Report on field quality in the main LHC dipole collared coils: September-October 2002

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This report gives data relative to field quality measured in collared coils during the period September 1– October 31 2002, comparison to beam dynamics targets and status of the holding points. Updated graphs can be found in the LHC-MMS field quality observatory http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs.html.

What's new

- Available measurements: 56 collared coils, 24 cold masses, 14 cryodipoles.
- In these two months, 11 collared coils have been received. No collared coils from Noell. The highest rate of production belongs to Alstom: 3.5 collared coils/month, i.e. a factor three less of the foreseen maximal production rate.
- All the manufacturers are now producing collared coils with the new cross-section. The total number of collared coils with the old cross-section is 34 (Alstom 1-12 and 15, Ansaldo 1 to 11, Noell 1-9 and 11).
- We include for the first time graphs for systematic a_5. Control limits on this multipole are based on the LHC Project Report 501 and on communications of S. Fartoukh to the Magnet Evaluation Board. The systematic is within specifications.
- Control limits on collared coil data are set through correlations with measurements at 1.9 K of 14 cryomagnets made by LHC-MTA. Four more magnets have been added with respect to the previous report of September 1, 2002.

1. Measured magnets and assembly data

- 11 collared coils have been measured (collared coils 46th to 56th)
  - 7 Alstom (1022 to 1028)
  - 4 Ansaldo (2011 and 2016 to 2018)

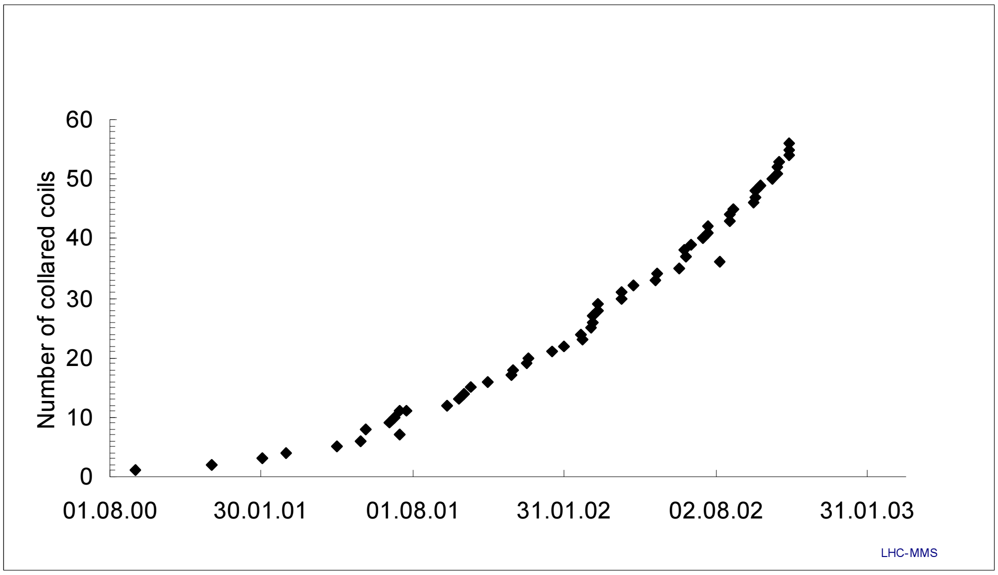

Fig. 1: Number of measured collared coils versus time

- Cross section: 2011 has X-section 1 (the old one); all the others have X-section 2.
- Shims (see table I and Fig. 2 for a summary over all the collared coils produced so far):
  - Azimuthal sizes of Ansaldo coils are still larger than nominal, and therefore thinner shims have been used (see Table I). 2016 has 0.1 mm less on both layers, whilst 2017 and 2018 has 0.1 mm less on the inner layer only
  - 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)		X-section
		Inner	Outer	
46th	1026	0.20	0.80	2
47th	1022	0.20	0.80	2
48th	2016	0.10	0.80	2
49th	1023	0.20	0.80	2
50th	1024	0.20	0.80	2
51st	1025	0.20	0.80	2
52nd	2017	0.10	0.80	2
53rd	2018	0.10	0.80	2
54th	1027	0.20	0.80	2
55th	1028	0.20	0.80	2
56th	2011	0.20	0.80	1

