MT-19 REVIEWER'S REPORT

Paper Number FRM20R1 **Paper Title** TRENDS IN FIELD QUALITY ALONG THE PRODUCTION OF THE LHC DIPOLES AND DIFFERENCES AMONG MANUFACTURERS

First Author E. TODESCO

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Trends in Field Quality Along the Production of the LHC Dipoles and Differences Among Manufacturers

E.Todesco, B. Bellesia, P. Hagen, C. Vollinger

Abstract—More than two thirds of the dipoles of the Large Hadron Collider have been manufactured and their magnetic field has been measured at room temperature. In this paper we make a review of the trends that have been observed during the production. In some cases, the trends WERE ~~have been~~ traced back to displacements of conductors with respect to the nominal lay-out. The analysis allows detecting the most critical zones in the superconducting coil as far as field quality is concerned. The second part of the paper makes the point of the observed differences in field quality between the three manufacturers. The analysis allows evaluating which multipoles are more affected, what magnitudes of displacements are necessary to explain these differences (the manufacturers all producing the same baseline), and what could be the origin of such differences.

Index Terms—LHC, Superconductivity, Field Quality.

FOR THE DIPOLES NEEDED

I. INTRODUCTION

V To guide the particle beams in the Large Hadron Collider (LHC) [1], 1232 superconducting dipoles with a nominal field of 8.3 T are being produced. More than ¾ of the superconducting coils have already been manufactured. One of the requirements imposed by the beam dynamics is that the deviations of the magnetic field from ideal are of the order of 10-100 ppm [2]. In this type of magnets [3],[4], the shape of the magnetic field is mainly determined by the position of the conductors, which have to satisfy tolerances better than 0.1 mm, and by the superconducting properties of the cable. As in the case of the previous superconducting magnet mass V production, (the Relativistic Heavy Ion Collider [5]), magnetic measurements are carried out at room temperature over 100% of the production, and over a sample of 15-20% in operational conditions at 1.9 K. THESE ARE USED TO STEER ~~Using this information,~~ the magnetic field quality ~~is steered~~ towards the beam dynamics targets [6]. Magnetic measurements are also a powerful tool to carry out a quality control since anomalies in the field can be traced back to assembly errors or faulty components [7],[8].

In this paper we review the results of magnetic measurements at room temperature of 844 dipoles of the LHC, relating the magnetic field properties to the assembly procedures and components [9-12]. The aim of the work is to show ~~what~~ THE degree of homogeneity THAT has been obtained in this mass production, ~~what are~~ the most important mechanisms driving the magnetic field at room temperature, and the relation with the design tolerances. We recall that in the LHC dipole, field harmonics are by far dominated by the geometric contribution, since the persistent current and saturation are well reproducible ? EXPLAIN BETTER: THEIR EFFECT IS WELL COMPENSATED ?

II. DIPOLE COMPONENTS, MANUFACTURERS AND ASSEMBLERS

The main dipoles of the LHC are made up of superconducting coils clamped in austenitic steel collars inside an iron yoke, the whole structure being contained in a shrinking cylinder (see Fig. 1). The cables are ~~of~~ 15.1 mm wide, NbTi RUTHERFORD-TYPE CABLES, cooled to 1.9 K,. Two layers with different type of cables are wound to form ~~the~~ A coil pole. Four copper wedges are used BETTER to approximate a cos θ geometry, thus dividing the coil in six conductor blocks (see Fig. 2). CONTRARY ~~Compared~~ to previous projects, this is the first dipole design with two apertures in a common collar (twin design), and therefore the issue of possible coupling of the magnetic fields between the two apertures is of relevance. The main components suppliers, and assemblers of the dipoles are the following ~~ones~~:

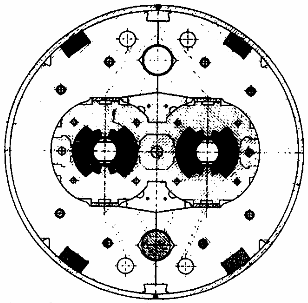

Fig. 1: Cross-section of the main LHC dipole.

- Superconducting cables are manufactured by 2 different suppliers (labeled B,E) for the inner layer and 5 (coded B,C,G,D,K) for the outer one [13].
- Copper wedge spacers are manufactured by one company [9].
- Collars are manufactured by two suppliers S1 (5/8 of the production) and S2 (3/8) [11], [12].

