Report on field quality in the main LHC dipole collared coils: May-June 2002

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This report gives data relative to field quality measured in collared coils during the period May 1st–June 30th 2002, comparison to beam dynamics targets and status of the production holding points. Updated graphs can be found in the LHC field quality observatory http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs.html. Please note that the web address has changed.

1. Measured magnets

- 6 collared coils have been measured (collared coils 33rd to 38th)
    - 4 Ansaldo (HCMB__A001-02000009, HCMB__A001-02000010, HCMB__A001-02000012 and HCMB__A001-02000013)
    - 2 Alstom (HCMB__A001-01000016, HCMB__A001-01000017)

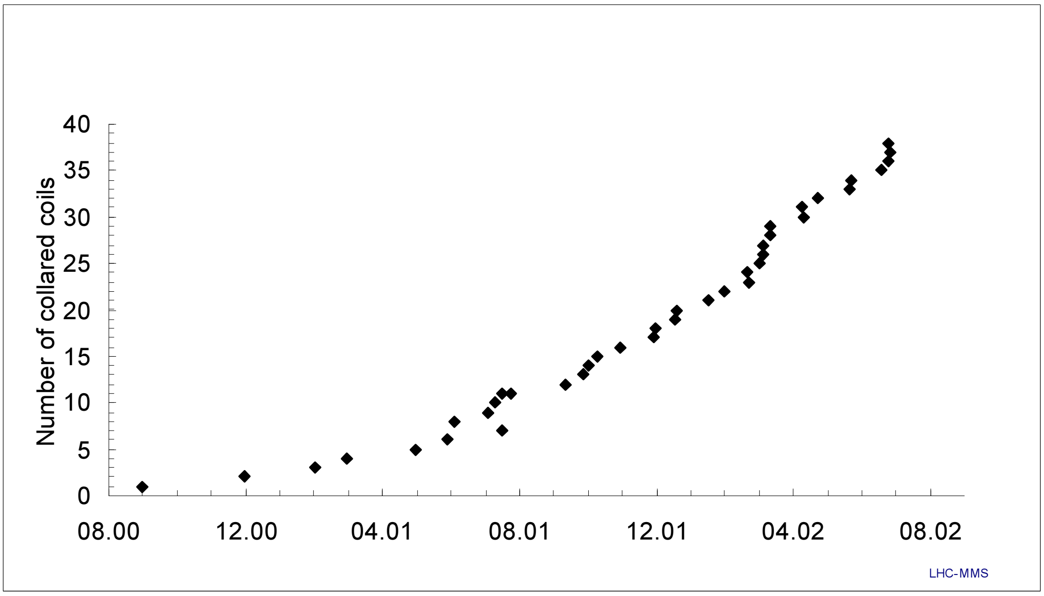

Fig. 1: Number of measured collared coils versus time

- Beam dynamics targets for systematics are worked out using correlations with 7 cryomagnets tested at 1.9 K.

2. Assembly data

- Cross section: Ansaldo 9-10 have X-section 1 (the old one), Ansaldo 12-13 and Alstom 16-17 have X-section 2 (the new one).
- Shims:
  - Azimuthal sizes of Ansaldo 12-13 coils are 0.1-0.15 mm larger than the nominal (both inner and outer layer), and therefore thinner shims have been used (see Table I). This should not be related to the new cross-section, where the inner layer only has been changed. Larger coils have also been measured for 14, 15 and 16 that have not been collared yet. The problem is under investigation.
  - The remaining collared coils have nominal shims.

Table I: Shims thickness and coil cross-section type of measured collared coils.
Nominal shims: 0.2 mm inner layer, 0.8 mm outer layer

Magnet Number	Magnet name		Shim (mm) Inner	Shim (mm) Outer	X-section
33rd	HCMB__A001	2000010	0.20	0.80	1
34th	HCMB__A001	2000009	0.20	0.80	1
35th	HCMB__A001	1000016	0.20	0.80	2
36th	HCMB__A001	2000013	0.10	0.70	2
37th	HCMB__A001	2000012	0.10	0.70	2
38th	HCMB__A001	1000017	0.20	0.80	2

3. Magnetic length and transfer function

- Magnetic length of collared coils 33rd to 38th are within 1 sigma of the allowed random per arc (see Fig. 2). No difference between old and new cross-section is observable, as expected.