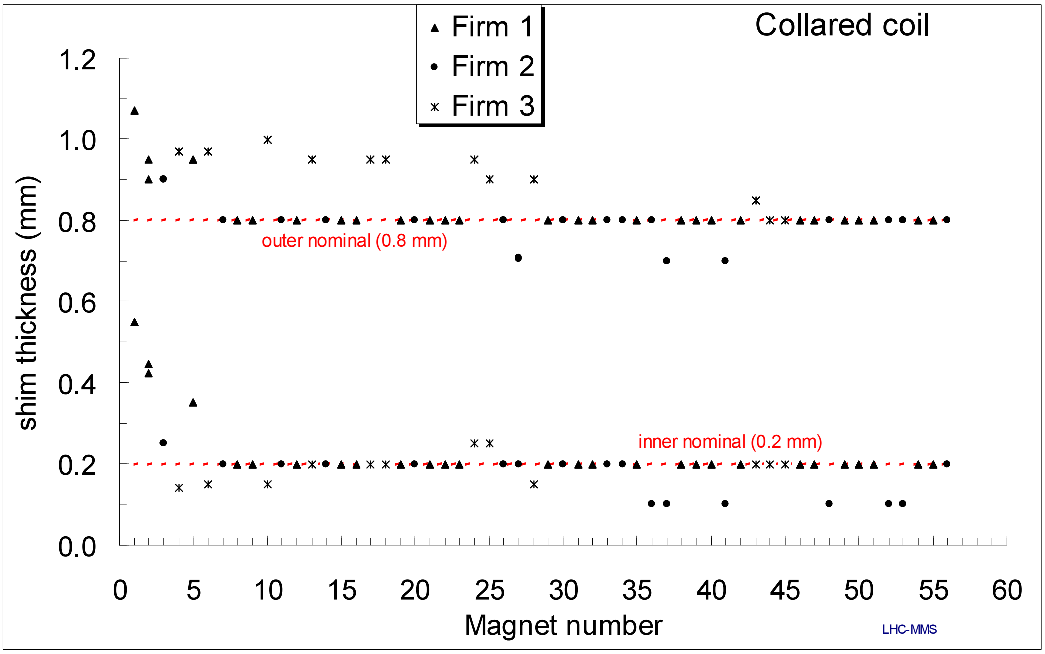

Fig. 2: Thickness of the polar shims used in the collared coils

2. Magnetic length and transfer function

- Magnetic lengths of collared coils 46th to 56th are within targets (see Fig. 3). No difference between old and new cross-section is observable, as expected.

