Impact of Coil Deformations on Field Quality in the Large Hadron Collider Main Dipole

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***Abstract*—In superconducting accelerator magnets the coils are usually pre-stressed in order to avoid conductor movements induced by electro-magnetic forces. In this paper we use a finite element mechanical model of the main LHC dipole to evaluate the coil deformations determined by the pre-stress and their impact on magnetic field quality. The model explains the origin of the offsets between the nominal multipole values and those measured at room temperature in prototype and pre-series dipole magnets. We also present an experiment carried out to analyze the impact on field quality and coil stresses of coil azimuthal spacers (pole shims). A 1 m long dipole collared coil has been re-assembled several times with pole shims of different thickness and the field components have been measured each time. Experimental data are compared to numerical computations based on the mechanical model. One finds that variations of shim thickness induce not only a change of the azimuthal coil length, but also a different pattern in coil deformations. A good agreement is found between measurements and simulations.**

***Index Terms*—Field quality, shimming, superconducting coil, superconducting magnet.**

I. Introduction

THE SUPERCONDUCTING coils of high field magnets for particle accelerators are clamped by a containment structure that exerts an azimuthal pressure of the order of some tens of MPa. The resulting deformation of the magnet structure and of the coils affects the magnetic field quality. Since these effects are difficult to foresee, a fine tuning of the magnet design may be necessary to recover the optimal magnetic field for beam dynamics. Different corrective strategies have been implemented in planned or built accelerators based on superconducting magnets [1]–[4].

In this paper we analyze the impact on field quality of mechanical deformations at 300 K in the collared coil of the Large Hadron Collider (LHC) main dipole. The correlations between the magnetic measurements at 300 K and at 1.9 K are discussed in [5]. By means of a finite element model of the dipole cross-section [6], we study the stress-strain distribution inside the dipole after the assembly [7]. The conductor displacements obtained as output of the mechanical computations are implemented in a magneto-static model of the dipole coil [8]. We show that these deformations are responsible for most of the magnetic errors observed in the LHC main dipoles. Moreover, deformations must be taken into account in the corrective strategies foreseen for the fine tuning of the field quality.

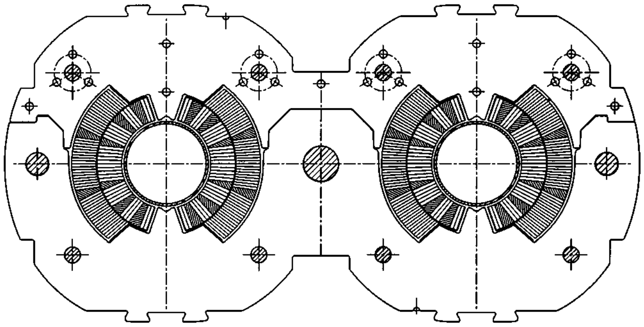

Fig. 1. The collared coil cross-section of the main LHC dipole.

II. Magnetic Measurements

We analyze the magnetic measurements performed at 300 K on the collared coil of the main LHC dipole made with austenitic steel collars (see Fig. 1). The data of five prototypes and of eleven dipoles of the pre-series production are discussed.

Measurements are carried out in both the apertures at 300 K with a low current (12 A): the average harmonics along the axis (end effects excluded) are considered and then an average over the two apertures is taken (see values of normal sextupole and decapole versus the test date in Fig. 2, markers). Data are given in units of 10^{-4} of the main field at the reference radius of 17 mm. As the dipoles have been built with different shim thicknesses, the shown values of the magnetic measurements are given after subtracting the effect on the magnetic field of nonnominal shims [9]. Dipoles are built by three different manufacturers (Alstom, Ansaldo and Noell) whose tooling does not show a specific effect on field quality.

The solid lines in Fig. 2 represent the averages over the pre-series and over the prototypes, that are also given in Table I (row "Prototypes" and "Pre-series"). A statistical error of two standard deviations has been associated to these averages. Some difference is observed between prototypes and pre-series dipoles: this is due to a change of the inner collar profile, which in the pre-series magnets has been designed to compensate the vertical deflection of the collars induced by the pre-stress. In Section III we evaluate with the finite element model the impact of this modification on the field quality, comparing simulations with the experimental data.