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- Iron laminations are manufactured by two suppliers (5/8 by S2 and 3/8 by S3, for the straight part). IN ENDS?

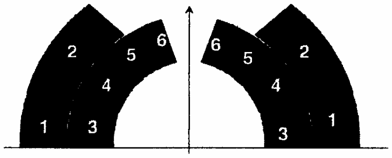

Fig. 2: Cross-section of the LHC dipole coil (upper half of one aperture) and conductor block numbering.

- The assembly of the magnet, involving the coil winding and curing, the collaring, the assembly of the yoke, and the welding of the cylinder is carried out by three manufacturers (dipole assemblers) denoted by Firm1, 2 and 3. The assembly of the collared coilS follow~~s~~ different procedures in each assembler [11], [12]:
  - In Firm1 the pre-assembly is done with the collared coilS in a vertical position, whereas in Firm2 and Firm3 ~~it is~~ THEY ARE horizontal.
  - In Firm1, collars are mounted using two configurations (~~up-down~~ LEFT-RIGHT flip); in Firm3 they are mounted in two other configurations (rotation by 180 degrees); in Firm2 the four configurations are used. More details are given in [11].

EITHER PUT -S OR SPECIFY THAT THE WHOLE IS CALLED "COLLARED COIL"

Systematic differences in the coil geometry can be due to:

- the cable manufacturer, in case of systematic differences in the cable size and mechanical properties [10];
- the collar manufacturer, in case of systematic differences in the collar geometry [11];
- the cold mass assembler, in case of systematic differences in the tooling used for the coil curing, in the procedure for the assembly of the collars and for the collaring [11].

Another difference in the dipoles stems from the tuning of the lay-out that ~~have been~~ WAS carried out during the production to better match the beam dynamics targets [6]. Three cross-sections have been produced: the baseline (cross-section 1, also denoted by version V6-1 [14]) ~~has been~~ WAS replaced by a new version with a different geometry of the copper wedges of the inner layer (cross-section 2 [6]), and then a mid-plane shim of 0.125 mm thickness ~~has been~~ WAS added (cross-section 3 [6]). 34 magnets have cross-section 1, 145 cross-section 2, and the rest of the production is with cross-section 3.

III. MAGNETIC MEASUREMENTS

The magnetic field in a dipole ~~is~~ CAN BE expressed as a power series

$$B_y(x,y)+iB_x(x,y)=10^{-4}B_1\sum_{n=1}^{\infty}(b_n+ia_n)\left(\frac{x+iy}{R}\right)^{n-1}$$

where (x,y) are the transverse coordinates, R is the reference radius (17 mm in our case), and B_1 is the main dipolar component. The harmonics terms b_3, b_5, b_7 ..., are generated by a coil lay-out that satisfies the up-down and left-right symmetry ("allowed" components), whereas the other harmonic terms are due to a break of these symmetries ("not allowed" components). The field harmonics are expressed in units, and one has b_1=10^4 by definition. The main component and the field harmonics are measured at room temperature with a rotating coil of 750 mm length. 20 consecutive positions are measured, along the 14.3 m dipole. Position 1 and 20 cover the ends of the coils, and 2 to 19 the so called straight part. In this paper we will neglect the variations of the field harmonics along the magnet axis, and each dipole will be characterized by two values of the average harmonics (usually called integral), one for each aperture. These values are averages weighted with the main field component.

Measurements are carried out at the manufacturerS [15] at two different stages of the assembly procedure, namely after the collaring (collared coil, i.e. the superconducting coils clamped in the collars), and after the welding of the shrinking cylinder (the so called cold mass, i.e. the collared coil inside the iron yoke and the stainless steel cylinder). Here we will present the results relative to the cold masses. Indeed, the magnetic effect of the iron yoke is very reproducible and therefore the collared coil measurement already contains the bulk of the information about the coil geometry. ✓ ?

Measurements are carried out in operational conditions (1.9 K) at CERN on 15% of the production, the sampling having been 100% in the pre-series phase to build solid warm-cold correlations [16]. In the mature phase of the production the sampling is around 10%. A summary of the available measurements at room temperature and at 1.9 K is given in Table I. This paper focuses the features that can be deduced by room temperature measurements.

