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STATUS REPORT ON FIELD QUALITY IN THE MAIN LHC DIPOLES

E. Todesco, L. Bottura, S. Pauletta, V. Remondino, S. Sanfilippo and W. Scandale

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We give the present status of the field quality in the main LHC dipoles. Special emphasis is given to the collared coil data: a few tens of coils have been built, allowing a first analysis of the variability between producers, and estimates of the random part. Effects of the corrective actions implemented to fine tune the systematics components of low-order multipoles are presented. Correlations of collared coil data to the magnetic field measurements in operational conditions are discussed. Comparison to specifications imposed by beam dynamics allows to pin out the most critical requirements that will have to be met during the LHC dipole production.

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We give the present status of the field quality in the main LHC dipoles. Special emphasis is given to the collared coil data: a few tens of coils have been built, allowing a first analysis of the variability between producers, and estimates of the random part. Effects of the corrective actions implemented to fine tune the systematics components of low-order multipoles are presented. Correlations of collared coil data to the magnetic field measurements in operational conditions are discussed. Comparison to specifications imposed by beam dynamics allows to pin out the most critical requirements that will have to be met during the LHC dipole production.

1 INTRODUCTION

The magnetic field of the main LHC dipoles is measured in three conditions. Measurements of the superconducting coils in the collars (collared coil) at 300 K provide a first indication of the field quality, and a powerful instrument to detect assembly errors or faulty components. Then, the magnetic field of the cold mass (collared coils plus the iron yoke and the shrinking cylinder) is measured at 300 K. Both measurements are carried out at the manufacturer's premises. The cryomagnet is finally tested at CERN at 1.9 K and under the nominal current cycle. This provides the final assessement of field quality and of correlation with the previous measurements [1].

Here, we present data relative to 34 collared coil, 10 cold masses and 7 cryomagnets. In the early phase of the production, a wide range of thickness of the spacers between collars and coil poles (shims) has been used to compensate out of tolerance in the coil geometry, aiming at a nominal pre-stress. The successive magnets have been built with a narrower range of shim thickness, and during the production we aim at using nominal shims. Therefore, measurements data are reduced to nominal shims using the approach defined in Ref. [2]. This helps to define strategies to steer the magnet production. At a later stage, unmodified data will be used to optimize the magnet installation for beam operation.

2 SYSTEMATICS

Magnetic measurements of prototypes and first pre-series magnets showed that the systematic part of b_3 and b_5 were out of tolerance of about +3 units and +1 units respectively [3]. The origin of this discrepancy is rather well understood, i.e. some changes in the magnet structure after the definition of the coil cross-section, the influence of coil deformations [4], and some variations in the targets [5]. To recover nominal values for these multipoles, a cross-section correction has been implemented [6]. Copper wedges of the internal layer have been modified by at most 0.4 mm, keeping the same coil shape to avoid costly changes in the toolings and in the collars. The correction has been based on measurements of 9 collared coils and of 4 cryomagnets. Two collared coils with the new cross-section (magnets 29 and 31 in Figs. 1-3) have been built. The obtained shift in field harmonics is shown in Table 1. Measurements are given with a two sigma error. The multipolar variation due to tolerance on the copper wedges (± 30 microns) is associated to model estimates. One finds agreement between simulations and experimental data.

Table 1: Differential effect of cross-section correction in the collared coil on low-order allowed multipoles

	δb_3	δb_5	δb_7
Model	3.6 ± 1.0	1.3 ± 0.3	0.15 ± 0.10
Measurements	4.1 ± 0.3	1.2 ± 0.2	0.35 ± 0.13

The measured values of the allowed low-order multipoles in the straight part of 34 collared coils are shown in Figs. 1-3. Different markers are used to single out the three manufacturers, and the two apertures are plotted for each magnet. The best estimate for the running systematic is shown as a solid line. Since each firm will produce one third of the dipoles, the systematic is defined as the average of the three manufacturers averages. Comparisons are given to the allowed range for the systematic (dashed line), deduced by extrapolating the beam dynamics targets in operational conditions to the straight part of the collared coil through correlations discussed in Section 4.

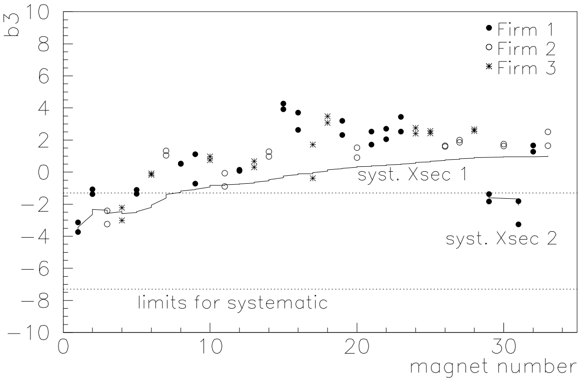

Figure 1: Average b_3 in the straight part of the collared coil versus magnet number: values of the three manufacturers (one marker per aperture) and running systematic (solid line) versus allowed range for the systematic (dashed line)

The graph of b_3 (see Fig. 1) shows an upward trend from magnet 1 to magnet 15 of up to 7 units. This trend, common to all manufacturers, is relevant since the allowed range for the systematic b_3 is 6 units. The change of the cross-section has been carried out when the average had already drifted by 3 units, and therefore the new magnets feature a systematic b_3 in the upper part of the allowed range. No systematic differences between manufacturers are observed.