The measured multipoles are then compared in Table I with the nominal values of the collared coil, i.e., the multipoles expected for a coil that under an azimuthal compression of

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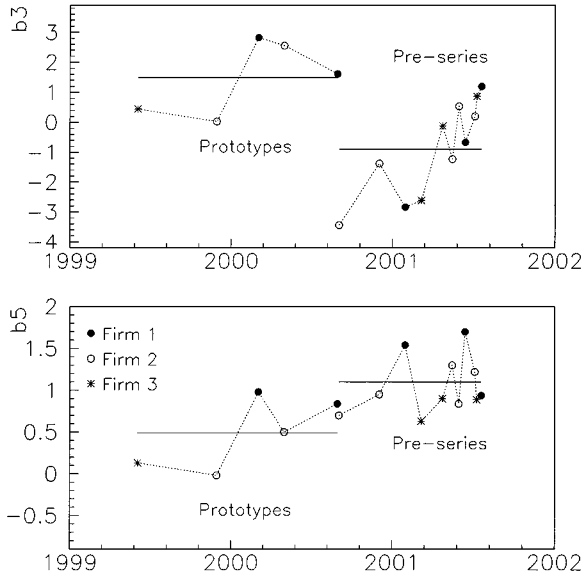

Fig. 2. Sextupole and decapole measured in collared coils of the prototypes and the pre-series dipoles (markers) and averages (solid lines) versus the test date, in units 10^{-4} of the main field at 17 mm.

70 MPa fits the circular cavity given by infinitely rigid collars (i.e., collars without deformations). Moreover, the magnetic effect of the collar permeability is included [9]. This nominal design has been chosen to generate a nonzero value of the low order odd multipoles which partially compensate the effect of the persistent currents at injection [10]. Both the prototypes and the pre-series dipoles feature a discrepancy with respect to the expected values: this is particularly important for the b_5. In Section IV we trace back the origin of these discrepancies between the nominal and measured harmonics.

III. DIFFERENCES BETWEEN PROTOTYPE AND PRE-SERIES MAGNET FIELD HARMONICS

Since the inner shape of the collars is modified by the pre-stress with respect to the nondeformed state, the collar cavity in the pre-series dipole magnet has been designed in order to compensate this deformation and to obtain after the magnet assembly a circular collar cavity. The impact of the pre-stress on the collar cavity can be described in a first approximation by a vertical deflection (ovalization), which increases the vertical diameter of the collars keeping unchanged the horizontal one. This deflection has been corrected by shifting downward of 0.1 mm the center of the upper collar cavity.

To evaluate the impact of this collar modification on the coil geometry we used the finite element model, reproducing the new collar profile in our code and computing the impact on the magnetic field with respect to the previous configuration. In Table II we compare this simulation with the difference of the average multipoles measured in the pre-series and in the prototypes. The results of the numerical computation are in agreement with the experimental data.

TABLE I
MEASURED AVERAGE WITH 2 σ UNCERTAINTY AT 300 K AND NOMINAL ODD MULTIPOLES, IN UNITS 10^{-4} OF THE MAIN FIELD AT $R_{ref} = 17$ mm

	b_3	b_5	b_7
5 Prototypes	$+1.5 \pm 1.3$	$+0.5 \pm 0.5$	$+0.81 \pm 0.07$
11 Pre-series	-0.9 ± 1.0	$+1.1 \pm 0.2$	$+0.66 \pm 0.05$
Nominal	$+2.6$	-0.7	$+0.65$

TABLE II
DIFFERENCES BETWEEN PROTOTYPE AND PRE-SERIES MAGNETS: MEASUREMENTS AND MODEL RESULTS, IN UNITS 10^{-4} OF THE MAIN FIELD AT $R_{ref} = 17$ mm

	b_3	b_5	b_7
Measur.	-2.4 ± 2.3	$+0.6 \pm 0.7$	-0.15 ± 0.12
Model	-1.5	0.0	-0.03

TABLE III
DIFFERENCES WITH RESPECT TO THE NOMINAL VALUES: MEASUREMENTS ON PRE-SERIES DIPOLES AND MODEL RESULTS, IN UNITS 10^{-4} OF THE MAIN FIELD AT $R_{ref} = 17$ mm

	b_3	b_5	b_7
Measur.	-3.5 ± 1.0	$+1.8 \pm 0.2$	$+0.01 \pm 0.04$
Model	-4.7	$+1.2$	-0.15

IV. DIFFERENCES BETWEEN MEASURED AND NOMINAL FIELD HARMONICS

The nominal values of the collared coil presented in Table I take into account the geometry of the current distribution in the nominal coil, (see Section II for a definition of nominal values). Moreover, there is a nonnegligible contribution of the permeability of the collar stainless steel [9]. These expected harmonics are considerably different from the measured ones, especially for the b_5 (see Table I). Indeed, the nominal value neglects the effect of the azimuthal pre-stress on the shape of collar cavity, which gives rise to important displacements (a few tenths of mm). Moreover, one has radial loads that induce additional deformations of the coil layers. All these effects can be evaluated via the aforementioned finite element model.