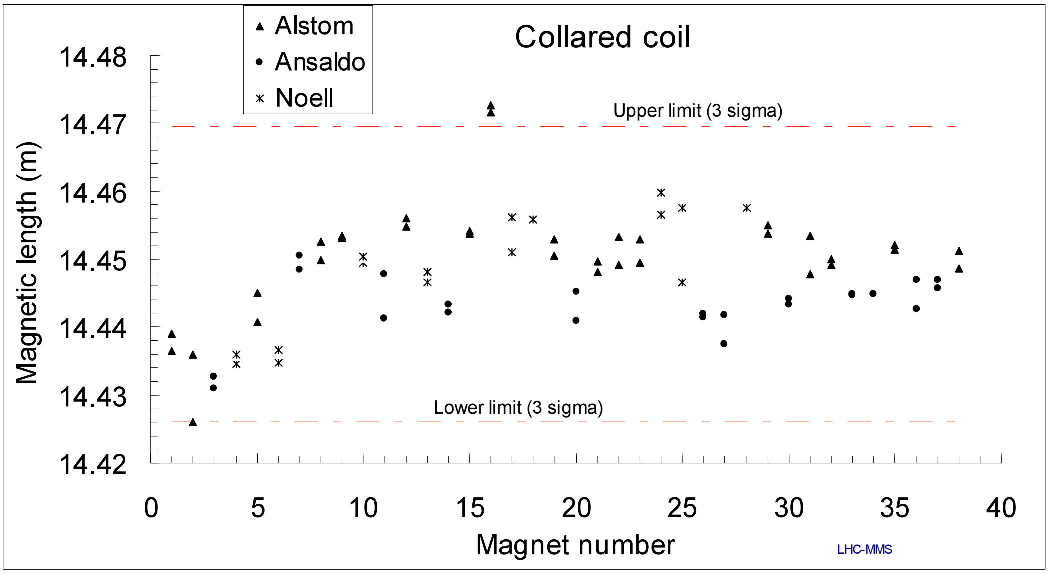

Fig. 2: Magnetic length of the measured collared coils

- Main field in the central part of Ansaldo 12 and 13 (collared coils 37th and 36th in Fig. 3) is 4.5 sigma lower than the average. This is partly due to the non-nominal shims (0.1 mm less on both layers) that reduce the main field of around 11 units in the collared coil (i.e., around 2 times the specified sigma). When this effect is corrected, collared coils 36th and 37th fall in the lower part of the 3 sigma range (see Fig. 4). A corrective action will be taken on both magnets, adding ferromagnetic laminations to increase the magnetic length. This should allow to recovering an integrated transfer function within the 3 sigma limit. This procedure, foreseen in the specification, will be tested for the first time.

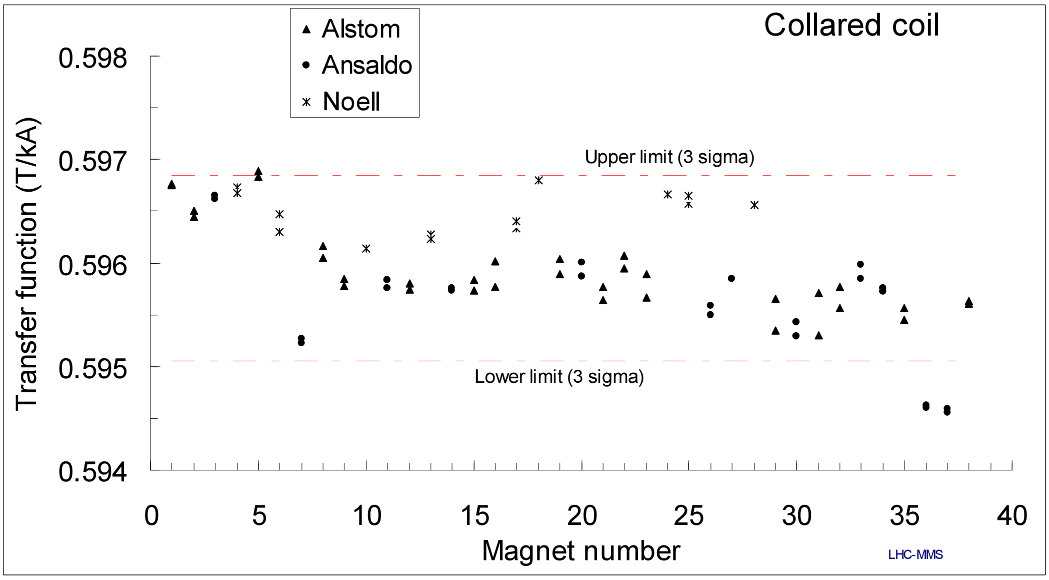

Fig. 3: Average main field in the straight part of the measured collared coils

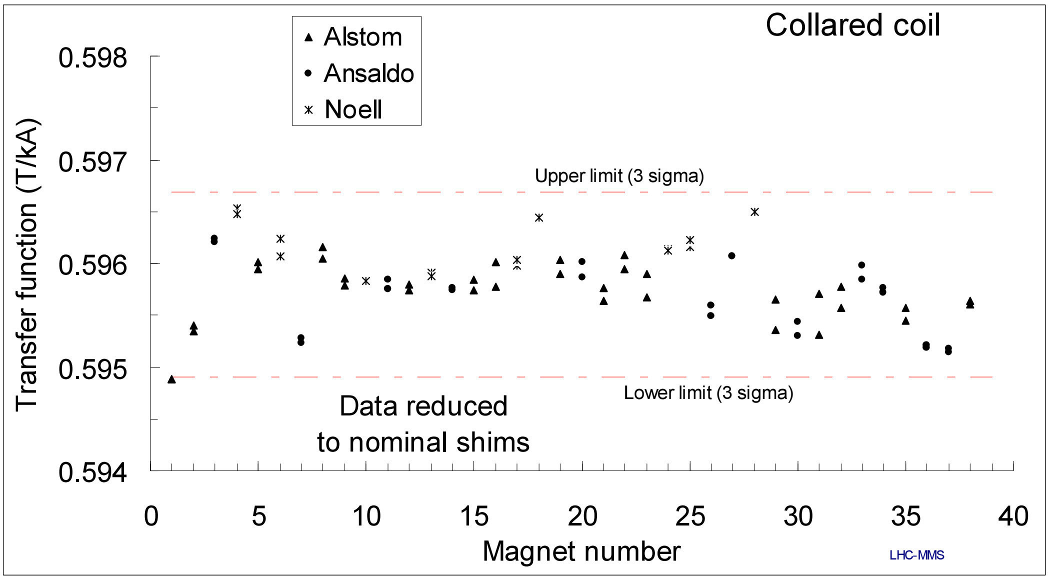

Fig. 4: Average main field in the straight part of the measured collared coils. Data reduced to nominal shims