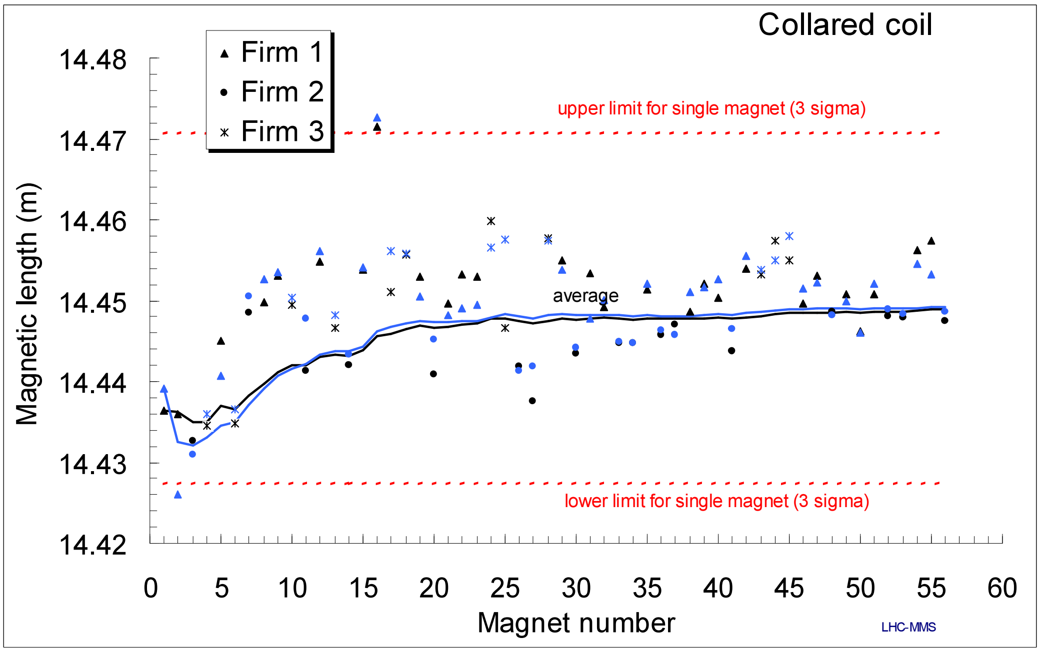

Fig. 3: Magnetic length of the measured collared coils

- Main field in the central part of 2016,2017 and 2018 (collared coils 48th 52nd and 53rd in Fig. 4) is lower than the average. This is partly due to the non-nominal shims, as it happened in previous Ansaldo (see also report of May-June 2002). When this effect is corrected, these collared coil data fall in the lower part of the 3 sigma range (see Fig. 5). A corrective action will be taken: ferromagnetic laminations will be added to increase the magnetic length.
- Difference between average main field in old and new cross-section is small (less than 5 units), as expected from simulations (see Fig. 5).
- Noell coils have a main field of about 15 units higher than Alstom or Ansaldo (see Fig. 5). This systematic difference is half of the allowed range at three sigma (30 units).
- All produced collared coils fit within the 3 sigma limit when data are reduced to nominal shims (see Fig. 5).

