Dependence of Magnetic Field Quality on Collar Supplier and Dimensions in the Main LHC Dipole

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Abstract— **In order to keep the electro-magnetic forces and to minimize conductor movements, the superconducting coils of the main Large Hadron Collider dipoles are held in place by means of austenitic steel collars. Two suppliers provide the collars necessary for the whole LHC production, which has now reached more than 800 collared coils. In this paper we first assess if the different collar suppliers origin a noticeable difference in the magnetic field quality measured at room temperature. We then analyze the measurements of the collar dimensions carried out at the manufacturers, comparing them to the geometrical tolerances. Finally we use a magneto-static model to evaluate the expected spread in the field components induced by the actual collar dimensions. These spreads are compared to the magnetic measurements at room temperature over the magnet production in order to identify if the collars, rather than other components or assembly process, can account for the measured magnetic field effects. It has been found that in one over the three Cold Mass Assemblers the driving mechanism of the magnetic field harmonics b_2 and a_3 is the collar shape.**

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

I. Introduction

In superconducting magnets for particle accelerators, the quality of the magnetic field is given by the precise position of the coils. The exact location of the cables with respect to coil aperture is strongly influenced by the geometry of the mechanical components of the assembly. In the Large Hadron Collider (LHC) main dipoles [1], such components are superconducting cables, copper wedges, insulation films and tapes, coil protection sheets, polar shims and austenitic steel collars, which clamp all the components and retain the Lorentz forces during the powering of the magnet.

The dipole magnetic field is measured at room temperature (r.t.) by the Cold Mass Assemblers (CMAs) after the assembly of the coil in the collars ("collared coils", Fig. 1) and after the welding of the shrinking cylinder ("cold mass") around the collared coil and the iron yoke. These measurements provide relevant information on the geometry of the coil, also allowing the detection of faulty assembly or components [2]. Moreover, they are used to forecasting the magnetic behavior in operational conditions through the warm-cold correlations [3].

The scope of this work is to analyze if the collars have played a relevant role in the variation of the field quality of the LHC dipoles during the production. We aimed at answering the following questions

- Are the tolerances over the collar geometry kept and are there trends along the production?
- Are the collar suppliers and the procedures of collar assembly affecting the field quality?
- What is the expected impact of actual collar shape on field quality and how does it relate to magnetic measurements?

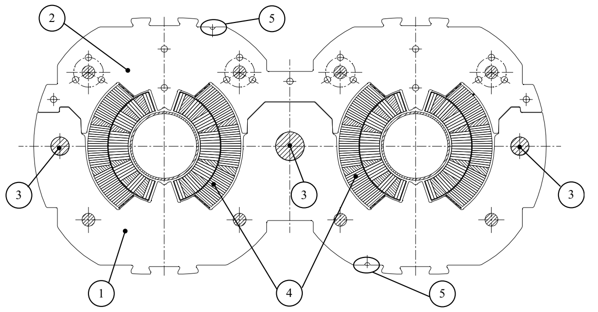

Fig. 1: Collared coil layout. 1- Collar type A1; 2- Collar type A2; 3- collaring rods; 4- Superconducting coils; 5 – Collar witness marks

II. Collar Production and Mounting Procedures

The collars are manufactured through a process of fine-blanking starting from 3 mm thick austenitic steel coil, with tolerances of the order of 20-30 μm. There are three shapes of collars along the magnet length to fit the different geometry of the cross section and each shape is manufactured in two types. Since in this work we are interested in the quality of the magnetic field, which is by far dominated by the straight part of the magnet, we will analyze only the production of the types that fill this part of the dipoles: A1 and A2, as shown in Fig. 1.

CERN has shared the collar production between two firms:

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S_1 (5/8 of the total) and S_2 (3/8 of the total). The same raw material is delivered to both firms. Collars are delivered in batches which count around 4300 pieces, enough to fill a magnet plus some spare pieces used for the acceptance tests. All collars have a witness mark on one side to distinguish the right from the left part.

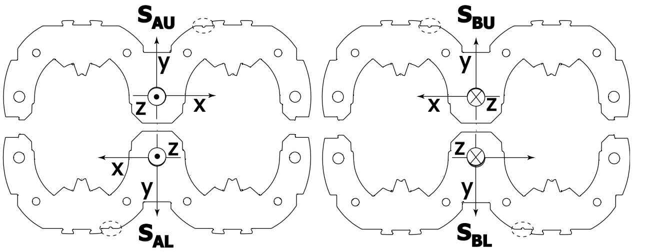

Fig. 2: The four possible assembly positions for the straight part collars type A1; the witnesses are marked with a dashed circle.