TABLE I: NUMBER OF MAGNETS MEASURED AT ROOM TEMPERATURE AND AT 1.9 K FOR EACH DIPOLE ASSEMBLER AND CROSS-SECTION TYPE

	Room temperature				1.9 K			
Firm	Xs1	Xs2	Xs3	all	Xs1	Xs2	Xs3	all
1	12	58	174	244	13	26	14	53
2	10	31	182	223	9	13	17	39
3	9	51	317	377	8	18	37	63
all	31	140	673	844	30	57	68	155

IV. BENDING STRENGTH

A. Transfer function

The transfer function is defined as the average main field in the straight part of the dipole (position 2 to 19) divided by the current. The moving average per cold mass assembler has been stable after the last change of cross-section (see Fig. 3), and is oscillating along the production in a range of ±15 units. We remind the reader that 15 units of main field can be generated by a deviation in the coil diameter of 0.04 mm, which is of the same order of magnitude as the tolerances on the collar radius (0.03 mm). Since the beginning of the production, we have a systematic difference of around 10 units between Firm3 and Firm1, Firm2 being in between.

ARE YOU SURE?

ALSO BEFORE!

AROUND DESIGN VALUE? WHAT'S THE ZERO?

B. Magnetic length

The magnetic length is defined as the integral of the transfer function divided by the transfer function in the straight part. ~~The~~ ITS moving average per manufacturer has been stable within 1-2 units since the beginning of the production (see Fig. 4). One CAN observe~~s~~ a small systematic difference of 10 units, corresponding to 14 mm, between the dipoles assembled in

DIFFERENT LENGTH
OR WHAT?

Firm3 and in Firm1, Firm2 being in between. Part of this difference is due to the iron yoke: in the collared coils the difference in magnetic length between Firm3 and Firm1 is smaller (5 units).

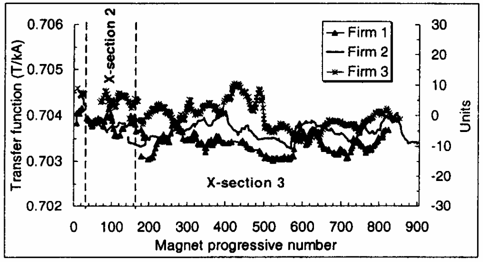

Fig. 3: Transfer function measured at r.t. along the production: moving average for each cold mass assembler.

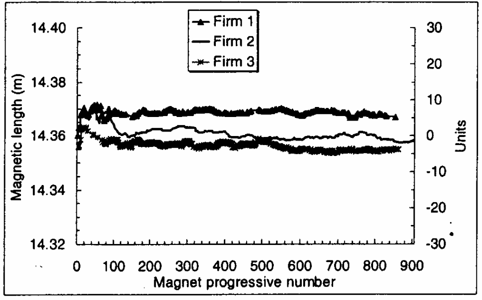

Fig. 4: Magnetic length measured at r.t. along the production: moving average for each cold mass assembler.

C. *Integrated transfer function*

The integrated transfer function is the product of the magnetic length times the transfer function. This quantity gives the actual bending strength of the dipoles, and is the only one relevant for the beam. In the technical specification it was foreseen to have a fine tuning of the length of the iron laminations to reduce the spread of the bending strength between the assemblers. This method has been tested successfully in three dipoles at an early stage of the production. Indeed, the systematic differences between Firm1 and Firm3 in the transfer function and magnetic length compensate each other, and the difference of the bending strength average between the assemblers is below 3 units. This accidental compensation has avoided the necessity of carrying out the fine tuning with the iron laminations. To date, the standard deviation of the bending strength of all manufactured dipoles at room temperature is 5.5 units, well below the specification of 8 units [2]. This corresponds to a spread in the coil radius over all the production of 15 μm (one standard deviation). The initial installation baseline was to allocate the same dipole assembler in the same octant, to minimize the spread: the absence of significant systematic differences between assemblers has allowed to relax this constraint.

V. ALLOWED MULTIPOLES

Average and standard deviation of the odd normal multipoles are given in Table II, where we analyzed only the dipoles with cross-section 3 to have a homogeneous sample. The motivations for the cross-section changes and their effectiveness have been already presented in [6]. Here we focus our analysis on the systematic differences between dipole assemblers, which are negligible for the b_3, and rather large for b_5, b_7 and b_9 (see Table II, last two lines). The normal decapole b_5 in Firm1 is 0.75 units larger than in Firm2-3, and b_7 in Firm2 is 0.3 units smaller than in Firm1-3. The mechanism that drives the difference in b_5 is probably also affecting b_9 which is 0.09 units higher in Firm1.

