EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 625

AN ESTIMATE OF MULTIPOLAR ERRORS IN THE LHC DIPOLES

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Abstract

Magnetic measurements of 60 collared coils and of 14 cryomagnets are available for the LHC dipoles. These data are used to work out an estimate of the systematic and random components of the field harmonics, in the hypothesis of a complete mixing of the manufacturers.

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Geneva, 20 December 2002

1. Introduction

The magnetic field of two third of the collared coils of the pre-series LHC dipoles has been measured at room temperature [1], and of 14 cryomagnets at 1.9 K in operational conditions [2]. At an early stage of the pre-series production, a strong evidence of an important out of tolerance of the systematic multipoles b_3 and b_5 was found [3]. Corrective actions have been taken by a reshaping of the inner layer copper wedges to obtain an improved layout of the conductors [1]. 25 collared coils with this second coil cross section have been measured, showing a relevant improvement of the b_3 and b_5 and some deterioration of b_7. Indeed, these multipoles are still out of the field quality specifition given in [4].

In this paper we give an estimate of the multipolar content of the main LHC dipoles that are being produced (i.e., with the second cross-section) based on measurements. Previous estimates [5] were relying on simulations and on the experience of previous projects. Systematic and random parts are evaluated in an installation scenario based on the hypothesis of a complete mixing of the manufacturers along the machine. This estimate will be used by accelerator physicists to evaluate if additional corrective actions are needed to improve dipole field quality.

2. Available data

The number of collared coils and cryomagnets whose magnetic field is used in our analysis is shown in Table I. For the collared coil, a very poor statistic is available for the second cross-section produced by Firm 3. For cryomagnets, only a few data are available for Firms 2 and 3, and for cross-section 2.

Table I: available magnetic measurements of collared coils and cryomagnets.

	Collared coils				Cryomagnets			
	Total	Firm 1	Firm 2	Firm 3	Total	Firm 1	Firm 2	Firm 3
X-section 1	35	13	11	11	13	10	1	2
X-section 2	25	15	7	3	1	1	0	0
Total	60	28	18	14	14	11	1	2

3. Estimate of systematics

- Straight part of the collared coil (measurements). The systematic components c_n^{ccs} are defined as the average of the three averages relative to each manufacturer. In the case of the non-allowed multipoles, all the available data are used (60 collared coils). For the allowed multipoles (odd normal multipoles) we only consider data relative to the new cross-section (25 collared coils) and we reduce data to nominal shims. The contribution of dipole heads is not included in this estimate, since they are affected by the iron yoke, especially with regard to b_2 and b_4. We compute separate averages for each aperture: indeed, only in the case of b_2 and b_4 there is evidence of a systematic difference between the two apertures. This symmetry break is due to the two-in-one structure of the LHC dipole cross-section.

Table II: best estimate for systematic c_n^{ccs} in the collared coil straight part, new cross-section.

	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	-0.51	-0.29	-1.40	-0.14	-0.09	-0.03	0.27	0.00	0.00	0.00	1.07	0.01	0.00	0.01	0.54	0.01	0.00	0.00	0.77	0.00
Ap. 2	0.78	0.06	-1.29	-0.10	0.07	0.01	0.39	-0.01	-0.02	0.01	1.08	0.01	0.00	0.01	0.54	0.01	0.00	0.00	0.77	0.00

- <u>Correlations from collared coil to injection or high field (measurements)</u>. The collared coil data are projected to high energy and injection using correlations of all measured cryomagnets, making the assumption that these correlations are independent of the cross-section type. We evaluate the difference $c_n^{off,high}$ between measured values at high field c_n^{high} and the measured values of the collared coil straight part c_n^{ccs} divided by the measured main field rescaling by a factor k=1.18 due to the iron yoke.

$$c_n^{off,high} = c_n^{high} - \frac{c_n^{ccs}}{k}$$

A similar formula holds for the injection case

$$c_n^{off,inj} = c_n^{inj} - \frac{c_n^{ccs}}{k}$$

These correlations also include the contribution of dipole heads that is not included in the collared coil straight part c_n^{ccs}. Owing to the fact that the statistics on cryomagnets from Firms 2 and 3 is very poor, a simple average is taken over all cryomagnets (see Table III). We therefore assume that correlations are not dependent on the manufacturer. This hypothesis will be verified when more data are available.