Collars of type A1 and A2 are assembled in pairs, and locked by four pins inserted in the four smaller holes (see Fig.1). Then, collar pairs are assembled around the coil, each CMAs using a different procedure:

- *Firm1* mounts collar pairs by flipping them around the “x” axis, i.e. using only two over the four possible configurations shown in Fig.2 (S_{AU} and S_{BL}).
- *Firm2* assembles packs of 5 pairs that are then mounted using all the four possible positions of Fig.2.
- *Firm3* also assembles packs of collars (10 pairs) but the packs are only rotated around the “z” axis, perpendicular to the plane of the drawing, hence only two possible mounting positions are used (in Fig.2, S_{AU} and S_{AL}).

These different procedures have an impact on the symmetry of the final assembly:

- *Firm1*: up-down asymmetries of a same aperture are cancelled, but the two apertures are independent (no correlation).
- *Firm2*: up-down asymmetries are cancelled, and the two apertures are symmetric (perfect correlation).
- *Firm3*: up-down asymmetries are not cancelled, but the two apertures are correlated.

III. Available Data

Collar Dimensions: the geometrical dimensions of the collars are measured at the supplier. From the available production we only used the last 330 batches (see Table I), since the measurement of the first 212 batches of the supplier S_1 and the first 177 of S_2 were not precise enough for our analysis.

TABLE I
NUMBERS OF COLLAR BATCHES USED IN THE GEOMETRICAL ANALYSIS.

Collar Supplier	Batches available
S2	**182** - used in Firm 03
S1	**76** - used in Firm 01
S1	**71** - used in Firm 02

Magnetic measurements: 741 collared coils have been measured at r.t.. For the not allowed components of the magnetic field we used the whole set of data. On the other hand, for the allowed components we restricted the analysis to the subset of magnets built with the last modification of the coil cross section, denoted by cross-section 3 (548 collared coils). Previous cross sections had a different coil lay-out that gives different systematic values for the allowed components.

TABLE II
NUMBERS OF COLLARED COILS USED IN THE MAGNETIC FIELD QUALITY ANALYSIS

Collar supplier	CMA	C.C. - all	C.C. - X-sec.3
S2	Firm 01	**13**	**8**
	Firm 02	-	-
	Firm 03	**335**	**279**
S1	Firm 01	**199**	**139**
	Firm 02	**182**	**119**
	Firm 03	**9**	**0**

IV. Trends in Collar Geometrical Data

During the dimensional controls of the collars, about ninety measurements per piece are taken. We choose to analyze all the measurements performed in the “cavity”, which is the part where the superconducting coil is allocated. The nominal shape of the inner cavity of the collar is defined by the arc of circles A and B, with a radius of 60.98 mm and 44.88 mm respectively and a tolerance of +/-0.030 mm, and the straight lines C and D, both having a tolerance of +/-0.025 mm (see Fig. 3, left). The precision of the measurements performed in the industry is about 0.010 mm; this estimate is based on a comparison with measurement performed at CERN.

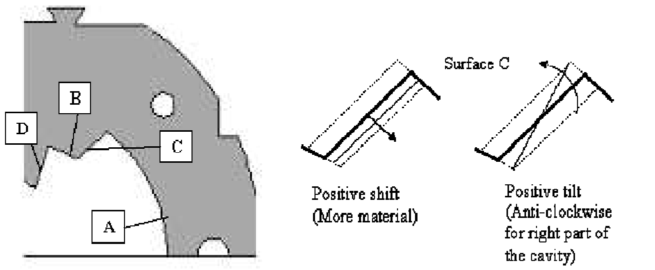

Fig. 3: Labeling of the analyzed collar surfaces (left). Conventions on signs for a shift and for a tilt (right).

The surfaces B, C and D are measured in two points at the edges and only the surface A is measured in an additional point in a central position. Measurements are always reported as deviation from nominal shape. We do not discuss here the effect of errors in the holes for the locking rods, which is a very complex analysis since it can lead to shifts in the position of the collars and to collar deformations during the assembly. Indeed, an analysis carried out in [6] shows that some of these effects are not negligible.