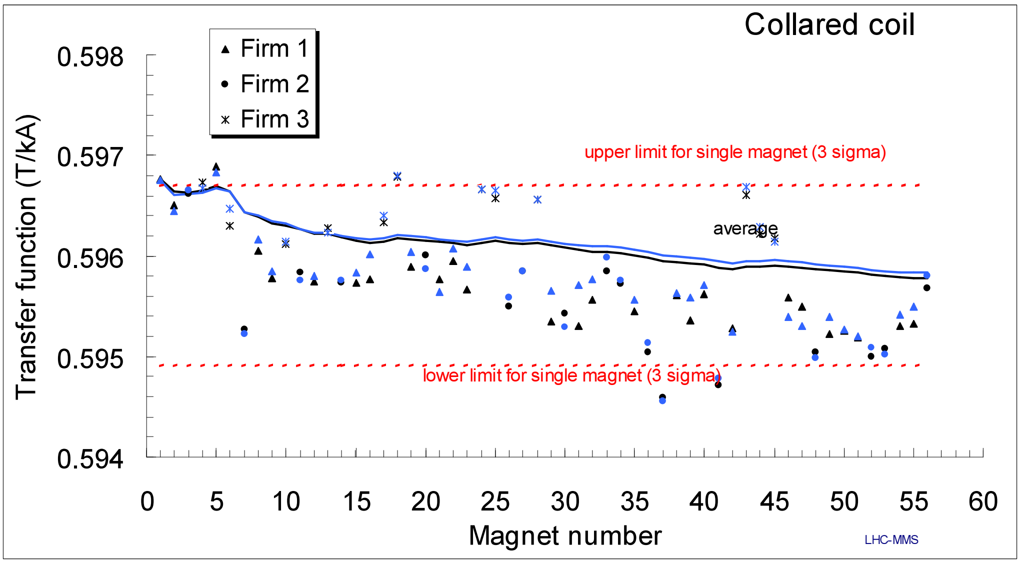

Fig. 4: Average main field in the straight part of the measured collared coils

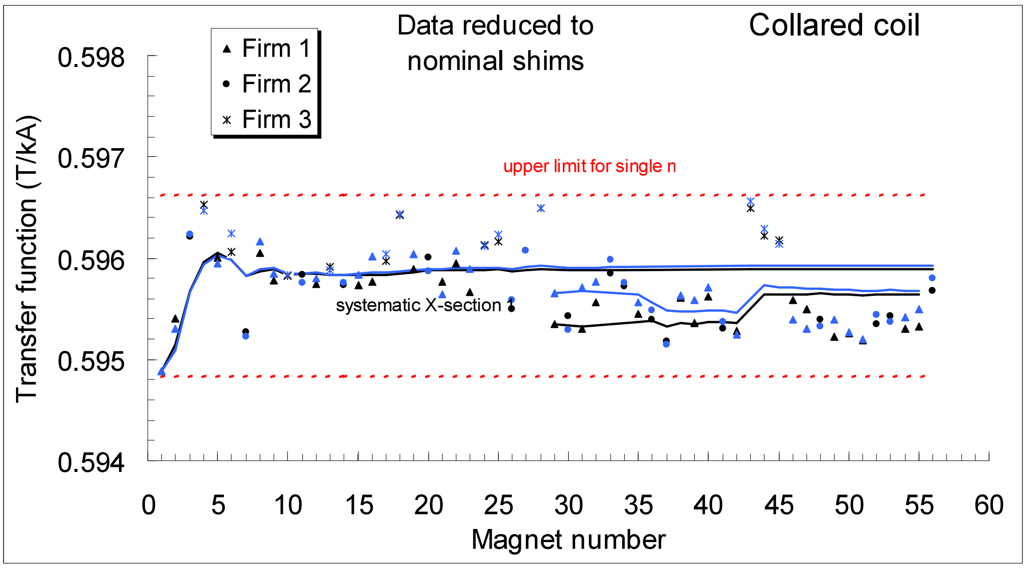

Fig. 5: Average main field in the straight part of the measured collared coils. Data reduced to nominal shims

- Integrated transfer function of magnets 46th to 56th is within the 3 sigma budget of the allowed random per arc (see Fig. 6).
- When data are reduced at nominal shims (see Fig. 7), one finds some systematic difference (around 20 units) between Noell and Ansaldo-Alstom. This is well within the total width of the band allowed by beam dynamics (at three sigma) in the hypothesis of a complete mixing of the manufacturers.

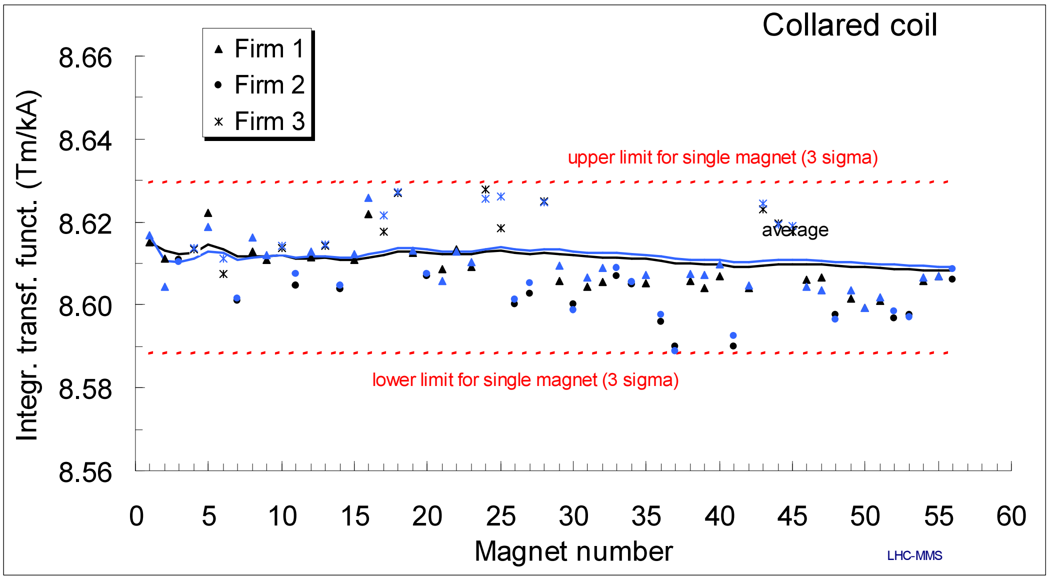

Fig. 6: Integrated transfer function in the measured collared coils.