WITHIN
1-σ

TABLE II: AVERAGE AND STANDARD DEVIATION OF ODD NORMAL MULTIPOLES MEASURED AT R.T. IN EACH DIPOLE ASSEMBLER (X-SECTION 3 ONLY)

	b3		b5		b7		b9	
Firm	μ	σ	μ	σ	μ	σ	μ	σ
1	3.0	0.9	0.24	0.27	1.02	0.07	0.50	0.02
2	2.1	1.2	-0.54	0.38	0.73	0.12	0.41	0.02
3	3.1	0.8	-0.44	0.18	0.99	0.06	0.41	0.02
all	2.7	1.0	-0.25	0.42	0.91	0.15	0.44	0.04
1-3	-0.1		0.68		0.03		0.09	
2-3	-1.0		-0.10		-0.26		0.00	

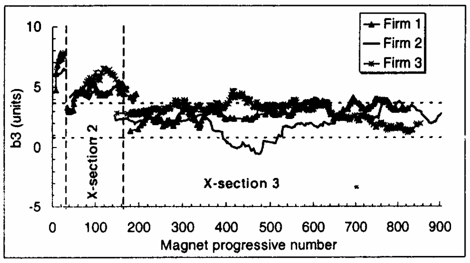

Fig. 5: Multipole b_3 measured at r.t. along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

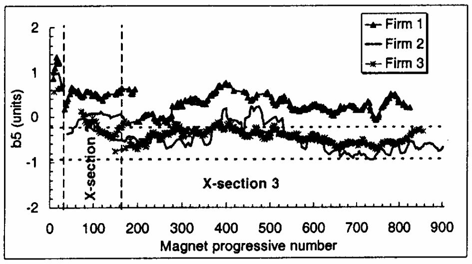

Fig. 6: Multipole b_5 measured at r.t. along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

These differences are also visible in the previous cross-sections (see Figs. 5-7). They cannot come from the collar supplier, since Firm1 and Firm2 use the same supplier S1. The best candidate for the difference between Firm2 and Firm3 is a 0.075 mm inward radial shift of block5 (see Fig. 8) in all quadrants, which gives a large effect on b_7 (-0.27 units), without affecting b_5, with a relatively small impact on b_3 (-1.6

units), close to what has been measured. On the other hand, no simple movement of a conductor block can account for the systematic differences between Firm1 and Firm3. Indeed, the order of magnitude of displacements that can give the measured difference of 0.7 units of b_5 (see Table II) is also in this case of 0.05 to 0.1 mm, i.e. not far from the tolerances of the design.

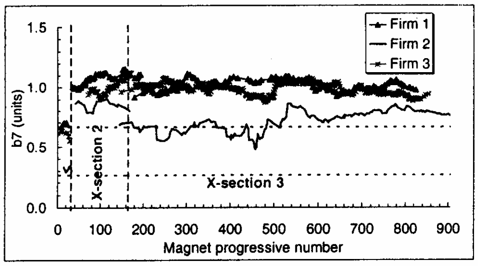

Fig. 7: Multipole b_7 measured at r.t. along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

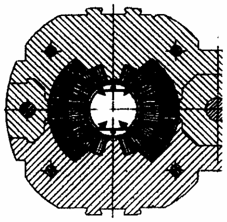

Fig. 8: Coil displacement of block5 that could account for the difference in allowed multipoles measured at r.t. between Firm2 and Firm3 (not in scale).

Using the approach developed in [17], we find that the measured spread of the allowed multipoles in each assembler matches the spread due to a random movement of the conductor blocks of 0.05 mm amplitude (one sigma). Neither the copper wedges [9] nor the collars [11] tolerances are found to be the driving mechanism of the allowed multipoles. We finally point out that a fairly good correlation (r=0.7-0.8) is found between the apertures [11] for the allowed multipoles. This beneficial feature allows sorting the magnets in the machine to carry out a local compensation of b_3 [18].

VI. NOT ALLOWED MULTIPOLES

A. *Even normal*

Even normal multipoles are excited by a break down of the left-right symmetry in the coil. The LHC dipole features two-in-one collars that produce a systematic asymmetry between the left and the right part of each aperture. This asymmetry comes from both the mechanical structure of the collared coil, and from the magnetic structure due to asymmetry of the iron.