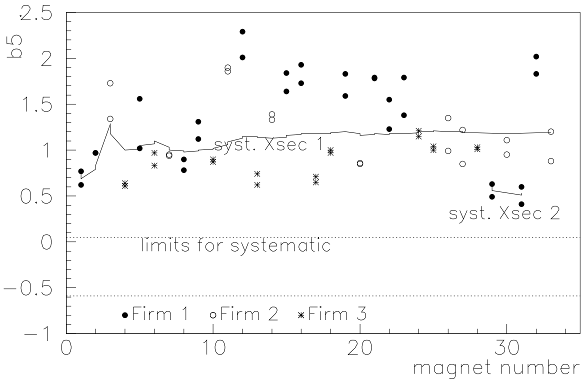

Figure 2: Average b_5 in the straight part of the collared coil versus magnet number: values of the three manufacturers (one marker per aperture) and running systematic (solid line) versus allowed range for the average (dashed line)

The control of b_5 (see Fig. 2) is critical since the variability (1.5 units peak-to-peak) is large compared to the allowed range for the systematic (0.6 units). No drift is observed in the production, but there are differences between the manufacturers after the first 10 magnets. Manufacturer 1 has an average of 1.8 units, whilst firms 2 and 3 are around 1 unit. If the same difference will be preserved in new cross-section magnets, the systematic b_5 will be around -0.1, i.e. in the upper part of the allowed range.

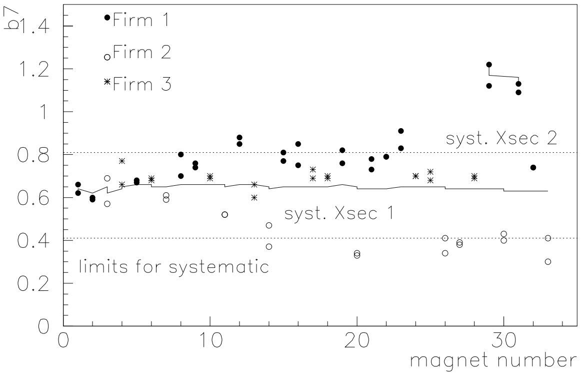

Figure 3: Average b_7 in the straight part of the collared coil versus magnet number: values of the three manufacturers (one marker per aperture) and running systematic (solid line) versus allowed range for the average (dashed line)

The control of systematic b_7 is also rather critical, since the spread of this multipole is close to the allowed range for the systematic (see Fig. 3). Also in this case, a difference between manufacturers is observed after the first 10 magnets: manufacturer 3 has an average b_7 of about 0.4 units, whilst b_7 in firms 1 and 2 are around 0.7 - 0.8 units. After the correction, some changes in the correlation to field in operational conditions and in beam dynamics targets have shifted downward and reduced the allowed range. The best estimate for the systematic b_7 is now out of the allowed range by a small amount (+0.1 units), if the difference between firm 2 and firm 1,3 are preserved (see Fig. 3).

Data relative to the new cross-section show that the measurements are now within or close to the allowed range for low-order multipoles (see Figs. 1-3). The effect on the integrated main field is shown to be negligible, as designed. More statistics is needed to determine the average of the new production, and if additional corrections are necessary.

LHC dipoles have a two-in-one collar structure that breaks the left-right symmetry, giving rise to systematic even normal multipoles. These components are analysed in Ref. [7]: data show that the modification of the iron laminations implemented in the pre-series dipoles has been successful and that both b_2 and b_4 are within targets.

3 RANDOMS

The standard deviation of the measured main field and harmonics in the collared coil is shown in Fig. 4 (markers) for each manufacturer. The solid line represents the allowed budget for the random component. In section 6 we will show that the main source of the randoms is already in the collared coil, and therefore the comparison of collared coil standard deviations to beam dynamics budget is significant. Measured values are close or within the bounds already in this early stage of the production. The only exception is b_3, due to the drift that has been observed in the first 15 magnets. The random b_3 of the successive magnets is within the target of 1.5 units. In the same figure we also plotted the standard deviation of the multipoles of the distribution of all magnets. Also in this case, this quantity is close or within targets with the exception of b_3. This means that the allowed budget for the random part could be compatible with an installation scenario where magnets of all manufacturers are mixed in the arcs.