Using an assumption of linearity between two measured points of the same surface, the deviations from the nominal values are split in a shift and a tilt (see Fig. 3). The shift is defined as the average of the measurements, and the tilt is the difference between the average of the measurements taken on the surface and one measurement taken on the edge. For each of the two collar types we take under control 16 surfaces in the two cavities for a total of 16 shifts and 16 tilts analyzed.

The dimensional analysis is performed over the sample given in Table I and the results show that we do not find significant differences in the geometry between the two suppliers (Fig.4 for an example); the only difference is that the shifts of the collar type A1 of the producer S_1 have slightly larger spreads with respect to the ones of the collars of S_2. No trends are observed during this period of the production.

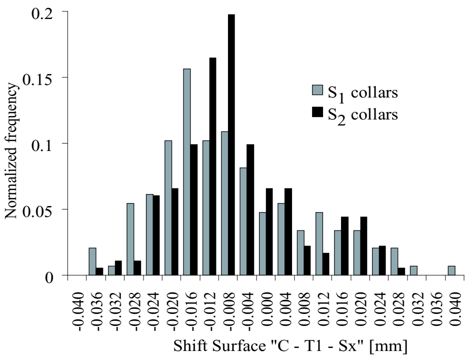

Fig. 4: Histograms of the values of the surface "C" of the cavity T1-left side of the two collar suppliers.

V. DEPEDENCE OF MAGNETIC FIELD ON THE ASSEMBLY PROCEDURES AND ON THE COLLAR SUPPLIER

A. Multipolar expansion of the magnetic field

In a dipole, the magnetic field can be expressed in a 2-D form that can be expanded in series in a complex domain:

$$B(x,y) = B_y + iB_x = B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{\text{ref}}} \right)^{n-1}$$

where b_n and a_n are the so called multipoles (respectively: "normal" and "skew"), (x,y) are the transverse coordinates, B_1 is the reference magnetic field and R_{ref} the reference radius (for the LHC is 17mm). In a "perfect dipole geometry" all the coefficients are zero except b_{2n+1} ("allowed" multipoles) because both up-down and left-right symmetries are satisfied. Tolerances of the mechanical components break the symmetry and consequently also "not allowed" harmonics are generated; they can be divided in three classes with respect to the symmetry break-down:

1- Even normal (b_{2n}): generated by a left-right anti-symmetry
2- Even skew (a_{2n}): generated by an up-down anti-symmetry
3- Odd skew (a_{2n+1}): generated by an anti-symetrization related to a rotation of 180 degrees w.r.t the center of the aperture.

B. Magnetic field versus collar supplier

We computed averages and standard deviations for the field harmonics, splitting the data among collar suppliers and dipole assembler. Results are given in Table III.

Allowed multipoles: the collar supplier does not affect the allowed multipoles: Firm1 has 8 magnets made with collars S_2 and 139 with collars S_1, and the two sets have similar averages (Table III). The systematic differences between Firms observed for b_5 (Firm1 has 1 unit more than Firm2-3) and b_7 (Firm2 has 0.2-0.3 units less that Firm1-3) cannot be due to the collar supplier, since Firm1 mostly uses S_1 collars.

Not allowed multipoles: the comparison of 13 magnets of Firm1 assembled with collars S_2 to the 199 assembled with collars S_1 shows no relevant systematic difference in the not-allowed components. The strong negative systematic a_3 component in Firm1 (around 0.4 units) is observed both with collars S_2 and S_1 and therefore it is not due to the collar supplier. A similar remark can be made for the systematic a_4 observed in Firm2 with S_1 collars if compared with the values of the same multipole of Firm1 with collars S_1 and S_2

TABLE III
AVERAGES AND STANDARD DEVIATIONS OF MAGNETIC FIELD HARMONICS, IN UNITS OF 10-4 AT RREF=17MM, MEASURED AT ROOM TEMPERATURE AND SORTED W.R.T. COLLAR SUPPLIERS AND DIPOLE MANUFACTURERS.