- Integrated transfer function reduced at nominal shims of magnets 33rd to 38th is within 2 sigma of the allowed random per arc (see Fig. 5). In the last 15 collared coils we start to observe some systematic differences in the integrated transfer function between the three firms. Indeed, values are always within the 3 sigma bound. We recall that the only limit relevant to beam dynamics is on the integrated main field (see also Appendix B).

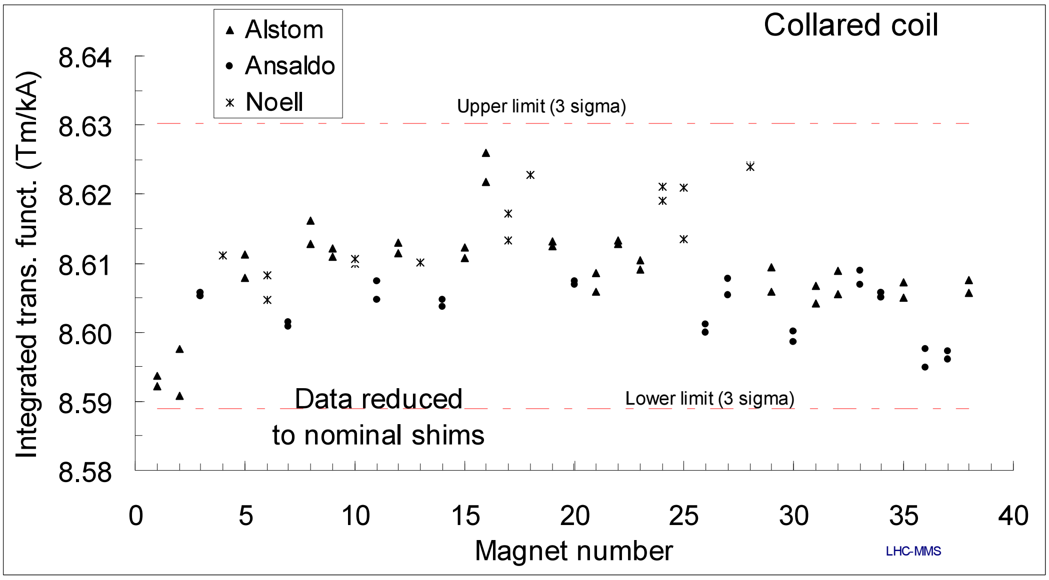

Fig. 5: Integrated transfer function in the measured collared coils. Data reduced at nominal shims.

4. Estimated coil waviness

- Coil waviness estimated from the variation of the multipole along the axis is very low for Ansaldo 9, 10, 12 and 13 (around 15 microns, see Fig. 6, collared coils 34th, 33rd, 37th, 36th). We still have anomalous coil waviness for one aperture of both Alstom 16 and 17 (around 40-50 microns, see Fig. 6, collared coils 35th and 38th).

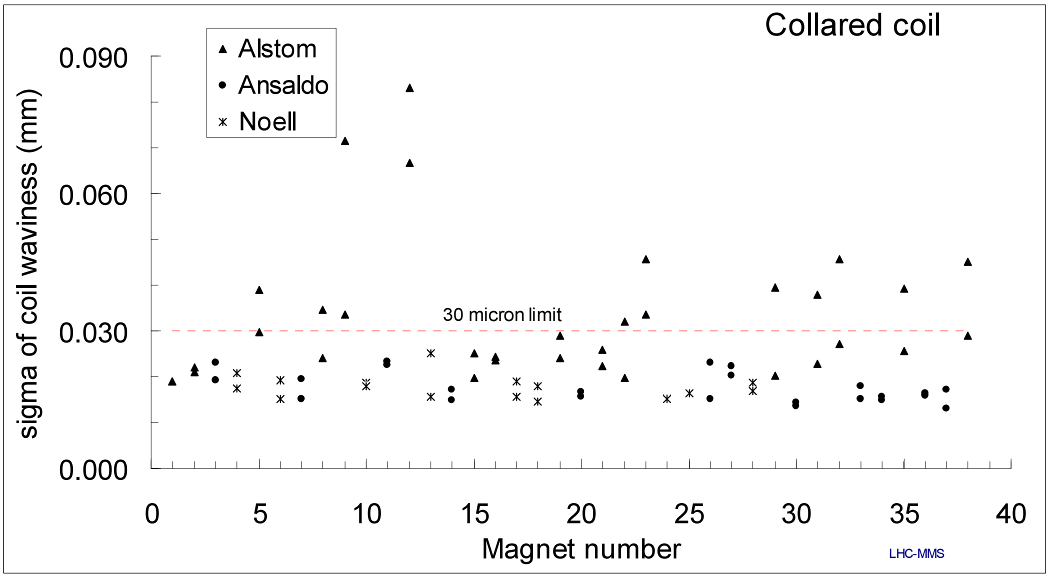

Fig. 6: Estimated coil waviness in the straight part of the measured collared coils.

