mm,10^{-4} units).

	b_2	b_4
MBP2N2 - A1	4.0	-0.40
MBP2N2 - A2	3.7	-0.40
MBP201 - A1	3.8	-0.26
MBP201 - A2	4.8	-0.14
MBP2A2 - A1	4.4	-0.26
MBP2A2 - A2	4.6	-0.08
Average	4.2	-0.26
Std. Dev.	0.4	0.13

To recover a field quality within the specifications with a minimal impact on the magnet design and on the production costs, we proposed to change the shape of the ferromagnetic insert placed between the iron yoke and the collars (see Fig. 1). When the iron is not saturated, the insert effect on the field multipoles only depends on the shape that faces the apertures, which freezes the boundary conditions for the geometry of the field lines. Therefore, we investigated modifications of the lower insert profile.

The insert also has an important role in the trasmission via the yoke to the collars of the forces generated by the shrinking cylinder, and in the centering of the two half yokes. The proposed modifications should not have a detrimental effect for these aspects. More details can be found in [2] and [3].

Simulations pointed out that the most sensitive regions

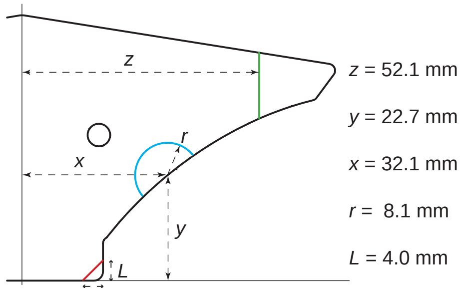

Figure 2: Insert modifications tested on the prototypes MBP2A2

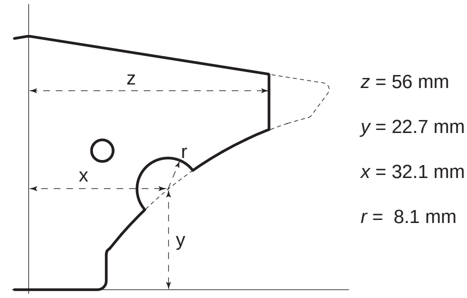

Figure 3: Final insert chosen for the pre-series dipoles

Table 2: Measured vs. computed sensitivity to insert modifications. A confidence level of $2\,\sigma$ is given for the error. See Fig. 2 for the modification nomenclature. ($R_{ref} =$ 17 mm, 10^{-4} units).

	δb_2	δb_4
Triangle Comp.	-1.22	-0.04
Triangle Meas.	-1.15 $\pm$ 0.30	0.00 ± 0.06
Circle Comp.	-1.56	0.04
Circle Meas.	-1.84 $\pm$ 0.24	0.06 ± 0.14
Toe cut Comp.	-3.43	0.29
Toe cut Meas.	-3.09 $\pm$ 0.26	0.29 ± 0.06

of the insert on b_2 and b_4 are the ones shown in Fig. 2. The choice of the final insert design was based on an experimental validation of the sensitivity table calculated with the BEM-FEM module of ROXIE [4]. The dipole prototype MBP2A2 was built with different yoke sections: it was assembled with three 3 m long sections featuring the three modifications shown in Fig. 2. The rest of the magnet was assembled with the standard insert. This provided a section with the nominal design to be used to calculate the b_2 and b_4 changes induced by each modification. In Table 2 we compare measured and computed sensitivities. A very good agreement is found within the error band of the measurements (95 % confidence level). These modifications have a negligible effect on the odd harmonics [3].

In Fig. 3 we give the final insert design used in the dipole pre-series. We shortened by 14 mm the side toe of the insert and we drilled an 8 mm radius semihole in the center of the elliptical part that faces the magnet apertures. These modifications intended to decrease b_2 by 3.9 units and increase b_4 by 0.26 units, thus compensating most of the offsets of Table 1.

3 RESULTS ON PRE-SERIES MAGNETS

Magnetic measurements of the average b_2 and b_4 in the straight part of nine pre-series dipoles at 300 K are shown in Table 3. Measurements in operational conditions at 1.9 K of six dipoles are given in Table 4.

The straight part of the cold mass measured at 300 K features around 1 unit of b_2 and 0.0 units of b_4 (see Table 3), i.e. our correction has been successful. The cooling down at 1.9 K reduces b_2 by one unit in the straight part, leaving b_4 unchanged (see Table 4, second and fifth lines). This is probably due to the strong pre-stress loss from 300 K to 1.9 K [5] that induces deformations that do not obey to a left-right symmetry with respect to the aperture, due to the two-in-one collars. At injection, both b_2 and b_4 in the straight part are close to zero.