It must be pointed out that, using the same model, in the previous section we evaluated the impact on field quality of the collar profile variation implemented in the pre-series. Now, we compute the magnetic field given by the coil deformation induced by the realistic map of loads. This second goal is more challenging, since it involves the estimate of an absolute quantity (i.e., multipoles due to loads) that is sensitive to all systematic effects neglected in the model. On the other hand, in the previous case a differential effect has been analyzed and therefore systematic errors would have had no impact on our estimates.

In Table III the results of the FEM are compared to the measurements for the pre-series magnets, where more statistics are available. The net effect of coil and collar deformation is given. For measurements, this corresponds to the difference between pre-series data and nominal values. For the model, the effect of deformations is added to the change of the collar profile. One

TABLE IV
EFFECT ON AN ADDITIONAL SHIM OF 0.1 mm: MEASUREMENTS AND MODEL RESULTS, IN UNITS 10^{-4} OF THE MAIN FIELD AT 17 mm

Δb_3	Inner layer	Outer layer
Measur.	$+1.85 \pm 0.26$	$+1.36 \pm 0.10$
Uniform compression	$+2.18$	$+1.62$
Compens. compression	$+1.96$	$+1.46$
Finite element model	$+1.93$	$+1.44$
Δb_5	Inner layer	Outer layer
Measur.	-0.24 ± 0.06	-0.05 ± 0.04
Uniform compression	-0.40	-0.08
Compens. compression	-0.36	-0.07
Finite element model	-0.30	-0.04
Δb_7	Inner layer	Outer layer
Measur.	$+0.13 \pm 0.04$	-0.01 ± 0.00
Uniform compression	$+0.15$	-0.02
Compens. compression	$+0.14$	-0.02
Finite element model	$+0.13$	-0.02

observes an important reduction of the sextupole and a strong increase of the decapole. These trends are clearly confirmed by experimental data. Even though the b_5 and b_7 estimates do not agree with the measured values within the associated error, these data show that deformations modeled through finite element methods account for a large part of the discrepancy between nominal and measured values.

The offset between nominal and measured multipoles can be compared to the constraints on systematic multipoles given by beam dynamics. Recent work [11] shows that the allowed range for systematic b_3 and b_5 is 6 units and 0.6 units respectively. Therefore, the discrepancy with respect to the nominal design is half window width for the b_3, and three times the window width for the b_5: this shows that in the LHC main dipole these effects cannot be neglected [9].

V. CORRELATION BETWEEN POLE SHIM THICKNESS AND FIELD QUALITY

In the LHC main dipole, glass-fiber spacers called pole shims are inserted at the top of the coil, between the coil and the collars. A variation in the shim dimension allows to change the total azimuthal coil length, thus modifying the multipolar contents of the superconducting coil. The shim thickness modification is therefore an easy and effective way to control field quality.

It must be pointed out that any variation of the shim size also determines a modification of the coil and collar loads and deformations. In a first approximation, an increase in the shim size can be modeled as a uniform azimuthal compression of the coil. Indeed, the change in the load patterns implies that the impact of a larger shim on coil geometry can be more complicated. Also in this case, the aforementioned finite element code can be used to evaluate this effect. In this Section we compare results of a dedicated experiment with numerical simulations.

A. Experimental Measurements

A same 1 m long dipole was re-assembled with different shims. The dipole was collared five times changing by ±0.15 mm the thickness of the inner and of the outer layer shims separately with respect to the nominal configuration. Each time, the top–bottom and left–right symmetries were kept, so that only the sensitivity on the odd multipoles was studied. To simplify our procedure, we avoided assembling the iron yoke and we restricted our magnetic measurements to ambient temperature. At each collaring iteration the vertical deformation of the collars and the azimuthal pre-stress on the coil were measured [7].

In Table IV we give the sensitivity on the shim thickness measured for b_3, b_5 and b_7 (the higher order multipoles are almost unaffected by the shim size): we point out that the values of the sextupole strongly depend on the azimuthal coil length. An additional shim of 0.1 mm, respectively, in the inner and in the outer layer determines an increase of b_3 of 1.85 units and 1.36 units. On the other hand, b_5 and b_7 are mostly affected by the inner layer shim, as expected.

B. Comparison With Models

The dependence of field quality on shim thickness can be modeled by a uniform compression of the conductors along the azimuthal direction. With this approximation, a difference in the shim thickness provokes an equal reduction of the azimuthal coil length. This is based on the assumption that both the copper wedges and the collar cavity are infinitely rigid. Results of this model overestimate the sensitivity experimentally measured (see Table IV, row "uniform compression"): in particular the decapole differs by 60% with respect to the experimental data.