5. Systematic odd multipoles

5.1 Normal sextupole

- Ansaldo 9 and 10 confirm that the positive trend in b_3 observed for the cross-section 1 is over (collared coils 34th and 33rd in Fig. 8). Average b_3 in collared coils 15th to 34th rescaled to nominal shims (see Fig. 8) is around 2.5 units. We still have no explications for this large trend, common to all manufacturers.
- Six collared coils with cross-section 2 feature a b_3 around –1.5 units, i.e. 4.0 units less than the previous cross-section. This is in agreement with simulations (-3.9 units, see Appendix B). Due to the positive trend, the best estimate for the systematic in X-section 2 is at the upper edge of the allowed range (see fig. 8). The low systematic difference between Ansaldo and Alstom observed in X-section 1 seems to be preserved in X-section 2.

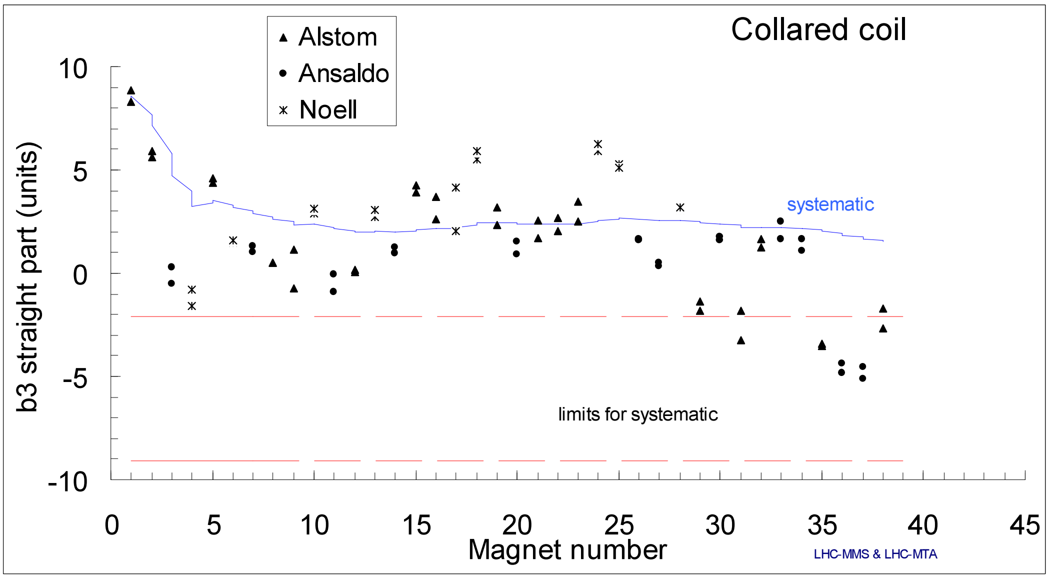

Fig. 7: Average b3 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 7 cryodipoles.

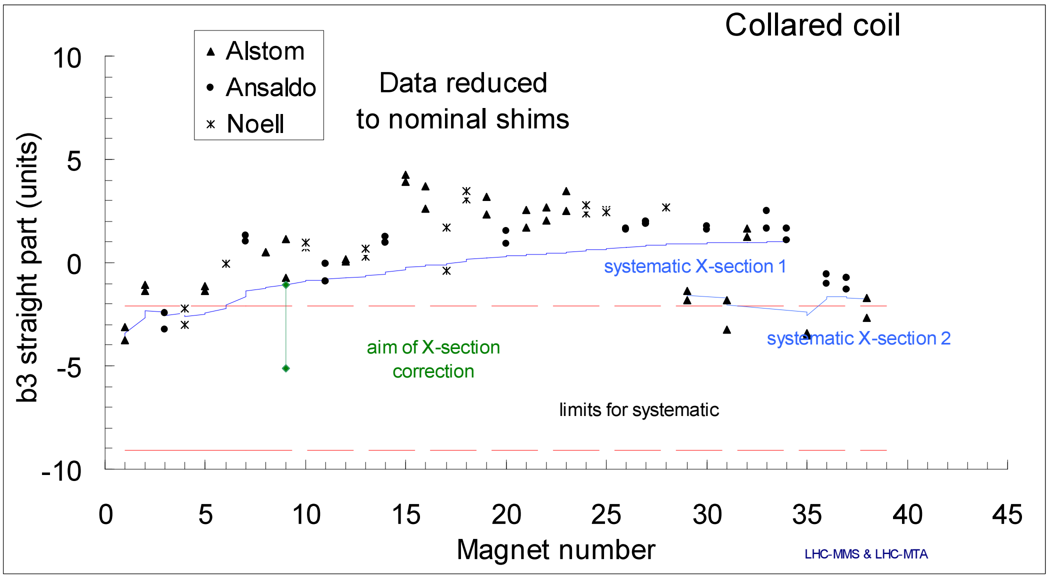

Fig. 8: Average b3 in the straight part of the collared coils (dots), best estimate for systematic (blue line) and beam dynamics limits for the systematic (red line) based on correlations with 7 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