Table 3: Measured b_2 and b_4 in the straight part of nine pre-series dipoles at 300 K (average $\pm$ two standard deviations)

	b_2	b_4
Collared coil	-0.34 ± 0.82	0.03 ± 0.08
Cold mass	0.93 ± 0.62	0.01 ± 0.21

The overall contribution of the heads was not included in the optimization since the final design of head laminations was not yet finalized. This contribution (see Table 4, third column) is around 1.5 units for b_2 and negligible for the b_4, bringing the total values at injection to 1.3 and 0.0 units respectively (see Table 4, fourth column). This is well inside the allowed ranges of ± 1.9 units and ± 0.6 units allocated by the beam dynamics (see Ref. [1]).

Due to the symmetry of the coil, persistent currents do not give any contribution to even multipoles: therefore, the non-negligible shift observed in b_2 and b_4 from injection to high field is due to iron saturation. For b_2, one has around -1.8 units, bringing the average at high field at -0.5 units (see Table 4, 3rd line). This is within the allowed range of ± 1.9 units at high field. Saturation gives 0.2 units of b_4 at high field (Table 4, 6th line), that are within the range of ± 0.6 units allocated at high field. Both saturation effects are in agreement with simulations [3].

The reproducibility of the effect of cool-down and of sat-

Table 4: Measured b_2 and b_4 in six pre-series dipoles at 1.9 K (average $\pm$ two standard deviations)

b_2	Straight	Heads	Total
Inject.	-0.15 ± 0.62	1.45 ± 0.44	1.30 ± 0.60
High f.	-2.21 ± 0.62	1.70 ± 0.22	-0.52 ± 0.60
b_4	Straight	Heads	Total
Inject.	-0.05 ± 0.20	0.05 ± 0.06	0.00 ± 0.18
High f.	0.16 ± 0.20	0.05 ± 0.06	0.21 ± 0.18

uration is given in Table 5. Here, we evaluate the standard deviations of the differences between cold mass and injection, and between injection and high field in each measured pre-series magnet. These standard deviations are small compared to the allowed ranges. If these preliminary data are confirmed, during the production even multipoles can be steered through magnetic measurements at 300 K performed at the manufacturers.

Table 5: Measured standard deviations of the impact of yoking (cold mass - collared coil), cool-down (injection - cold mass) and saturation (high field - injection) on b_2, b_4

	b_2	b_4
Yoking	0.19	0.04
Cool-down	0.21	0.03
Saturation	0.10	0.03

4 MAGNETIC SHIMMING

Between the insert and the collars, and between the insert and the iron yoke, one has shims of 0.3 mm and 0.5 mm thickness respectively. The first one is made of non-ferromagnetic material, whilst the second one is ferromagnetic. During the assembly phase of cold mass HCMBB_A001-01000002, the shim between insert and iron yoke has been removed, and the thickness of the shim between insert and collars has been increased to 0.8 mm of non-ferromagnetic material. This modification has been implemented to test the possibility of simplifying the assembly procedure [7]. From a mechanical point of view, the modification has shown no drawbacks: quench performances of the cryodipole were extremely good, showing no problems in the straight part [8].

Indeed, according to measurements, the upward shift of 0.5 mm of the insert decreases b_2 in the straight part of 1.8 units. Moreover, the effect of saturation is reduced by 0.5 units with respect to the nominal pre-series design. These results are in agreement with simulations carried out by M. Aleksa [9]. This test has shown that a modification of the insert shim thickness can be a useful and costless tool to steer b_2 during the production. The impact on b_4 is negligible.

5 CONCLUSIONS

We presented data and simulations relative to even normal multipoles in the main dipoles of the Large Hadron Collider. First results of prototypes showed a systematic value of b_2 far beyond tolerances. To recover tolerable values, a modification of the ferromagnetic insert placed between the iron yoke and the two-in-one collars has been proposed, thus minimizing the impact on magnet design and costs. Three modifications have been worked out through simulations and have been tested on a prototype. Good agreement between measurements and simulations has been found. A final insert design to minimize b_2 and b_4 has been selected.

Data on seven pre-series magnets have shown that the b_2 correction has been successful at 75-80 %. Evaluation of the contribution of heads and of iron saturation shows that they are not negligible. Available measurements of b_2 in operational conditions show that it is within the allowed range of ± 1.9 units both at injection (1.3 units) and at high field (-0.5 units). The b_4 optimization has reduced its value to a fraction of unit in the straight part. Measurements at 1.9 K show that it is well inside the allowed range of ± 0.6 units both at injection (0.0 units) and at high field (0.2 units).

A modification of the insert position has been tested in one of the pre-series magnet, showing some impact on b_2 in agreement with simulations. This action could be an effective and costless way of steering b_2 during the production.

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