Here we aim at analyzing the coil asymmetries, and therefore we consider the measurements at r.t. of the collared coil *without iron yoke*. We select data of Aperture 1 (on the right looking from the connection side), and similar results hold for Aperture 2. Data of Table III and Fig. 9 show that systematic components are within one standard deviation, with the exception of b_2 in Firm3. This means that the deformations of the two-in-one collars well preserve the left-right symmetry of each aperture. This is an expected result since the material chosen for the collar (austenitic steel) aims at minimizing the deformations of the structure. In Firm3, the negative systematic and the spread of b_2 are driven by the imperfections of the collars, which are supplied by S2. This is proven (see [11], [12]) by the fact that, contrary to Firm1 and 2, a strong correlation between apertures is observed. V Moreover, the expected average and spread of multipoles evaluated on the SHOW! basis of the collar dimensions (and on infinitely rigid collars) agree with the measured ones [11]. Multipole b_4 is well within targets and no trends are observed (see Fig. 10). FOR FIRM 1 & 2

TABLE III: AVERAGE AND STANDARD DEVIATION OF EVEN NORMAL MULTIPOLES IN APERTURE 1 MEASURED IN THE COLLARED COILS AT R.T.

	b2		b4		b6		b8	
Firm	μ	σ	μ	σ	μ	σ	μ	σ
1	-0.20	0.47	0.02	0.11	0.00	0.03	0.004	0.015
2	-0.22	0.44	-0.01	0.09	0.00	0.04	-0.003	0.019
3	-0.64	0.53	-0.06	0.09	0.00	0.03	-0.001	0.011
all	-0.35	0.53	-0.02	0.10	0.01	0.03	0.000	0.015

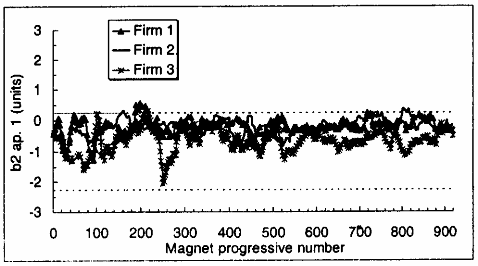

Fig. 9: Multipole b_2 measured at r.t. in the collared coil along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

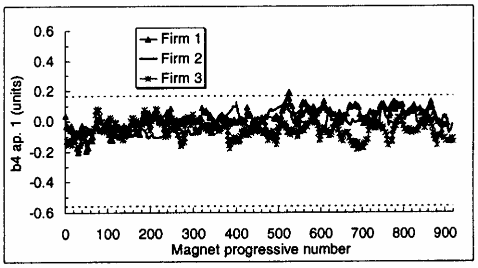

Fig. 10: Multipole b_4 measured at r.t. in the collared coil along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

The iron yoke is adding a b_2 shift, of different sign in ~~each~~ THE TWO apertures of 2.5 units. This shift is very reproducible, with some systematic differences between the dipole assemblers, and aims at compensating the effect of cool down and saturation, thus optimizing b_2 with respect to the beam dynamics targets.

AZIMUTHALLY

B. Odd skew

Odd skew multipoles are excited by a break down of the symmetry associated to a rotation of π of the coil cross-section. A systematic left-right asymmetry in the coil curing can excite these multipoles since the poles (i.e., the half coils) are assembled by rotating them by π. FOR EXAMPLE, If the left part of the pole is longer than the right one, the coil obtains a tilt of the coil mid-plane after assembly. Therefore, odd skew multipoles can give relevant information on the tolerances kept in the coil curing procedure. Another possible source of odd skew is a horizontal mismatch of the upper and the lower poles which could be due to collar imperfections [11], [12].

Average a_3 has a non-zero systematic ~~component~~ VALUE in all dipole assemblers of 0.3-0.4 units, with positive sign in Firm3 and negative in Firm1 and 2 (see Table IV and Fig. 11). A tilt of the mid-plane of 3 mrad gives 3.5 units of a_3, 0.3 units of a_5, and 0.07 units of a_7 [19]. A comparison of these sensitivities with the a_3 measurements of Table IV shows that the coil mid-plane tilt is kept within 0.15 mrad for the average of the production, within 0.4 mrad for the average of each dipole assembler, and within a spread (one stdev) of 0.3 mrad for the whole production. Indeed, it seems unlikely that the source of the systematic odd skews in Firm1 and in Firm2 is a mid-plane tilt, since ±0.3 units of a_3 would give rise to ±0.03 units of a_5, which does not match the experimental value.