Table III: differences $c_n^{off,inj}$ (or $c_n^{off,high}$) between injection c_n^{inj} (or high field c_n^{high}) and collared coil straight part c_n^{ccs} divided by k.

Inj-cc/k	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	1.75	-0.13	-2.25	-0.14	0.07	0.00	0.72	0.03	-0.02	0.00	-0.34	0.03	-0.01	0.00	0.16	-0.02	0.00	0.00	0.02	-0.04
Ap. 2	-1.76	-0.42	-2.18	-0.15	-0.07	-0.04	0.71	0.03	0.02	-0.02	-0.33	0.03	0.01	0.00	0.16	-0.02	0.01	-0.01	0.02	-0.04
High-cc/k	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	0.14	-0.23	5.34	-0.17	0.28	-0.03	-0.54	0.04	-0.02	0.00	0.02	0.03	0.00	0.00	-0.08	-0.01	0.00	0.00	-0.01	-0.04
Ap. 2	-0.14	-0.36	5.39	-0.14	-0.28	0.00	-0.55	0.03	0.02	-0.01	0.03	0.03	0.01	0.00	-0.08	-0.01	0.01	-0.01	0.00	-0.04

- <u>Values at high energy and injection (expected)</u>. Values at high field $c_n^{e,high}$ and at injection $c_n^{e,inj}$ (see Table IV) are computed from the collared coils data (Table II) divided by the measured main field rescaling k and adding the offsets of Table III.

$$c_n^{e,high} = c_n^{off,high} + \frac{c_n^{ccs}}{k} \qquad c_n^{e,inj} = c_n^{off,inj} + \frac{c_n^{ccs}}{k}$$

Table IV: expected values at injection $c_n^{e,inj}$ and at high field $c_n^{e,high}$.

Injection	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	1.31	-0.37	-3.44	-0.26	-0.01	-0.03	0.95	0.03	-0.02	-0.01	0.57	0.04	-0.01	0.01	0.62	-0.01	0.00	0.00	0.67	-0.04
Ap. 2	-1.10	-0.37	-3.27	-0.23	-0.01	-0.04	1.04	0.02	0.00	0.00	0.58	0.04	0.01	0.00	0.62	-0.01	0.01	-0.01	0.67	-0.04
High field	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	-0.29	-0.47	4.15	-0.29	0.20	-0.05	-0.31	0.04	-0.01	-0.01	0.93	0.03	0.00	0.01	0.38	0.00	0.00	0.00	0.64	-0.03
Ap. 2	0.52	-0.31	4.29	-0.22	-0.22	0.01	-0.22	0.03	0.00	0.00	0.94	0.04	0.01	0.01	0.38	0.00	0.01	-0.01	0.65	-0.04

- <u>Beam screen (simulations).</u> This contribution c_n^{bs} is evaluated through simulations [6], since no measurement of the final beam screen is available. Measurements of the magnetic effect of a previous design of the beam screen showed good agreement with simulations [7].

Table V: beam screen contribution c_n^{bs} (simulations).

b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
0.00	0.00	-0.42	0.00	0.00	0.00	0.39	0.00	0.00	0.00	-0.24	0.00	0.00	0.00	0.15	0.00	0.00	0.00	-0.08	0.00

- Effect of decay (expected): we measure the field harmonics changes during 1000 s at 760 A (injection), with a precycle of 30 minutes at 11850A (high energy). The average of these values are rescaled to an infinitely long flat top (corresponding to a 10% increase with respect to the cycle used for measurements); this provides the expected values c_n^{dec} of Table VI. This contribution reduces the absolute values of b_3 and b_5 at injection, and is negligible for the other multipoles.

