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A Correlation Study between Geometry of Collared Coils and Normal Quadrupole Multipole in the Main LHC Dipoles

F. Bertinelli[1], E. Boter-Rebollo[2], S. Berthollon-Vitte[1], D. Glaude[1], I. Vanenkov[1]

Abstract

The quality control implemented at all LHC dipole assemblers includes precise mechanical measurements of the geometry of collared coils. A cross-analysis performed between mechanical and magnetic measurements data shows a correlation between collared coils outer dimensions and the normal quadrupole multipole (b_2) for one dipole assembler. The profile geometry of the single collars - as determined from 3D measurements at the collar suppliers and CERN - could not account alone for the significant left – right aperture asymmetry observed. This triggered a deeper investigation on different elements of the geometry of single collars. The results of this work show that the relative positioning of the collaring holes, allowing a small bending deformation of collars under the effect of coil pre-stress, is an important effect that generates a b_2 multipole at the limit of specification. The study has deepened the understanding of the factors affecting collared coil geometry and field quality. The precision of 3D measurements at the collar suppliers and at CERN has been improved, and a tighter quality control has been introduced at the collar suppliers.

1 CERN, Geneva, Switzerland
2 CELLS, Barcelona, Spain

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CERN
CH - 1211 Geneva 23
Switzerland

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***Abstract*—The quality control implemented at all LHC dipole assemblers includes precise mechanical measurements of the geometry of collared coils. A cross-analysis performed between mechanical and magnetic measurements data shows a correlation between collared coils outer dimensions and the normal quadrupole multipole (b_2) for one dipole assembler. The profile geometry of the single collars - as determined from 3D measurements at the collar suppliers and CERN - could not account alone for the significant left – right aperture asymmetry observed. This triggered a deeper investigation on different elements of the geometry of single collars. The results of this work show that the relative positioning of the collaring holes, allowing a small bending deformation of collars under the effect of coil pre-stress, is an important effect that generates a b_2 multipole at the limit of specification. The study has deepened the understanding of the factors affecting collared coil geometry and field quality. The precision of 3D measurements at the collar suppliers and at CERN has been improved, and a tighter quality control has been introduced at the collar suppliers.**

***Index Terms*— Magnetic Field Quality, Austenitic-Steel Collars, Superconducting Magnets, Warm Magnetic Measurements.**

I. Introduction

IN superconducting magnets, the field quality is mainly determined by the coil geometry. The coil geometry is affected by the dimensional tolerances of the coil and of adjacent components, specifically the inner profile of collars. The overall effect of mechanical tolerances on the field quality of the LHC main dipoles was first estimated for magnet and components design [1]. Later, measurement data on pre-series dipoles and a magneto-static model were used to review the dependence of field harmonics on the tolerances of the collared coil components [2]: the measured standard deviations of most of the field harmonics were reported to be significantly higher than the computed ones. The model assumed that collars are infinitely rigid.

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F. Bertinelli: AT Department, CERN, Geneva, Switzerland. (corresponding author: phone +41 22 767 9791, fax +41 22 767 6300; e-mail: Francesco.Bertinelli@cern.ch)
S. Berthollon-Vitte, I. Vanenkov: AT Department, CERN, Geneva, Switzerland.
D. Glaude: TS Department, CERN, Geneva, Switzerland.
E. Boter-Rebollo: CELLS, Barcelona, Spain.

For series dipoles, the data on mechanical measurements implemented at the dipole assemblers show significant variations in collared coil dimensions along the production. A cross-analysis performed between mechanical and magnetic measurement data shows the correlation between some field components - namely the b_2 multipole - and deformation of collared coils, in particular for one of the three dipole assemblers [3]. In this paper we describe this study, and identify how specific aspects of the geometry of single collars account for the higher standard deviations of the field harmonics previously reported.

II. Observations on Mechanical and Magnetic Tests

A. LHC dipole collars

The coil cavity of LHC dipoles is determined by twin type collars, types A1 and A2, see Fig. 1. The collar material is special austenitic steel, with very low magnetization and high mechanical resistance. Collars are manufactured by two suppliers S_1 and S_2, both using fine blanking technology but differing in the details of their tooling design. The collars are produced in batches - including ~4400 of types A1 and A2 - each corresponding to one dipole. The quality control and acceptance procedure at the suppliers includes the 3D measurement of sample collars from each batch.