TABLE IV: AVERAGE AND STANDARD DEVIATION OF ODD SKEW MULTIPOLES IN EACH DIPOLE ASSEMBLER (BOTH APERTURES?)

	a3		a5		a7		a9	
Firm	μ	σ	μ	σ	μ	σ	μ	σ
1	-0.38	0.22	0.01	0.07	0.02	0.03	-0.023	0.018
2	-0.39	0.22	0.00	0.07	0.07	0.04	-0.003	0.025
3	0.30	0.27	0.13	0.08	0.04	0.03	-0.009	0.014
all	-0.16	0.42	0.05	0.09	0.04	0.04	-0.011	-0.011

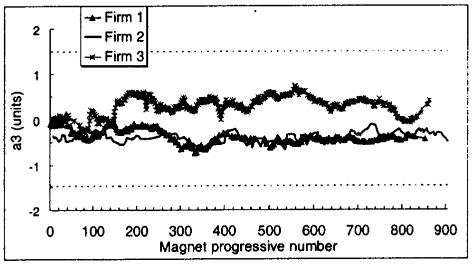

Fig. 11: Multipole a_3 measured at r.t. along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line). (BOTH APERTURES?)

Along the production, one observes that Firm3 has developed a positive systematic a_3 since magnet 150th (see Fig. 11), and that a wide spike of negative a_5 ~~has been~~ WAS found in Firm2 between magnets 400th and 550th (see Fig. 12). In both cases, the sources of these trends are unknown.

The source of the systematic a_3 in Firm3 could be a systematic left-right asymmetry of the collars, since the used assembly procedure does not cancel this type of asymmetry (see [11] for details). This is confirmed by the fact that a good correlation is found between the two apertures of the same magnet, as expected from the assembly procedure. Moreover, the a_3 values deduced from the collar dimensions through a magneto-static model agree with the measured ones both for the average~~s~~ and for the sigma. The same conclusion cannot be drawn for a_3 in Firm1 and 2, since the collar assembly procedure automatically cancels out the odd skews. Therefore the source of the systematic a_3 is ~~a~~ different ~~one~~. V

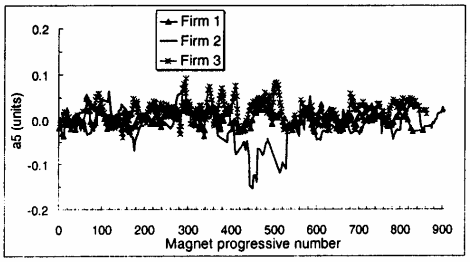

Fig. 12: Multipole a_5 measured at r.t. along the production: moving average for each dipole assembler (markers). (BOTH ?)

C. Even skew

Even skew multipoles are excited by a break down of the up-down symmetry. A systematic up-down asymmetry can arise during the assembly of the collar around the coils (pre-collaring) in Firm2 and Firm3, where this operation is carried out horizontally, and during insertion of the locking rods under the press (collaring) in all assemblers. The possible source of asymmetry is the collar weight.

Average a_2 has systematic ~~components~~ VALUES close to zero in all dipole assemblers (within 0.2 units, i.e., ¼ to 1/5 of the spread, (DIFFERENT STYLE) see Table V and Fig. 13). Therefore, the vertical assembly procedure used in Firm1 does not improve the up-down symmetry with respect to the other two assemblers. A shift of the mid-plane of 0.1 mm gives 9.0 units of a_2, -1.0 units of a_4, and 0.27 units of a_6 [19]. A comparison of these sensitivities with the a_2 measurements gives the remarkable result that the coil mid-plane shift is kept within JUST 1 μm ~~only~~ for the average of the production, within 2 μm for the average of each dipole assembler, and within a spread (one standard deviation) of 10 μm for the whole production.