5.2 Normal decapole

- Ansaldo 9 and 10 (34th and 33rd in Fig. 10) confirm the lower value of normal decapole in Ansaldo with respect to Alstom-Jeumont in X-section 1.
- A lower value of b_5 in Ansaldo with respect to Alstom is also observed in the six collared coils manufactured with the new cross-section (see Fig. 10). Average b_5 is shifted downward from 1.8 to 0.6 units in Alstom, and from 1.1 to -0.1 units in Ansaldo. This agrees with what expected from simulations (-1.36 units) within statistical errors.
- The best estimate for the systematic b_5 is now 0.2 units larger than the upper limit. This is due to three reasons: first, the drift in the systematic of 0.2 units (see fig. 10) from collared coil 9 (where the correction was defined) to collared coil 25. Moreover, we still miss measurements of Noell collared coils that should feature a b_5 lower than Alstom and Ansaldo and therefore the estimate of the systematic is biased (see Appendix C). Finally, the correction as measured in six magnets gives –1.2 units instead of –1.36. More statistics is needed to obtain a reliable estimate of the systematic b_5.

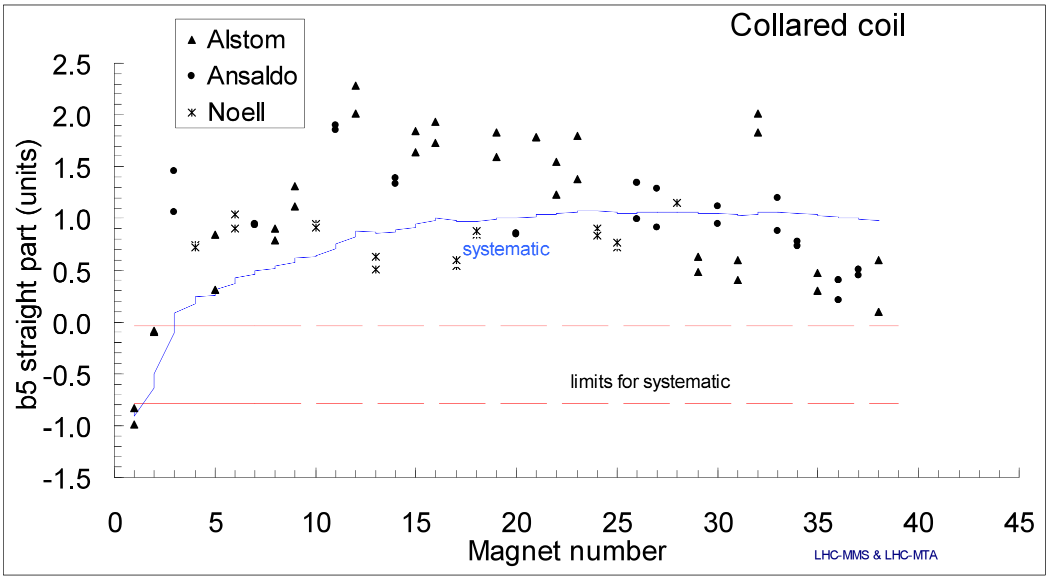

Fig. 9: Average b5 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 7 cryodipoles.

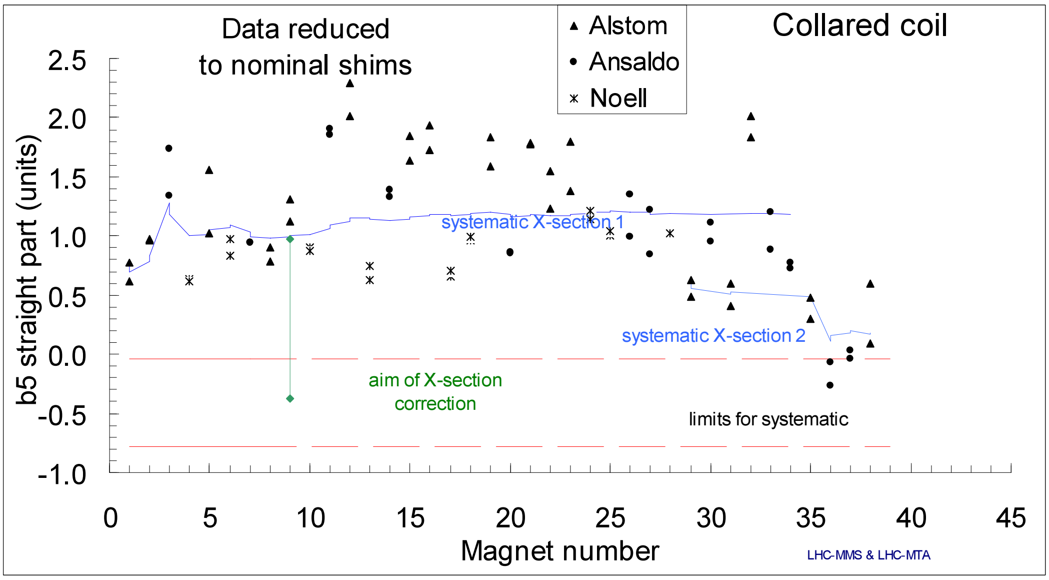

Fig. 10: Average b5 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 7 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

5.2 Normal 14-th pole

- Old X-section collared coils Ansaldo 9 and 10 (34th and 33rd in Figs. 11 and 12) confirm the systematic difference of normal 14th pole in Ansaldo with respect to Noell and Alstom-Jeumont.
- New X-section collared coils Alstom 16 and 17 (35th and 38th) confirm the unexpected high value of b_7 featured by Alstom 13 and 14 (29th and 31st). The 14-th pole in the collared coil was shifted upward of 0.4 units, against a calculated shift of 0.18 units.
- New X-section collared coils Ansaldo 12 and 13 (37th and 36th in Fig. 12) have an unexpected normal 14th pole. The systematic difference of –0.4 units between Ansaldo and Alstom observed in X-section 1 has disappeared. The overall shift of b_7 due to the new X-section in two Ansaldo magnets is 0.65 units against an expected value of 0.18 units.

