CONTROLLING FIELD QUALITY IN MAGNET PRODUCTION

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Abstract

   The field quality measurements at room temperature of around 100 collared coils of the main LHC dipoles are analysed. Using correlations to field measurements at 1.9 K, comparison with beam dynamics limits are discussed. Both random and systematic components are analysed, allowing to pin out the most critical multipoles. Corrective actions that have been taken during the pre-series phase are presented; we focus on the low order systematic multipoles that are shown to be the most difficult components to steer. A preliminary analysis of the integrated main field and of its implications on the possible scenarios for the installation are also carried out.

INTRODUCTION

   Magnetic measurements are carried out with a 75 mm long rotating coil on 20 consecutive positions in longitudinal direction to cover the 15 m-long LHC dipoles. For each position, the field harmonics up to order 15 are measured, in both apertures. Each harmonics averaged over the dipole axis is compared to beam dynamics requirements, whilst spikes in the longitudinal profile help in detecting local defects during assembly.

   In this paper we will discuss our approach for quality control, identify targets for field shape, present limits to corrective actions during production and finally examine the status of field quality in the pre-series LHC dipoles. We will express units in 10^{-4}, at 17 mm reference radius.

QUALITY CONTROL

   In order to fix field-shape ranges for quality control, for each manufacturer, we select a sufficiently large group of data and we separate them into three sets: straight part, connection and non-connection heads. We compute the average and the σ for each set, rejecting cases clearly out of statistics [1], and we set control limits at $\pm 3.5\ \sigma$ (warning) and at $\pm 7\ \sigma$ (alarm). For Gaussian distributions, we should expect a single warning during the production. We use the same approach both for collared coils and for the cold mass. In the latter case, for a more stringent test, we compute the difference from collared coil harmonics, since the contribution of the iron yoke is very stable [2].

   Automatic checks of magnetic measurements allowed us to detect both faulty measurements (4 over 98) and assembly errors (2 over 98). We found the first error in collared coil 2002, having a big spike of 40 units in the main field, of 24 units in b_2, plus minor spikes in a_2, a_3 and b_3 along a length of 2 m in the central part. This was induced by the erroneous insertion of a second coil protection sheet, 0.5 mm thick, in the corresponding dipole section. We found the second error in collared coil 1027, showing a localized spike in b_2 of 5.5 units, with minor anomalies in b_3 and a_2. This was induced by a missing shim, 0.8 mm thick, along a length of 1.5 m, in the pole outer layer. We could predict its location by field simulations considering the sign of the faulty harmonics.

FIELD QUALITY TARGETS

   Targets for field shape harmonics are given in terms of systematic (average along the ring), random (σ for one arc – a priori the same in each arc) and uncertainty (σ of the average per arc) [3]. Random and uncertainty targets result from a compromise between what is needed for beam stability and what can be reached with realistic mechanical tolerances. The final choice mostly relies on experience of previous machines [4,5]. Systematic targets and their acceptance ranges, instead, result from beam dynamics considerations only: any target is achievable by the design of the coil cross-section, whilst keeping it within the allowed range for the whole production is the true challenge. Ranges for systematic harmonics at injection and at high energy differ by an offset resulting from persistent currents, iron saturation and electro-magnetic forces [6]. Their intersection determines the effective range for field quality. Finally, targets and ranges for collared coil harmonics result from correlation of harmonics measured in warm and in cold conditions.

   The criticality of each harmonic is proportional to the ratio between its measured spread during production and the allowed range for the systematic value. In Table 1, lower order harmonics are evaluated for already produced collared coils. With our criterion, b_5, a_2 and a_4 are the most critical, whilst b_3, b_4 and a_3 are the easiest to control.

Table I: Measured random component versus the allowed range for the systematic, given in Ref. [3].

	b_3	b_5	b_7	b_2	b_4	a_2	a_3	a_4
σ	1.50	0.45	0.17	0.70	0.11	1.30	0.40	0.30
range	7.00	0.70	0.48	2.20	0.74	2.00	1.40	0.28

LIMITS TO CORRECTIVE ACTIONS

   The time sequence of the dipole production shows that we should take corrective actions already on collared coils in order to shorten the feedback delay. A correlation between measurements at 300 K in the industry and in cold operational conditions is needed for an effective steering of the field quality.