Coll.	CMA	N	b3	b5	b7	N	b2	b4	a2	a4	a3	a5
			averages				averages					
S2	1	8	–2.1	**0.05**	1.17	13	–0.18	–0.03	0.07	–0.03	**–0.23**	0.06
	2	–	–	–	–	–	–	–	–	–	–	–
	3	279	–1.59	–0.56	1.17	335	–0.1	–0.05	0.64	–0.09	0.51	0.18
S1	1	139	–1.88	**0.29**	1.21	199	–0.08	–0.02	0.26	–0.02	**–0.31**	0.04
	2	119	–2.87	–0.79	**0.87**	182	–0.14	–0.05	0.12	**0.37**	**–0.44**	0.00
	3	–	–	–	–	9	0.05	–0.04	–0.04	–0.05	0.16	0.07
			standard deviations				standard deviations					
S2	1	8	0.88	0.38	0.08	13	1.00	0.15	1.11	0.28	0.30	0.06
	2	–	–	–	–	–	–	–	–	–	–	–
	3	279	0.80	0.22	0.06	335	0.78	0.09	0.94	0.29	0.32	0.09
S1	1	139	1.10	0.32	0.08	199	0.52	0.12	1.21	0.26	0.27	0.08
	2	119	0.92	0.31	0.12	182	0.41	0.09	1.07	0.31	0.28	0.08
	3	–	–	–	–	9	0.58	0.12	0.90	0.18	0.29	0.05

C. Magnetic field versus assembly procedures and correlation between apertures

The different assembly procedures should have some impact on the not allowed multipoles and on the correlations between the apertures of the same magnet, which are given in Table IV.

TABLE IV
COEFFICIENTS OF THE CORRELATIONS BETWEEN THE FIELD HARMONICS MEASURED IN THE TWO MAGNET APERTURES. IN BOLD, COEFFICIENTS> 0.7.

Coll.	CMA	N	b3	b5	b7	N	b2	b4	a2	a4	a3	a5
S1	1	139	**0.76**	**0.83**	**0.79**	199	0.22	0.38	0.07	0.05	0.55	0.49
S1	2	119	**0.78**	**0.81**	**0.89**	182	0.29	0.30	0.06	0.14	0.60	0.56
S2	3	279	**0.70**	**0.83**	**0.80**	335	**0.77**	0.29	0.09	0.04	**0.71**	0.59

Allowed multipoles are always correlated. The three different procedures used to assemble the collars are not affecting the correlation, which is present in all Firms. This correlation should arise either during the collar assembly or during the collaring itself.

Not allowed multipoles:

- *Firm1:* no correlation is expected from the collars assembly procedure. Indeed, a weak one is observed for a_3 and a_5, which could come from a systematic left-right asymmetry in the production of the coils, creating an odd skew in the assembly. For even skew a_2 and a_4, if their only source were the collars, they should be zero because of the assembly procedure. The non-zero values measured for Firm1 mean that these multipoles are driven by other mechanisms, which are not correlated between apertures.
- *Firm2:* no correlation is observed on even normal b_{2n}. Since

from the assembly procedure a good correlation is expected for these multipoles, also in this case one can state that for Firm2 the main source of imperfections affecting b_2 and b_4 are not the collars. The weak correlation observed for a_3 and a_5 could be either due to the collar assembly procedure or to the production of the coil as discussed for Firm1. For a_2 and a_4 the same argument used for Firm1 holds.

- *Firm3:* we have a correlation for b_2, a_3 and partially for a_5; this means that the collars shape and the adopted assembly procedure is the driving mechanism for these harmonics in Firm 03. The fact that the correlation is not observed for, b_4 and a_{2n} implies that for these multipoles the main source of imperfections is given by other components, which are not correlated between apertures.

VI. Expected vs Measured Field Harmonics

A numerical magneto-static model has been used to determine the dependence of the harmonics on the geometrical dimensions of the collars. Here we assumed the collars to be infinitely rigid, i.e., the superconducting cable and the cable insulation absorb all changes of the collar shape.

In the numerical calculation, it is assumed that each surface of the inner part of the collar contributes in an independent manner. Calculating the sensitivities of the shift and tilt all of the surfaces A, B, C and D and multiplying them by the measured collar geometrical errors, one can reconstruct the expected shift in the multipoles due to the actual shape of the collar. Some care must be taken in the computation, in order to correctly take into account the assembly procedure [7].

The results of the calculation in terms of averages and standard deviations are showed in Table V. For b_2 we also give a plot in Fig.5, where for each magnet we compare the measurement of the aperture 1 with the expected values evaluated as mentioned above. Here the sample counts 331 magnets.