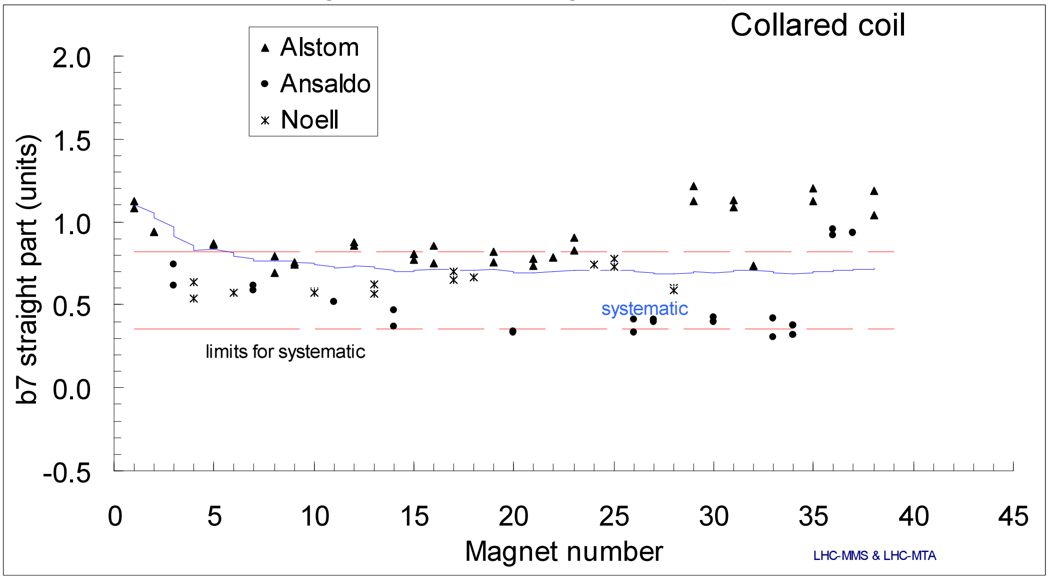

Fig. 11: Average b7 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 7 cryodipoles.

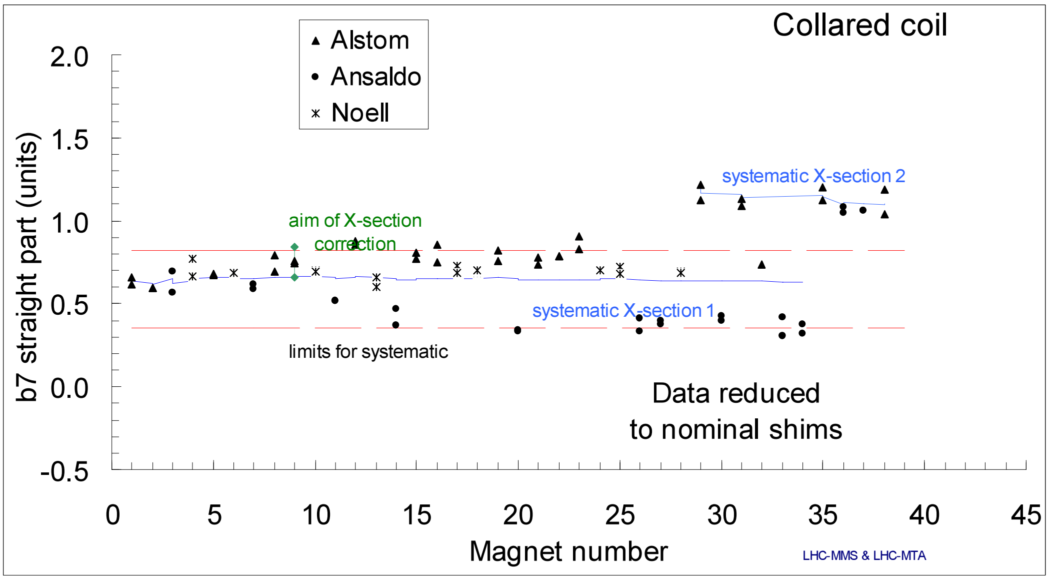

Fig. 12: Average b7 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 7 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

- The best estimate of systematic b_7 with the new X-section is now 0.3 units more than its upper limit, which corresponds to 0.3 units at injection energy. Simulations summarized in LHC project report 501 show that a systematic b_7 of 0.22 units may have some impact on dynamic aperture at injection (reduction of 0.4-0.8 sigma), whilst a systematic b_7 of 0.4 units reduces the dynamic aperture of 2 sigma.