   A predictive magnetic model is another key tool, since forecasting absolute values of field harmonics is essential in conceiving prototypes. With our numerical model which also evaluates iron contributions and coil deformations [6-9], we obtained an agreement between measured and expected values of 1 to 2 times the measured random component. Indeed, b_3 agrees within 3

units, b_5 within 1 unit and b_7 within 0.4 units. If deformations are neglected, the agreement on b_5 becomes much worse (4 σ, i.e. 2 units) [8-9]. This is however insufficient for steering the field quality, and iterations on the coil design are needed. In this case, our model is used in differential, to enhance the precision. For the LHC dipoles we carried out a comparison between model and measurements in three different cases:

- In reshaping the iron insert to reduce the systematic values of b_2 and b_4 [10].
- In resizing the polar shims to optimize the systematic values of b_3, b_5 and b_7 [11, 12].
- In choosing the size of the mid-plane insulation to optimize the systematic values of b_3 b_5 and b_7 [13].

The agreement, always found within 20%, is considered excellent. Indeed, just to evaluate the effect of a coil deformation we may use a different realistic hypothesis, which may already lead to differences up to 10%.

In comparing the harmonics of the collared coils with cold measurements we observe a linear correlation with a slope close to the theoretical value of 1/1.18, induced by the iron yoke effect of 18% on the main field [14]. The spread around the linear fit is to be compared to the allowed ranges for systematic components [3]. This spread is large only for a_2, a_4 and b_5. On the other hand, the influence of persistent currents on b_3, b_5 and b_7 seems to be well understood and reproducible.

FIELD QUALITY STATUS

Systematic harmonics

All systematic skew and even normal harmonics are within targets. The corrective action taken at the end of the prototype phase on the insert shape to correct b_2 and b_4 [10] has been effective. The odd normal harmonics are shown in the right part of Fig. 1, and are still too large for the second cross-section.
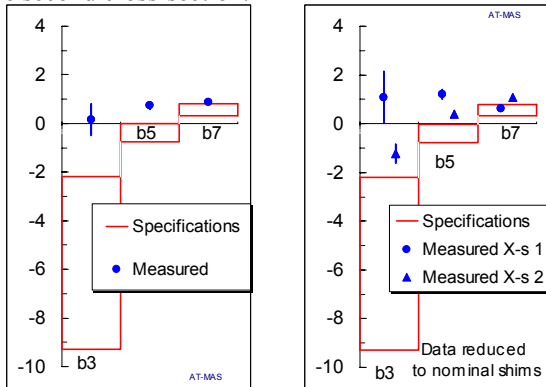

Figure 1: Systematic b_3, b_5 and b_7 (blue dots) versus beam dynamics targets (red), raw data (left) and data separated by cross-section, reduced to nominal shims (right).

In order to reduce b_3 and b_5, we decided on a reshaping of the internal copper wedges by less than 0.4 mm, keeping the same coil and collar shape [15]. Our aim was shifting b_3 by -3.5 units, b_5 by −1.35 units and b_7 by

+0.18 units. The observed effect instead was -3 units for b_3, -0.80 units for b_5 and +0.45 for b_7. We decided to change the cross section after 9 collared coils. Afterwards we saw an unexpected trend of 7 units of b_3 in the first 15 collared coils. We could explain only a part of the trend (2 units) by out-of-tolerance copper wedges [16].

Random harmonics

In Fig. 2, we show random harmonics in collared coils, reduced to nominal shims. Data relative to the first cross-section shows larger spreads than in the second cross-section, due to a learning process during the production. The random imperfections are well within specifications or at the limit as for the integrated main field BdL, for b_2 and for b_5. Only b_3 is out-of-tolerance because of the trend in first cross-section. This makes the installation scenario of a full dipole mixing compatible with beam dynamics targets from the point of view of geometric harmonics.
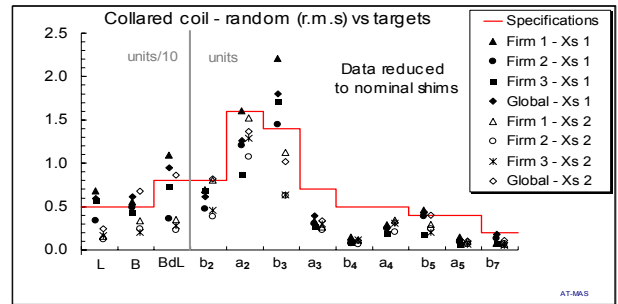

Figure 2: Random multipoles: targets versus measured values per manufacturer and for the full production, separated by cross-sections, reduced to nominal shims.

