STATUS REPORT ON FIELD QUALITY IN THE MAIN LHC DIPOLES

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Abstract

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 assessment 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

<table>
<thead>
<tr>
<th></th>
<th>( \delta b_3 )</th>
<th>( \delta b_5 )</th>
<th>( \delta b_7 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>3.6 ± 1.0</td>
<td>1.3 ± 0.3</td>
<td>0.15 ± 0.10</td>
</tr>
<tr>
<td>Measurements</td>
<td>4.1 ± 0.3</td>
<td>1.2 ± 0.2</td>
<td>0.35 ± 0.13</td>
</tr>
</tbody>
</table>

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)
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 system-
atic $b_3$ 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 manufactur-
ers (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 vari-
ability (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 be-
tween the manufacturers after the first 10 magnets. Man-
facturer 1 has an average of 1.8 units, whilst firms 2 and
3 are around 1 unit. If the same difference will be pre-
served 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 manufactur-
ers (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 mag-
ets: 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 be-
tween firm 2 and firm 1,3 are preserved (see Fig. 3).

Data relative to the new cross-section show that the mea-
urements are now within or close to the allowed range for
low-order multipoles (see Figs. 1-3). The effect on the in-
tegrated 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 (mark-
ers) 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 sig-
nificant. Measured values are close or within the bounds
already in this early stage of the production. The only ex-
ception 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 dis-
tribution 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 com-
patible 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 multi-
poles 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](image)

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 all magnets is within the budget allowed for the random component. Therefore, there is potential for steering the production.

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 variability 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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7 REFERENCES

[1] L. Walckiers et al, these proceedings.