Table VI: measured decay c_n^{dec} of multipoles.

b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
-0.03	0.00	1.73	0.03	-0.01	0.05	-0.29	0.00	0.00	0.00	0.04	-0.01	0.00	0.00	-0.02	0.00	0.00	0.00	0.00	0.00

- Effect of ramp (expected): the average c_n^{dec} of the influence on field harmonics due to a ramp rate of 10 A/s at injection is given of Table VII. This small systematic effect (less than 0.1 units) is evaluated on the basis of measurements of different cycles, using a linear regression to the nominal value of the rate of 10 A/s.

Table VII: measured effect of ramp c_n^{ramp} on multipoles.

b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7
0.01	0.05	-0.04	0.00	0.00	0.03	-0.02	0.00	0.00	0.01	0.00

- Values in operational conditions (expected). The sum of the beam screen (Table V) and of the expected values (Table IV) gives the expected systematic component at high field $c_n^{op,high}$ and at the beginning of the injection $c_n^{op,inj,beg}$.

$$c_n^{op,high} = c_n^{e,high} + c_n^{bs} = c_n^{off,high} + \frac{c_n^{ccs}}{k} + c_n^{bs}$$

$$c_n^{op,inj,beg} = c_n^{e,inj} + c_n^{bs} = c_n^{off,inj} + \frac{c_n^{ccs}}{k} + c_n^{bs}$$

At the end of injection $c_n^{op,inj,end}$ we have to add also the contribution of the decay (Tables IV+V+VI).

$$c_n^{op,inj,end} = c_n^{e,inj} + c_n^{dec} + c_n^{bs} = c_n^{off,inj} + \frac{c_n^{ccs}}{k} + c_n^{dec} + c_n^{bs}$$

At the end of the ramp $c_n^{op,ramp,end}$ we have to add the contribution of the ramp (scaled to the ratio between injection and high energy $\lambda = 760/11850$) to the estimate at high field $c_n^{op,high}$ (Tables IV+V+VII). Indeed, this rescaling reduces the systematic contribution of the ramp to less than 0.01 units.

$$c_n^{op,ramp,end} = c_n^{e,high} + c_n^{ramp} + c_n^{bs} = c_n^{off,high} + \frac{c_n^{ccs}}{k} + \lambda c_n^{ramp} + c_n^{bs}$$

Table VIII: best estimate of the integral values at beginning of the injection $c_n^{op,inj,beg}$, at the end of the injection $c_n^{op,inj,end}$, at the end of the ramp $c_n^{op,ramp,end}$ and at high field $c_n^{op,high}$ (beam screen included).

Inj. beg.	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	1.31	-0.37	-3.86	-0.26	-0.01	-0.03	1.33	0.03	-0.02	-0.01	0.32	0.04	-0.01	0.01	0.77	-0.01	0.00	0.00	0.59	-0.04
Ap. 2	-1.10	-0.37	-3.69	-0.23	-0.01	-0.04	1.43	0.02	0.00	0.00	0.34	0.04	0.01	0.00	0.77	-0.01	0.01	-0.01	0.59	-0.04
Inj. end	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	1.28	-0.37	-2.13	-0.23	-0.02	0.02	1.04	0.04	-0.02	-0.01	0.36	0.03	-0.01	0.01	0.74	-0.01	0.00	0.00	0.59	-0.04
Ap. 2	-1.12	-0.37	-1.96	-0.19	-0.02	0.01	1.14	0.02	0.00	0.00	0.38	0.03	0.01	0.00	0.74	-0.01	0.01	-0.01	0.60	-0.04
End ramp	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	-0.29	-0.47	3.73	-0.29	0.20	-0.05	0.07	0.04	-0.01	-0.01	0.69	0.03	0.00	0.01	0.53	0.00	0.00	0.00	0.56	-0.03
Ap. 2	0.52	-0.31	3.87	-0.22	-0.22	0.01	0.17	0.03	0.00	0.00	0.70	0.04	0.01	0.01	0.53	0.00	0.01	-0.01	0.57	-0.04
High field	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Ap. 1	-0.29	-0.47	3.73	-0.29	0.20	-0.05	0.07	0.04	-0.01	-0.01	0.69	0.03	0.00	0.01	0.53	0.00	0.00	0.00	0.56	-0.03
Ap. 2	0.52	-0.31	3.87	-0.22	-0.22	0.01	0.17	0.03	0.00	0.00	0.70	0.04	0.01	0.01	0.53	0.00	0.01	-0.01	0.57	-0.04

The best estimate is given by the average values between aperture 1 and 2 for all multipoles with the exception of b_2 and b_4, where two different values for each aperture should be used.