First estimates of uncertainty

We observe a non-negligible difference between manufacturers in the following quantities:

- Main field: approx. 20 units difference between Firm3 and the other Firms.
- b_2: 1.5 units smaller (larger) value in aperture 1 (aperture 2) for Firm3 than elsewhere, probably due to different collar manufacturers.
- b_5: 1 unit of differences between Firm1 and Firm2, Firm3 being in between.
- b_7: up to 0.4 units of difference between Firm1 and Firm2, Firm3 being in between.

Magnetic length, b_3, b_4 and skews show no systematic differences between manufacturers.

OPEN POINTS

Systematic odd normal multipoles

The present large values of systematic b_5 and b_7 seem to have a negligible impact on beam stability. However, in case of a drift, these multipoles can go out-of-tolerance. Moreover, at high field, b_3 should be corrected using chromatic sextupoles, thereby reducing operational flexibility. In order to reduce b_3 b_5 and b_7 a solution is to

increase the thickness of the insulation in the coil mid-plane [17]. An additional layer of 0.1 mm insulation would recover safer values for these multipoles, with a minimal cost. A test on a 1 m-long model is in progress, showing results in agreement with models [13].

Systematic differences in integrated main field

In collared coils 30 to 80, the integrated main field is systematically larger by about 20 units in Firm3, as shown in Fig. 3. This brings the random *BdL* at the limit of the target and stem in a variation of the main field in the straight part, whilst the magnetic length does not show relevant differences between manufacturers. A difference of 56 μm (0.2%) in the coil radius can explain it. Instead, nor copper wedge dimension errors, neither differences in collar manufacturers (contrary to the case of b_2) can explain this difference. We can correct the effect by acting on ferromagnetic laminations to compensate with a higher or lower magnetic length the offset in the main field. A decrease of magnetic length in Firm3 and an increase elsewhere according to the maximal values given in the dipole specification should allow to compensating half of this systematic offset. Data in operational conditions partially confirm this offset, but more statistics would be desirable before carrying out the corrective action.
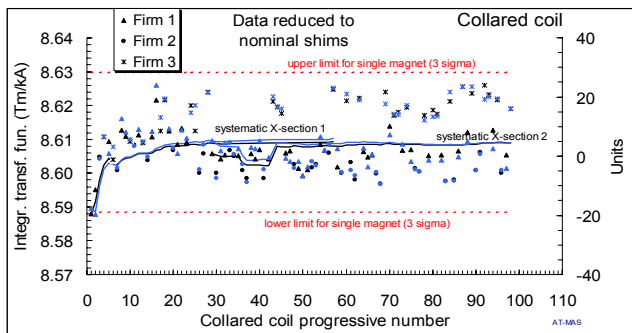

Figure 3: Integrated main field in the collared coil: measured data (markers) and ±3σ limit (dotted lines). Data reduced to nominal shims.

Field quality variation after re-collaring

Four magnets have been re-collared for electrical problems or assembly faults. Field quality measurements showed a non-negligible systematic variation of odd normal multipoles: the larger effect is a positive change of b_5 of around 0.5 units. This could be due to a plastic deformation of the coil or maybe of the collars. Indeed, this should not play a relevant role in the field quality control since we expect to collar more than once only a small fraction of collared coils.

CONCLUSIONS

The magnetic field of 98 collared coils, 56 cold masses and 24 cryomagnets has been measured. Magnetic measurements at room temperature are being successfully used as a tool to detect faulty components or assembly procedures. Two collared coils have been intercepted for anomalies in magnetic field, and in both cases assembly errors have been found. The automatic procedures to screen magnetic measurements are active. Measured random harmonics are within specifications for beam dynamics [3]. The hard part is steering systematic harmonics, like a_2 a_4 and b_5 where the allowed range is small compared to the random part.

Our capability of modelling field quality in the collared coil is rather good [10]. Sensitivities matrices can be estimated with 20% error. The absolute agreement between model and measurements is within two times the random component, coil deformations playing a strong role for the b_5 [8-9]. The steering of field quality should be based on collared coil data, due to the delay of months between coil assembly and final tests at 1.9 K. Correlations between collared coil data and measurements at 1.9 K are rather good since the contribution of persistent currents, saturation and Lorentz forces is well reproducible, but they should be carefully monitored during the whole production.

Systematic skew and even normal multipoles are within targets. For odd normal multipoles we applied corrective action on the coil cross-section [15], and the present values provide the required beam stability. However, we are at the limit of the targets for b_3, b_5 and b_7 hence an additional corrective action will be probably necessary.

A corrective action based on a change of the magnetic length is in preparation to compensate part of the 20 units difference in BdL between Firm3 and the other manufacturers.

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