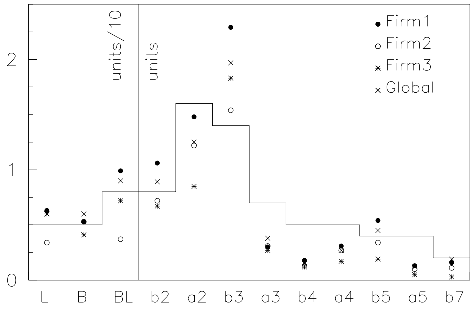

Figure 4: Standard deviation of magnetic length (L), main field (B), integrated main field BL), and low-order multipoles in the collared coil (markers) versus beam dynamics targets (solid line)

4 CORRELATIONS

Correlations between field harmonics measured in the collared coils and in operational conditions determine the possibility of steering the production through magnetic measurements carried out at the manufacturers [8, 9, 10]. Experimental data relative to b_3 are shown in Fig. 5. One observes very good correlations with a slope between 0.8 and 0.9. This value of the slope is due to the rescaling of multipoles by a factor $1/\kappa = 1/1.2$ since in the LHC dipoles the main field is enhanced by the iron yoke of 20 %. The deterministic part of the relation between harmonics in the collared coil and in the cold mass is

$$b_n^{cm} = \kappa b_n^{cc} + D_n$$

where D_n is negligible for multipoles with $n > 3$ (see [8]). The effect of cooling down, of persistent currents, of iron saturation and of Lorentz forces can be approximated at first order as additional offsets.

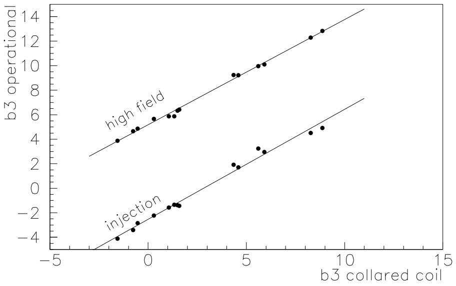

Figure 5: b_3 in the straight part of the collared coil versus b_3 at injection and at high field

The 7 magnets that have been tested cold feature a wide range of b_3 that is mainly due to difference in shim thickness. In a production phase where only nominal shims will be possibly used, the expected range of allowed multipoles will be much smaller. In this case, the above graph could be misleading, showing a poor correlation. Indeed, the quantity relevant to the dependence of field harmonics in operational conditions on the measurements in the collared coil is the standard deviation of the difference $b_n^{op} - \kappa b_n^{cc}$ (see Table 2). Comparison are given with the standard deviation of the harmonics in the collared coil. Data show that the variability of the collared coil is much larger than the variability due to cooling down, persistent currents, saturation and Lorentz forces, in agreement with previous estimates [11]. To steer field harmonics one has to compare these sigmas to the allowed ranges for the systematics. For b_3 and b_7 the range is much larger than the sigma (6 units against 0.4, and 0.4 units against 0.03 respectively). The case of b_5 is less confortable, since the range is 0.6 units and the correlation (one sigma) is 0.2: this quantity should be carefully monitored during the production. Since collared coil data give only estimates of the geometric component and no indication on persistent currents, correlations to operational conditions must especially rely on a careful control of the magnetization cable properties.

Table 2: Sigma of integrated main field and b_3, b_5, b_7 in the collared coil, and of differences between rescaled collared coil and operational conditions (see Eq. 4)

	BL	b_3	b_5	b_7
Collared coil	9.0	1.9	0.45	0.19
Injection - κ collared coil	4.3	0.4	0.14	0.03
High field - κ collared coil	3.6	0.2	0.15	0.02

5 CONCLUSIONS

We presented measurements of the magnetic field of the main LHC dipole, and comparison to beam dynamics targets. Systematic values of b_3 and b_5 in the first magnets were out of the allowed ranges. A change in the coil cross-section has been implemented. First data of 2 collared coils with the new cross-section show that we are close to acceptance ranges. Comparison between experimental data and allowed ranges for the systematics show that b_5 will be the most difficult component to control, since its random variation is large compared to the acceptance range.

The random part of the multipoles is within targets, with the exception of b_3 that has shown a large upward trend. Measurements show that we are close to a situation where the standard deviation of all magnets is within the budget allowed for the random component. Therefore, a mixing of the three manufacturers inside the ring could be tolerable for beam dynamics. This should be confirmed by a wider sample of measurements at 1.9 K.

We presented the dependence of the magnetic field measured in operational conditions on the collared coil measurements. This relation shows a good reproducibility; the collared coil is shown to be the main source of variablity in the magnetic field. Comparison to allowed ranges for beam dynamics show that correlations for b_5 are the most critical for the steering of the production.

6 ACKNOWLEDGEMENTS

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