- With respect to beam dynamics limits given in [4], we are out of specification for the following multipoles:
    - b_3 at high field (3.8 units against a maximum limit of 3.0 units)
    - b_5 at injection (1.4 units against a maximum limit of 1.1 units)
    - b_7 at injection (0.35 units against a maximum limit of 0.1 units)

  The others multipoles are within specifications. In particular, the corrective action carried out during the prototype phase on the ferromagnetic insert to optimise b_2 and b_4 has been effective [8].

4. Estimate of randoms

- Randoms in the collared coil (measured). In Table IX the standard deviation of multipoles measured in the straight part of all collared coils is given. This is a realistic estimate for the skew and even normal multipoles. We only exclude collared coil number 1001, which had a very high b_3 due to non-nominal shims, and is installed in the string. For odd normal multipoles these estimates can be considered as an upper bound, since they reflect the additional variability due to the cross-section change and to the non-nominal shims. We recall that, as in the case of systematics, these values must be divided by the main field increase of 1.18 due to the iron yoke.

Table IX: best estimate of the random r_n^{ccs} in the collared coil straight part.

b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
0.69	1.33	2.77	0.38	0.11	0.28	0.57	0.11	0.04	0.08	0.29	0.04	0.01	0.03	0.14	0.03	0.00	0.00	0.02	0.05

The analysis of data separated according to different cross-sections and reduced to nominal shims gives lower randoms for b_3 and b_7 (see Table X). In particular, the second cross-section collared coils systematically feature a lower sigma. Therefore the estimate given in Table IX for odd normal multipoles is pessimistic and could be reviewed when more data at 1.9 K are available.

Table X: best estimate of the odd normal random r_n^{ccs} in the collared coil straight part separated according to different cross-sections and reduced to nominal shims.

	b3	b5	b7
Cross-section 1	1.80	0.43	0.18
Cross-section 2	1.12	0.42	0.10

- <u>Randoms due to correlations from collared coil to injection and high field (measured).</u> We evaluate the standard deviation $r_n^{off,high}$ (and $r_n^{off,inj}$) of the differences between the multipoles measured at high field c_n^{high} (and injection c_n^{inj}) and measured in the collared coil straight part c_n^{ccs} rescaled by the main field increase *k*:

$$r_n^{off,high} = \sigma(c_n^{high} - \frac{c_n^{ccs}}{k}) \qquad r_n^{off,inj} = \sigma(c_n^{inj} - \frac{c_n^{ccs}}{k})$$

  Comparison of these data with Table IX shows that the collared coil is the main source of multipole variability. In the estimate for even normal multipoles we excluded cryomagnet 1002 since it was assembled without shims between insert and iron yoke (the so called Chinese hat).

Table XI: sigma $r_n^{off,high}$, $r_n^{off,inj}$ of differences between rescaled collared coil and injection or high field

	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
High	0.37	0.25	0.22	0.08	0.04	0.04	0.12	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.03
Inj.	0.24	0.44	0.47	0.06	0.06	0.15	0.15	0.03	0.02	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02

- <u>Randoms of the decay (expected)</u>. Also in this case, we rescale values that are measured with a pre-cycle of 30 mintues of flat top to an infinite flat top by adding 10%, as for the systematic. These expected values are much lower than the initial estimates based on measurements on 1-m long models [9].