To better model the effect of the shim size one has to take into account that the collars are not infinitely rigid. This means that an increase of the shim thickness is partially compensated by the collar vertical deformation. In [12] it has been proposed that the coil azimuthal length should be varied by the additional shim thickness minus the induced vertical deformation of the collars: geometric measurements [7] show that a 0.1 mm thicker shim on one layer increases the collar vertical radius of 0.01 mm. Therefore one should obtain a 10% lower sensitivity (see Table IV, row "compensated compression"). This second approximation shows agreement with experimental data for b_3 and b_7, but one still has a large discrepancy in b_5.

We perform thereafter a mechanical computation with the finite element model to evaluate the complete map of deformations determined by a change of the shim size. In Figs. 3 and 4 we plot the geometry of the coil with nominal shim thickness and the one with a 0.1 mm thicker shim, respectively in the inner and in the outer layer (drawn deformations are magnified by a factor 50): in both the situations we observe not only an azimuthal compression, but also a radial deformation of the coil. An increase of the shim size of 0.1 mm provokes an azimuthal compression of 0.095 mm in the inner layer and of 0.090 mm in the outer layer. On the other hand, an

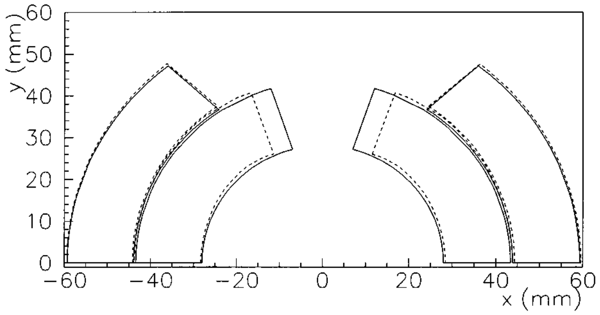

Fig. 3. Nominal coil geometry (solid line) and deformed geometry (dashed line) induced by a 0.1 mm thicker shim in the inner coil. Deformations are magnified by a factor 50.

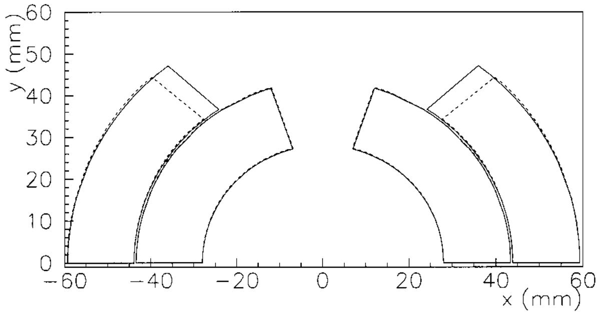

Fig. 4. Nominal coil geometry (solid line) and deformed geometry (dashed line) induced by a 0.1 mm thicker shim in the outer coil. Deformations are magnified by a factor 50.

important radial displacement of up to 0.017 mm of the inner coil is noticed. These nonuniform radial deformations, which are not taken into account in the simplified model proposed in [12], strongly affect the b_5. For instance, a 0.01 mm outward movement of the central blocks of the inner layer gives $+0.12$ units variations of b_5.

The maximum radial deformation occurs in correspondence of the outer layer pole (around 55 degrees), followed by a reduction on the last block close to inner pole. Indeed, the deformation of the coil cannot be described by a simple elliptic mode, but, as already observed in [13], also by higher order modes in the radial displacements.

When the complete map of deformations is transferred to the magneto-static code, one gets agreement with experimental data also for b_5 (see Table IV).

VI. CONCLUSIONS

We presented the magnetic measurements of the collared coils of the prototypes and of the pre-series main LHC dipoles. By means of a magneto-mechanical model, we have studied how collar and coil deformations affect the field quality. We explained the difference between field-shape in the prototypes and in the pre-series dipoles as due to the modification of the collar cavity implemented in the pre-series production. Through this numerical model, we then traced back the origin of most of the discrepancy between nominal and measured harmonics by computing the impact on the field quality of the actual deformation of coils and collars.

We analyzed the variation of the pole shim size as a corrective action for the odd multipoles, presenting the measurements of the dependence of the field quality on the shim thickness performed on a dipole. This correlation shim thickness versus field quality was compared with experimental data: good agreement is found using the finite element model that takes into account realistic coil and collar deformations. We compared field-shape harmonics induced by coil and collar deformations with the beam dynamics specifications, showing that they are not negligible. Taking them into account allows to better predict corrective actions to keep the average harmonics within the rather narrow bands requested for the LHC.

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