The dipole assemblers - firms 1, 2 and 3 - pre-assemble collars into collar packs using Ø10 mm assembly pins. Different collar pack designs are used, varying in number and relative orientation of the single collars: this affects the rigidity and precision of the assembled packs, specifically in the superposition of geometrical effects from single collars [4]. The collar packs are further assembled into collared coils using the Ø14 mm lateral and Ø22 mm central collaring rods.

Firms 1 and 2 use collars essentially from supplier S_1, firm 3 uses collars essentially from supplier S_2.

The collar material and geometry are designed to minimise coil deformations due to coil pre-stress forces at collaring and to magnet excitation in operation. After collaring the vertical elastic deformation of collars is observed to be greater in the middle than the sides. This creates a left-right coil asymmetry within one aperture and consequently generates the field multipole b_2 (normal quadrupole).

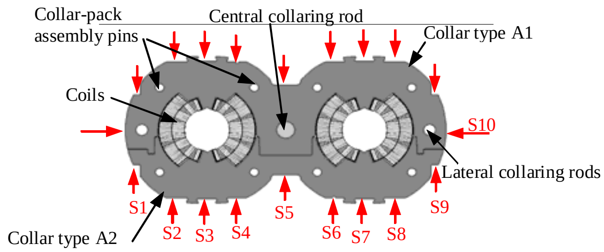
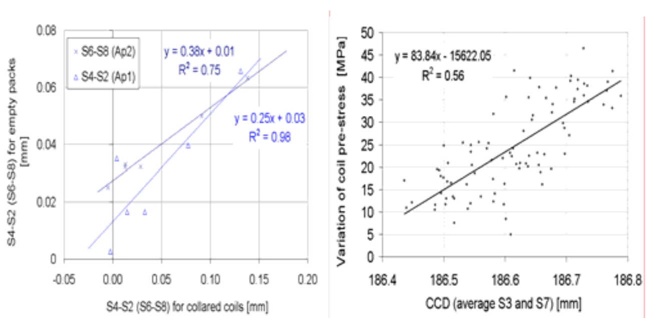


Fig. 1. Collared coil cross-section and position of CCD measurements points (S1 to S10).

B. *Mechanical and magnetic measurements procedure*

The quality control at the dipole assemblers includes the measurement of the outer dimensions of all collared coils. The collared coil dimensions (CCD) are taken at several longitudinal positions both in the straight part and in the ends. At each position, the dimension of the collared coil is measured at 10 specified points around the collars, see Fig. 1. The measurements are made using dedicated equipment fitted with displacement induction gauges. The absolute accuracy of these measurements was verified at the three dipole assemblers using the same CERN reference collar pack and found to be ± 0.03 mm: measurement reproducibility was found to be ± 0.01 mm.

The quality control at the dipole assemblers also includes a CCD measurement of empty collar packs, i.e. where the coil pre-stress is partially simulated by a water pipe under pressure. This cross-check is performed approximately every 20 collared coils, before collaring the magnet. Fig. 2(a) shows the CCD data on empty collar packs correlating with CCD data from the collared coils assembled with collars from the same batches.



(a) (b)

Fig. 2. (a) CCD data for empty collar-packs and corresponding collared coils (firm 3); (b) Coil pre-stress variation and CCD data (firm 3).

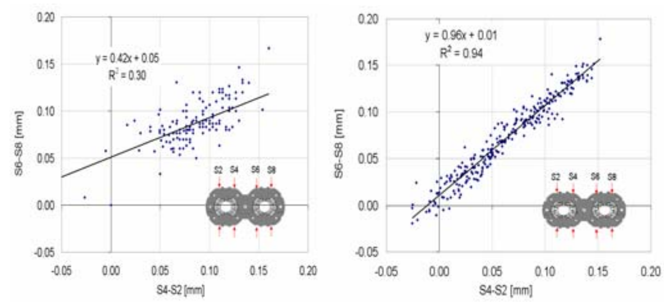
The warm magnetic measurements on collared coils are performed at 20 longitudinal positions, with positions 2 to 19 in the straight part, and positions 1 and 20 in the ends [5]. While CCD measurements are taken locally, the magnetic measurements represent values of multipoles integrated over the length of the measuring coil, typically 0.75 m. To account for longitudinal variations in CCD and magnetic measurements data along the coil, our analysis uses the average values of all measuring positions over the straight part.