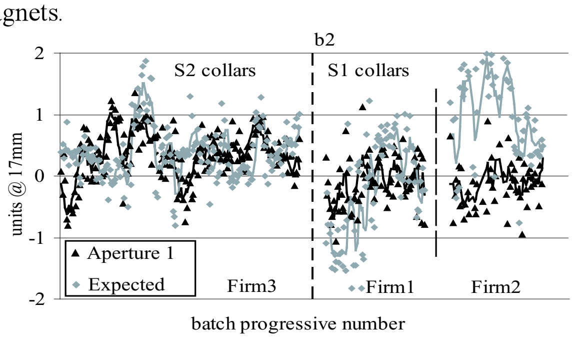

Fig. 5: b2, expected and measured (solid lines are moving averages).

We have shown in the previous section that the allowed multipoles are not driven by the collar imperfections. The comparison of expected versus measured multipoles confirms this result: the expected contribution of the collars to the spreads is one third of what measured. Moreover, the expected shift in the average multipoles between firms is negligible, whereas according to measurements is large for b_5 and b_7.

For Firm3, where we have shown using correlations that b2 and a3 are strongly affected by the collars, we have a good agreement between measured and expected values both for the average and for the sigma.

For the skew multipoles in Firm1 and Firm2 the assembly procedure guarantees no contribution from the collars, and therefore the observed spreads are due to other components.

The only inconsistency found is that from the collar measurements we expect a larger sigma than measured for b_2 and b_4 in Firm1 and Firm2. This is due to the geometrical measurement of the collars, since the spread of the differences between the dimensions of the left and right part of the cavities (that generates b_{2n}) of the collars supplied by S_1 is very large (twice the values measured for S_2 collars). This large spread does not match with the measurements.

TABLE V
MEASURED AND EXPECTED AVERAGES AND STANDARD DEVIATIONS OF THE MAGNETIC FIELD HARMONICS

Coll.	CMA		Δb3	Δb5	Δb7	b2	b4	a2	a4	a3	a5
averages - Aperture 1											
S1	3	meas	0.52	–0.26	0.06	**0.35**	**–0.05**	0.84	–0.12	**0.53**	0.19
		exp	0.16	–0.07	0.06	**0.39**	**0.03**	0.00	0.03	**0.67**	–0.01
S2	1	meas	0.39	0.71	0.13	–0.1	–0.09	0.15	0.02	–0.44	0.02
		exp	-0.17	0.00	0.01	–0.21	0.02	–	–	–	–
	2	meas	-0.92	–0.45	-0.19	–0.13	–0.1	–0.29	0.40	–0.48	0.00
		exp	-0.19	–0.01	0.01	0.94	0.00	–	–	–	–
standard deviations											
S1	3	meas	0.85	0.20	0.07	**0.42**	**0.08**	0.67	0.24	**0.26**	**0.09**
		exp	0.34	0.05	0.02	**0.45**	**0.05**	0.44	0.10	**0.30**	**0.06**
S2	1	meas	0.83	0.32	0.07	0.41	0.08	1.00	0.26	0.22	0.07
		exp	0.33	0.08	0.03	0.83	0.14	–	–	–	–
	2	meas	0.95	0.31	0.10	0.36	0.09	1.06	0.28	0.30	0.07
		exp	0.38	0.07	0.02	0.68	0.06	–	–	–	–

VII. Conclusion

The main result of the analysis is that the collar shape is the driving mechanism of field harmonics only for b_2 and a_3 in Firm3, where collars of the supplier S_2 are used. Two independent observations support this fact: firstly, we have strong correlations between apertures of the same magnet as expected from the assembly procedure. Secondly, the expected values based on the measured dimensions of the collars and on a magneto-static model agree with magnetic measurements both for the average and for the standard deviation.

For all the other cases the collar imperfections are not the driving mechanism of the field harmonics. In particular, we point out that the large systematic differences between dipole suppliers observed for b_5 and b_7 cannot be due to the collars. Moreover, the spread due to the measured imperfections of the collars is only one third of the measured spread of the allowed field harmonics.

One can conclude that both the collar specifications and the collar suppliers have reached the difficult goal of minimizing the impact of collar geometry on the spread of magnetic field harmonics.

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