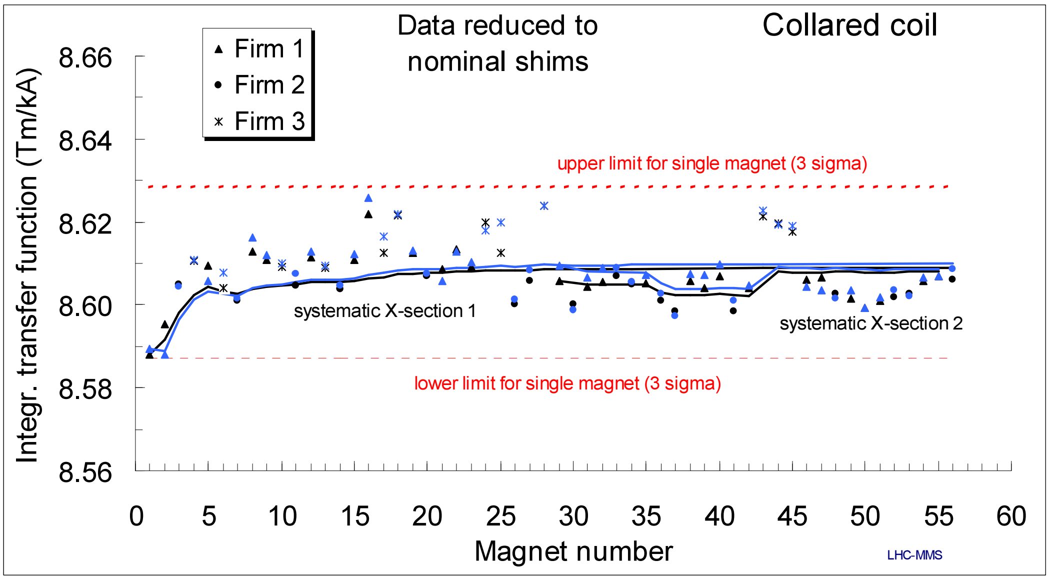

Fig. 7: Integrated transfer function in the measured collared coils. Data reduced at nominal shims.

3. Estimated coil waviness

- Coil waviness estimated from the variation of the multipole along the axis is getting better at Alstom (see Fig. 8). Corrective actions on the curing mould seem to be effective.

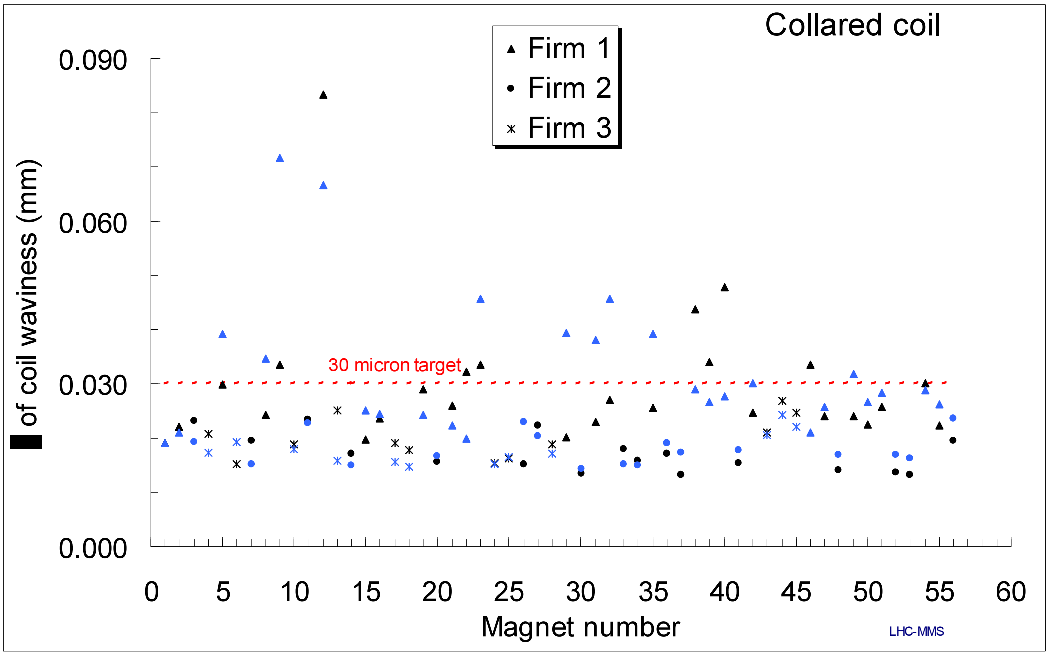

Fig. 8: Estimated coil waviness in the straight part of the measured collared coils.