C. *Observations and analysis*

The analysis of CCD data shows a good aperture-to-aperture symmetry in the vertical dimensions of collared coils (S3 and S7) for all dipole assemblers. However, the range of these dimensions is different among firms, and is almost twice larger at firm 3.

Measurements of coil dimensions show that the overall coil size variation at the three dipole assemblers is of the same order, ± 0.15 mm in azimuthal developed length. Variations of coil pre-stress alone cannot account for the observed variation of collared coil vertical dimension between firms - the "elliptical" cavity deformation. Fig. 2(b) shows this variation (calculated from measured coil size, E-modulus and actual shim thickness used) plotted against CCD data.

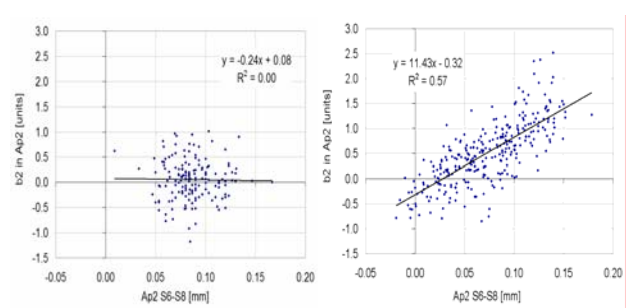
Another observation from CCD data concerns the left - right aperture asymmetry (S6 - S8 and S4 - S2), shown in Fig. 3. Firm 3 shows a characteristic, unique symmetry between the two apertures.



(a) (b)

Fig. 3. CCD data comparing the left - right aperture dimensions for the two apertures (Fig. 3(a) for firm 2, Fig. 3(b) for firm 3).

The analysis of magnetic measurements data, specifically the correlation between the CCD left-right asymmetry within one aperture and the b_2 multipole in the dipole field, is shown in Fig. 4: again firm 3 displays the highest correlation among firms. Also, the range of variation of the b_2 multipole is larger for firm 3.



(a) (b)

Fig. 4. Correlation analysis between CCD data and b_2 multipole (Fig. 4(a) for firm 2, Fig. 4(b) for firm 3).

The characteristic behaviour exhibited by firm 3 - uniquely associated to collars from supplier S_2 - motivated further investigations on the role of collars. Fig. 5 shows CCD and magnetic measurements data plotted sequentially against the corresponding collar batch number used. We observe a periodicity in data trends, indicating that its source is probably related to the production process of collars.

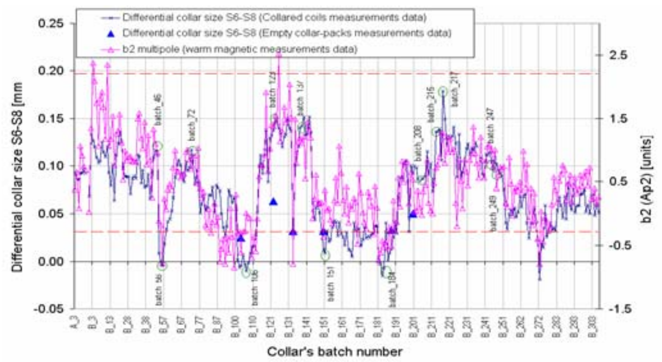


Fig. 5. CCD and magnetic measurements data on collared coils sorted by collar batch number (firm 3, collar supplier S_2): the dashed lines show the upper and lower limits for systematic of b_2 multipole.

The correlation between CCD data - associated with the outer collar dimensions - and the b_2 multipole - associated with inner, cavity collar dimensions – is particularly noteworthy.

III. SOURCE OF b_2 MULTIPOLE

A. 3D measuring method of single collars

In order to identify the source of collar geometry variations, 16 collar batches were selected, representing the full range of left-right asymmetry variation in CCD measurements data, see Fig. 5. The acceptance collars from these batches were retrieved and re-measured at CERN by the metrology service. Both A1 and A2 types of collars were measured.

Since during the LHC dipole design it was demonstrated that type A2 collars have negligible contribution to the structural rigidity of collared coils compared to type A1 collars [6], this analysis focused mainly on type A1 collars.