Table XII: sigma r_n^{dec} of the decay, rescaled to a long flat top.

b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7
0.11	0.24	0.44	0.07	0.05	0.09	0.10	0.03	0.02	0.04	0.03

- <u>Randoms of the ramp (measured)</u>. These are the standard deviations of the measured effect of the ramp at 10A/s and at injection on field harmonics. Also in this case, the effect is small (0.2 units at most) and becomes negligible when is rescaled to high field.

Table XIII: sigma r_n^{ramp} of the ramp effect.

b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7
0.06	0.19	0.18	0.02	0.02	0.07	0.04	0.01	0.01	0.02	0.02

- <u>Randoms in operational conditions (expected)</u>. The final estimate for the randoms in operational conditions is given in Table XII, summing in quadratures the rescaled sigma of the collared coil straight part r_n^{ccs} to the correlations $r_n^{off,inj}$ and $r_n^{off,high}$; at the end of the injection and of the ramp we also have to add the decay r_n^{dec} and rescaled ramp λr_n^{ramp} respectively. These formulas are valid in the hypothesis of a negligible cross-correlation between the different terms; data from the first 14 cryomagnets and related collared coils show that these correlations are small. Indeed, this quantity should be monitored during the production.

$$r_n^{op,inj,beg} = \sqrt{\left(\frac{r_n^{ccs}}{k}\right)^2 + \left(r_n^{off,inj}\right)^2}$$

$$r_n^{op,inj,end} = \sqrt{\left(\frac{r_n^{ccs}}{k}\right)^2 + \left(r_n^{off,inj}\right)^2 + \left(r_n^{dec}\right)^2}$$

$$r_n^{op,ramp,end} = \sqrt{\left(\frac{r_n^{ccs}}{k}\right)^2 + \left(r_n^{off,high}\right)^2 + \left(\lambda r_n^{ramp}\right)^2}$$

$$r_n^{op,high} = \sqrt{\left(\frac{r_n^{ccs}}{k}\right)^2 + \left(r_n^{off,high}\right)^2}$$

Table XIV: expected randoms in operational conditions.

	b2	a2	b3	a3	b4	a4	b5	a5	b6	a6	b7	a7	b8	a8	b9	a9	b10	a10	b11	a11
Inj. Beg	0.63	1.21	2.39	0.33	0.11	0.28	0.50	0.10	0.04	0.08	0.24	0.04	0.02	0.03	0.12	0.03	0.02	0.01	0.03	0.04
Inj. End	0.64	1.24	2.43	0.34	0.12	0.29	0.51	0.10	0.04	0.09	0.25	0.05	0.02	0.04	0.12	0.03	0.02	0.03	0.04	0.05
End ramp	0.69	1.16	2.36	0.33	0.10	0.24	0.50	0.10	0.04	0.07	0.24	0.04	0.02	0.02	0.12	0.03	0.02	0.01	0.03	0.05
High	0.69	1.16	2.36	0.33	0.10	0.24	0.50	0.10	0.04	0.07	0.24	0.04	0.02	0.02	0.12	0.03	0.02	0.01	0.03	0.05

- With respect to beam dynamics limits given in [4], we have a higher random b_3 (2.5 units against 1.4 specified). In the case of b_2, a_2, b_5 and b_7, values are similar to what specified, whilst the a_3, b_4 and a_4 are much lower than previous estimates.

5. Conclusions

We have given estimates of the expected field harmonic in the main LHC dipoles based on magnetic measurements of 60 collared coils and 14 cryodipoles, assuming an installation scenario where all the cold mass assemblers and cable manufacturers are mixed along the machine. Systematic values of b_3, b_5, and b_7 are outside the specification given in [4] of 0.8, 0.3 and 0.25 units respectively. The other systematic multipoles are within specifications. Random components are higher than expected for b_3; this is mainly due to the change of cross-section that has been implemented to correct the odd normal multipoles. This estimate could be probably biased by the low statistics and could be reviewed in the future. The other random components either agree with previous estimates (b_2, a_2, b_5 and b_7) or are much lower (a_3, b_4 and a_4).

6. Acknowledgements

We wish to acknowledge S. Fartoukh for very helpful comments and criticism.

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