6. Random multipoles

- Random per manufacturer and global random (i.e., the standard deviation of the distribution of all magnets) are shown in Figs. 13 and 14. For odd normal multipoles we exclude from the statistics the magnets with the new X-section.
- Data reduced at nominal shims (see Fig. 14) show that all the random components are within specifications with the exception of the normal sextupole, due to the upward trend.
- Integrated transfer function BdL is within targets (see Figs. 13 and 14). The global random of BdL is close to targets when data are reduced to nominal shims (see Fig. 14).
- In general Alstom magnets feature a much higher random part compared to Ansaldo and Noell. This could be related to the anomalous coil waviness.
- The standard deviation of the distribution of all magnets (marker global in the figures) is close or within the targets of the random per arc, with the exception of normal sextupole.

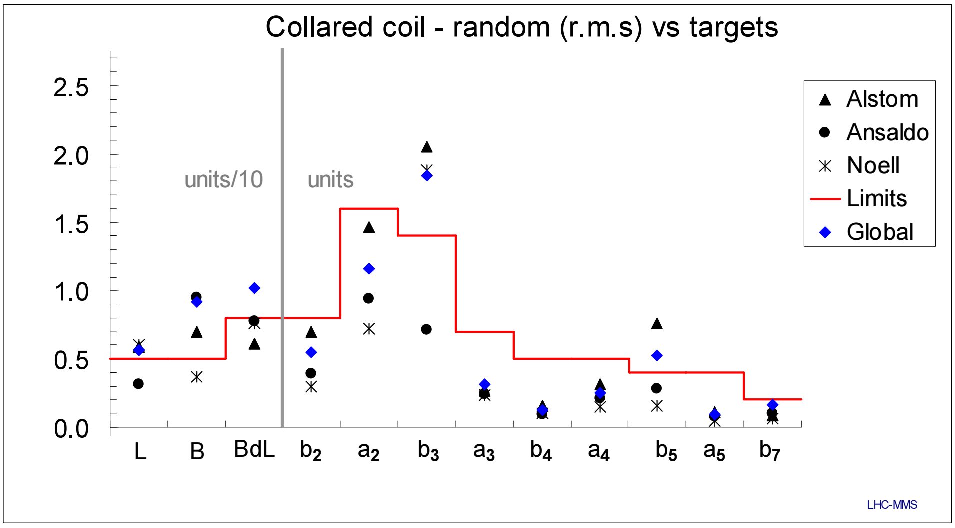

Fig. 13: Random component in the measured collared coils

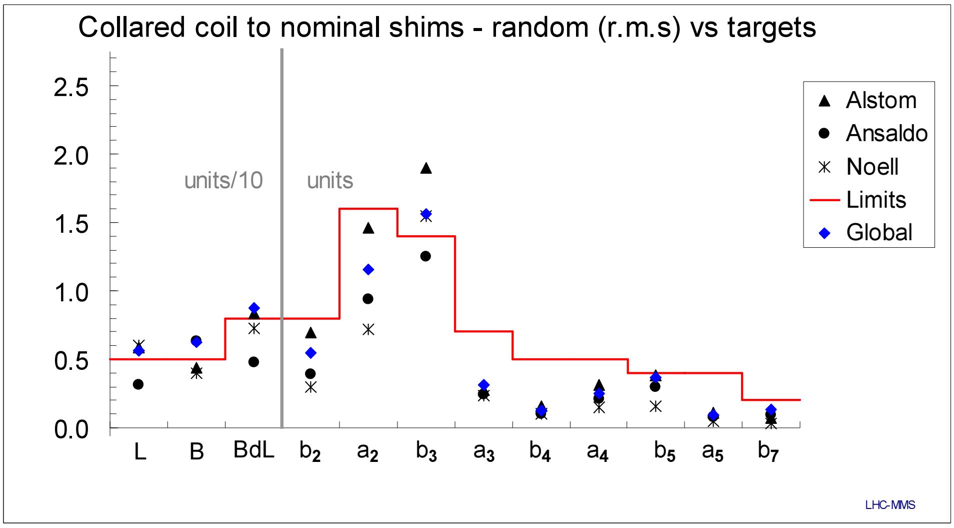

Fig. 14: Random component in the measured collared coils. Data reduced to nominal shims

8. Holding point results

Table II: results of the holding point for the measured collared coils

	Magnet name		Collared coil measure	Data at CERN	Answer to MMS-MD	Answer To manufact.	Result	Comments
33rd	HCMB__A001	2000010	22/05/02	22/05/02	23/05/02	23/05/02	Ok	
34th	HCMB__A001	2000009	23/05/02	23/05/02	27/05/02	27/05/02	Ok	
35th	HCMB__A001	1000016	19/06/02	19/06/02	19/06/02	21/06/02	Ok-w	Anomalous waviness in ap. 2
36th	HCMB__A001	2000013	26/06/02	26/06/02	27/06/02		STOP	First Ansaldo with new X-section. Very low main field partly due to non-nominal shims. b3, b5 agree with estimates, b7 higher than expected.
37th	HCMB__A001	2000012	27/06/02	27/06/02	27/06/02		STOP	Such as 2000013
38th	HCMB__A001	1000017	26/06/02	01/07/02	01/07/02		Ok-w	Anomalous waviness in Ap. 1

- Ansaldo 12 and 13 have been stopped to find out a rescuing procedure for the low main field. It has been agreed to add magnetic laminations to recover an integrated main field within tolerances.