The 3D measuring procedure of collars is a precision operation strongly affected by the method of collar support and fixing. The type A1 collar is positioned and clamped onto a jig with respect to Ø8 mm pins passing through the lateral holes C8 and C9, see Fig. 6, simulating the contact of the collar with the lateral collaring rods. The centres of these pins determine the orientation and position of the X-axis. The position of the orthogonal Y-axis is determined by the centre of the central hole C3. Each collar is measured for more than 90 pre-defined points and dimensions.

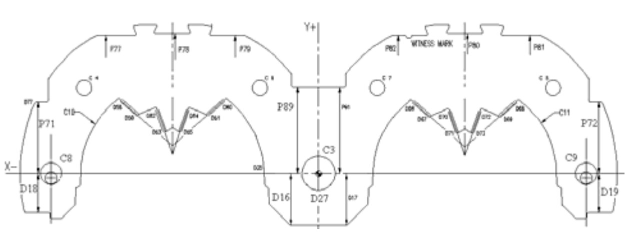


Fig. 6. Metrology data map for collars type A1.

This method implies that small changes in the vertical positions of holes C8 and C9 relative to the entire profile can affect the position of the reference axes, and therefore all subsequent measurements. For example, the wear on the fine-blanking tooling has been found to affect the diameter of the collaring holes typically by 0.03 mm, but not the outer collar profile: in this case the vertical position of the X-axis may be affected by 0.015 mm. Therefore the analysis of measurement results requires careful interpretation.

Indeed, collar supplier S_2 actively uses this effect by routinely adjusting through shims the position of the collaring holes with respect to the outer profile in order to optimize global collar precision.

B. Observations and analysis

The analysis of the 3D measuring data of the sampled type A1 collars did not show significant effects regarding those collar dimensions directly related with cavity geometry. Also, no dimensions of the outer collar profile were found having out-of-tolerances of the same magnitude as the observed CCD data. Unexpectedly however, a significant variation was found concerning dimension D27, representing the point of contact of the central collaring rod with respect to the reference X-axis, see Fig. 6, i.e. the relative vertical positioning of lateral and central collaring holes.

Fig. 7 shows D27 and the corresponding batch CCD data concerning the left - right aperture asymmetry (S6 - S8 and S4 - S2) for collar samples re-measured at CERN. We observe signs of a common trend between these values, although another effect - most likely the absolute position of the lateral collaring holes with respect to the outer profile - is also present.

Data for D27 from collar supplier S_2 is also presented, in Fig. 7 for the sampled collars and in Fig. 8 for the full collar production. The two measurement methods were investigated in detail to eliminate the smallest sources of errors: under optimal conditions, the same collar could finally be repeatedly measured at CERN and supplier S_2 with maximum differences below 0.01 mm. The effect of this campaign and tighter follow-up allowed to improve the measuring procedures starting from batch no. 177.

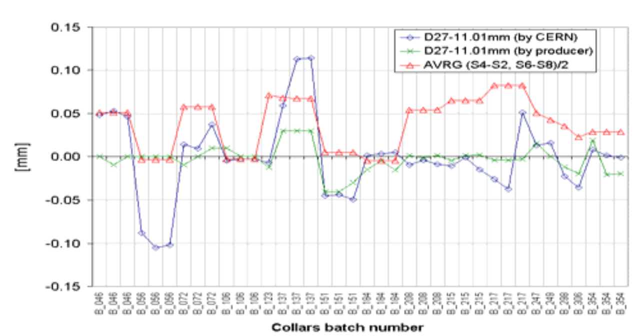


Fig. 7. Metrology data on measuring point D27 (measurements at CERN and collar supplier S_2) and CCD data for sampled collars, sorted by collar batch number (firm 3, collar supplier S_2).

The effect of a correction in collar geometry for D27 starting with a new production (February 2005, from collar batch 374), is clearly visible in Fig. 8, on both D27 and CCD data: in the latest data there is evidence of a further influencing effect, most likely from the absolute vertical positioning of the lateral holes, as highlighted in Fig. 9.

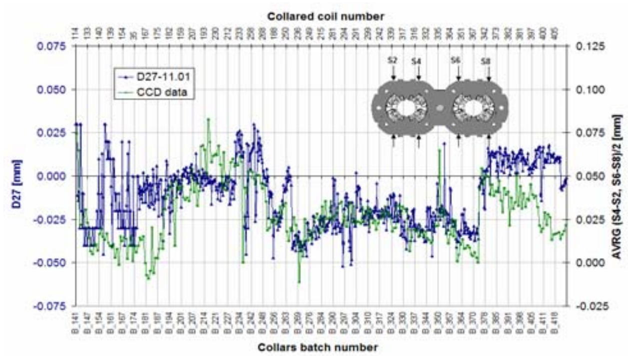


Fig. 8. Metrology data on point D27 (measurements at collar supplier S_2) and CCD data for collared coils of firm 3, sorted by collar batch number.