TABLE V: AVERAGE AND STANDARD DEVIATION OF EVEN SKEW MULTIPOLES IN EACH DIPOLE ASSEMBLER (BOTH ?)

	a2		a4		a6		a8	
Firm	μ	σ	μ	σ	μ	σ	μ	σ
1	0.2	1.0	-0.03	0.22	0.00	0.06	0.000	0.017
2	-0.2	0.9	0.28	0.28	-0.01	0.08	0.025	0.024
3	0.2	0.7	-0.15	0.24	0.02	0.06	-0.010	0.019
all	0.0	0.9	0.03	0.30	0.00	0.07	0.005	0.025

On the other hand, a large non-zero systematic value of a_4 is found in Firm2 (0.3 units), and a smaller one with opposite sign in Firm3 (see Fig. 14). The source of this systematic is not a coil mid-plane shift since 0.3 units of a_4 would be associated to -2.7 units of a_2, which are not found. A more probable explanation for Firm2 is an inward radial movement of block 6 in the upper pole only of 50 μm (see Fig. 15), which according to models gives rise to 0.3 units of a_2 and to 0.27 units of a_4. This hypothesis is also supported by the fact that inward radial movements of block 6, localized along the magnet longitudinal axis, in one quadrant only have been observed in Firm2 during the production (see [8] for more details).

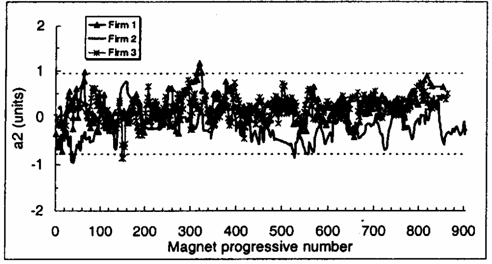

Fig. 13: Multipole a_2 measured at r.t. along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

(BOTH ??)

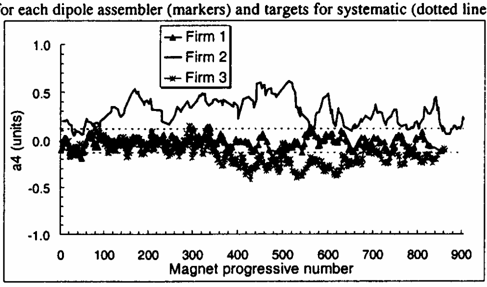

Fig. 14: Multipole a_4 measured at r.t. along the production: moving average for each dipole assembler (markers) and targets for systematic (dotted line).

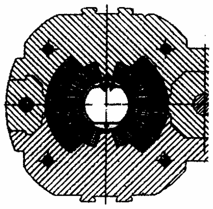

Fig. 15: Coil displacement of block 6 that could account for the systematic a_4 measured at r.t. in Firm2 (not in scale).

Since these asymmetries are found already in the measurements of the collared coils, a simple way to cure them is to assemble half of the collared coils turned upside down in the cold masses. In this way the spread is higher but the systematic is zero. This solution has been successfully tested on one collared coil of Firm2 after one third of the production, when Firm3 had not yet developed a negative a_4 and the situation was judged to be critical due to the absence of a_4 correctors in the machine. It has not been implemented since the average a_4 is within targets so far.

VII. CONCLUSIONS

We discussed the mechanisms driving the field quality at room temperature in the main LHC dipoles, and its relation with tolerances and assembly procedures. For the bending strength we show that the spread is about 5 units, corresponding to a coil radius difference of 10 μm, and that the differences between assemblers are small due to an accidental compensation of systematic differences in the transfer function and in the magnetic length.

The first order allowed component b_3 is within targets and no differences between dipole assemblers are found. On the other hand, a signature of the dipole assembler is found in the higher order multipoles. This can be traced back to differences in the coil lay-out of 50 to 100 μm. Allowed components are not driven by the collar imperfections.

We showed that the even normal multipoles are within beam dynamic targets, and that the left-right symmetry of the assembly is well preserved, notwithstanding the two-in-one collars. For Firm3 there is strong evidence that b_2 is driven by the collar imperfections. The analysis of skew multipoles shows that the up-down and rotational symmetry are well preserved. The coil mid-plane tilt is kept to zero within a fraction of mrad, and the shift is kept to zero within a few μm. A systematic component of a_4 can be traced back to a non-symmetric conductor displacement of 50 μm. Summarizing, the measured field quality at room temperature shows that [redacted] the component and assembly tolerances set in the design have been successfully fulfilled in most cases. A few unexpected asymmetries or differences between assemblers are compatible with systematic displacements of less than 0.1 mm.

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