9. Acknowledgements

Magnetic measurements have been taken through personnel and instrumentation of the LHC-MMS-IF section; in particular, J. Billan, V. Remondino, and G. Brun, G. Busetta, R. Camus, X. Reynes, A. Musso, and G. Peiro. We wish to acknowledge W. Scandale, L. Rossi, S. Pauletta, A. Devred, E. Wildner, S. Sanfilippo, and L. Bottura for comments and discussions.

Appendix A.

In Figs. 2 to 12, collared coils are identified by a progressive number. The link between this number and the official name is given in the following table.

Table III: relation between magnet numbers used in Figs. 2-12 and official names

Magnet Number	Magnet name		Magnet Number	Magnet name	
1st	HCMB__A001	1000001	20th	HCMB__A001	2000004
2nd	HCMB__A001	1000002	21st	HCMB__A001	1000010
3rd	HCMB__A001	2000001	22nd	HCMB__A001	1000011
4th	HCMB__A001	3000001	23rd	HCMB__A001	1000012
5th	HCMB__A001	1000003	24th	HCMB__A001	3000007
6th	HCMB__A001	3000002	25th	HCMB__A001	3000008
7th	HCMB__A001	2000003	26th	HCMB__A001	2000008
8th	HCMB__A001	1000004	27th	HCMB__A001	2000007
9th	HCMB__A001	1000005	28th	HCMB__A001	3000009
10th	HCMB__A001	3000003	29th	HCMB__A001	1000013
11th	HCMB__A001	2000002	30th	HCMB__A001	2000006
12th	HCMB__A001	1000006	31st	HCMB__A001	1000014
13th	HCMB__A001	3000004	32nd	HCMB__A001	1000015
14th	HCMB__A001	2000005	33rd	HCMB__A001	2000010
15th	HCMB__A001	1000007	34th	HCMB__A001	2000009
16th	HCMB__A001	1000008	35th	HCMB__A001	1000016
17th	HCMB__A001	3000005	36th	HCMB__A001	2000013
18th	HCMB__A001	3000006	37th	HCMB__A001	2000012
19th	HCMB__A001	1000009	38th	HCMB__A001	1000017

Appendix B. Control chart for magnetic length and main field

Control limits for the magnetic length (see Fig. 2) are put at 3 times the specified sigma from the measured average. No target is assumed for the average magnetic length. The same approach is followed for the control limits of the main field in the straight part (see Figs. 3 and 4): they are put at 3 times the specified sigma from the measured average, and no target is assumed for the average main field. We recall that beam dynamics specifications are given in terms of the sigma of the integrated main field. Therefore, the only chart relevant for beam dynamics is in Fig. 5. We assume an equal share of the integrated main field spread (8 units) between magnetic length and main field (5 units each), in the hypothesis of a Gaussian sum of the spreads.

Appendix C. Control chart for the systematic

Best estimates for systematic shown in Figs. 7-12 are defined as the average of the averages of each manufacturer. This definition takes into account for the quotas of dipoles assigned to manufacturers (one third each). For the case of the new cross-section, we still do not have collared coils from Noell and therefore we have a biased systematic, defined as the average between the Alstom average and the Ansaldo average.

Control limits for the systematic are given using the following formula for working out correlations between collared coil data b_n^{cc} and multipoles at injection b_n^i or at high field b_n^h

$$b_n^h = (b_n^{cc}/k) + b_n^{oh} \qquad\qquad b_n^i = (b_n^{cc}/k) + b_n^{oi}$$

where $k=B_1^{cc}/ B_1^{cm}$ = 1.18 is the multipole rescaling induced by the 18% increase of the main field due to the yoke as derived from magnetic measurements. This relation ensures a more precise correlation with respect to the approach used in the previous report based on a simple offset.

Appendix D. Remarks on the cross-section correction

We recall the aim of the cross-section correction:

$$\Delta B_1=0 \quad \Delta b_3=3.3 \quad \Delta b_5=1.15 \quad \Delta b_7=0.15$$

These shifts are expected in the cold mass, whilst in the collared coil they are scaled by the factor k = 1.18 (see Appendix C). Therefore in the collared coil we aimed at

$$\Delta B_1=0 \quad \Delta b_3=3.9 \quad \Delta b_5=1.36 \quad \Delta b_7=0.18.$$

The cross-section correction has been based on the best estimates of the systematics in the collared coil, on the correlations to measurements at 1.9 K, and on the beam dynamics acceptance ranges. Correlations also used data of prototypes (if homogeneous with pre-series) to increase statistics. Figs. 7 and 9 show that the cross-section correction carried out at collared coil 9 aimed at centring the allowed ranges for b_3 and b_5.

For the b_7 the situation is different (see Fig. 11). This is due to some change in correlations, and to a change of the b_7 acceptance ranges that has been carried out after the definition of the new X-section. We recall that due to the intense tracking campaign carried out in 2001, the tolerance for b_7 at injection has been reduced from [-0.4,0.4] as presented in Villars, LHC Days, March 2001, to [-0.3,0.3] in June 2001 to the final value of [-0.3,0.1] in the LHC Project Report 501 published in August 2001. The cross-section correction computed in June 2001 has been based on the range [-0.3,0.3].