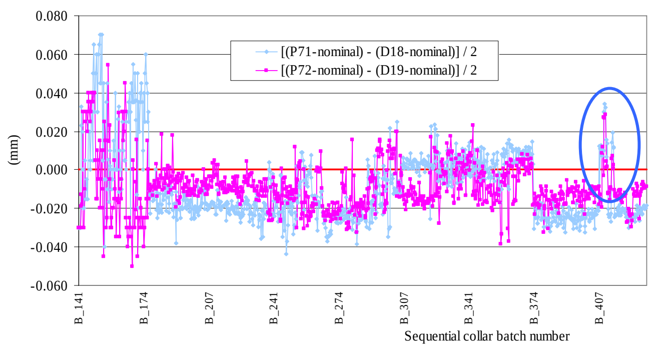


Fig. 9. Relative vertical positioning of the lateral collaring holes with respect to the outer profile – an additional effect to D27.

The importance of D27 is related to the possibility of collar deformation under internal coil pre-stress, within the limits allowed by the relative vertical positioning of the collaring holes.

IV. Structural Finite Element Analysis

Only a relatively simple Finite Element Analysis was pursued in order to check some basic hypotheses. The A1 collar is modeled as a 2D structure, using 8-node plane stress quadratic elements and ANSYS Workbench™ software. The average coil pre-stress is simulated by an internal radial pressure of 30 MPa and a cavity azimuthal pressure of 65 MPa: reaction forces from the A2 collar are included. Deformations are studied at two points P1 and P2, corresponding to the CCD data for the left - right aperture asymmetry.

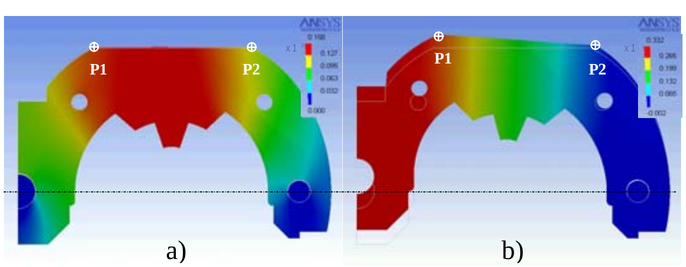


Fig. 10. (a) FEA model of ideal collar pair under coil pre-stress: P1=0.13 mm, P2 = 0.11 mm; (b) no central collaring rod: P1=2.78 mm, P2 = 0.52 mm

Ideal conditions - all collar dimensions nominal, lateral and central collaring holes blocked by their collaring rods - are shown in Fig. 10(a). The maximum vertical deformation is 0.15 mm, and only minimal left - right aperture asymmetry is generated through deformation of the cavity. The first finding is that any significant asymmetry does not originate from differences in stiffness of the collar geometry.

The effect of an out-of-tolerance D27 is simulated - only as an extreme condition - by eliminating the contact of the central collaring rod. This allows a large bending deformation at the centre of the collar pair, see Fig. 10(b). The second finding is that collar stiffness is insufficient to limit a significant movement made possible by an out-of-tolerance D27.

In practice the deformation is clearly limited by the real position of D27, i.e. until contact between the central collaring hole and its collaring rod is achieved. Therefore the out-of-tolerance of dimension D27 is directly associated with the magnitude of the CCD left - right asymmetry and consequently to the creation of the b_2 multipole.

V. Conclusion

Using the data on mechanical measurements of collared coils performed at the dipole assemblers and data on single collar geometrical measurements performed on pre-selected samples of collars at CERN, it was possible to identify the source of the significantly higher standard deviation of the b_2 multipole measured in LHC dipoles. The relative vertical position of the central and lateral collaring holes allows a limited bending deformation of the collars, introducing a left-right aperture asymmetry. While the b_2 multipole generated was not excessively affecting beam dynamics, in order to reduce its variation and improve magnet quality, CERN worked closely with the collar suppliers to optimize quality control procedures, with noticeable improvements in collar quality since the beginning of 2003.

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