4. Summary of systematics

- Best estimates of skew and even normal systematics are given in Fig. 9, with an error at 95% confidence limit (two sigma). All the multipoles are within specifications. Details are given in Sections 5 and 6.

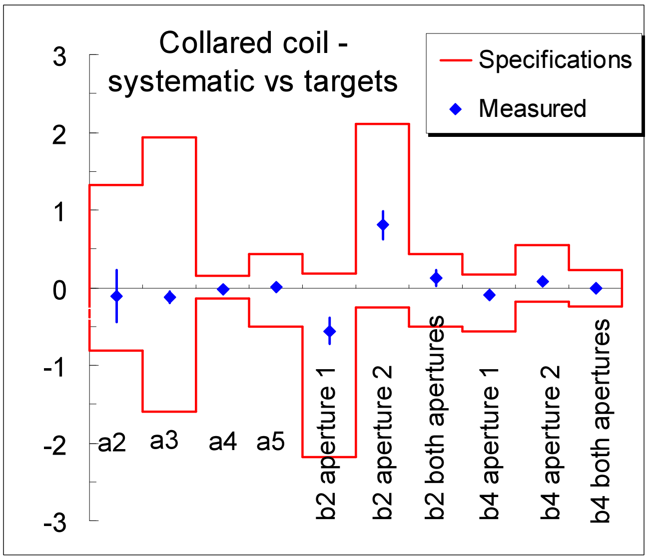

Fig. 9: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics.

- Best estimates for systematic odd multipoles are shown in Fig. 10. In the left part, raw data are plotted. This gives the actual situation for the manufactured collared coils: b_3 and b_5 are larger than the upper specifications of 3 and 0.85 units respectively.
- In the left part of Fig. 10, data are reduced to nominal shims and separated according the two cross-sections (34 collared coils have cross-section 1, 22 have cross-section 2). The change of cross-section under-corrected b_3 and b_5, and overcorrected b_7. Details are given in Section 7.

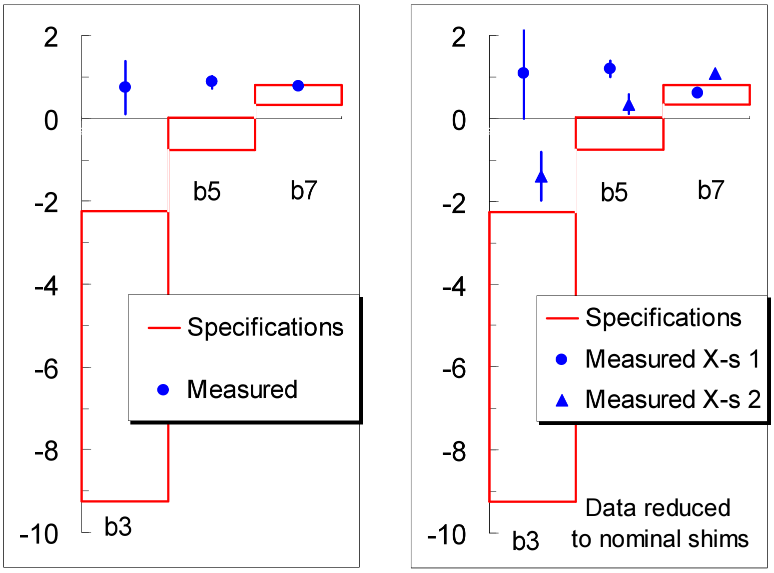

Fig. 10: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections (right).

5. Systematic skew multipoles

- Systematic skew multipoles a_2 a_3 and a_4 are within beam dynamics limits (see Figs. 11-13). We have a large margin for the a_3, whilst beam dynamics limits are tighter for a_2 and a_4.

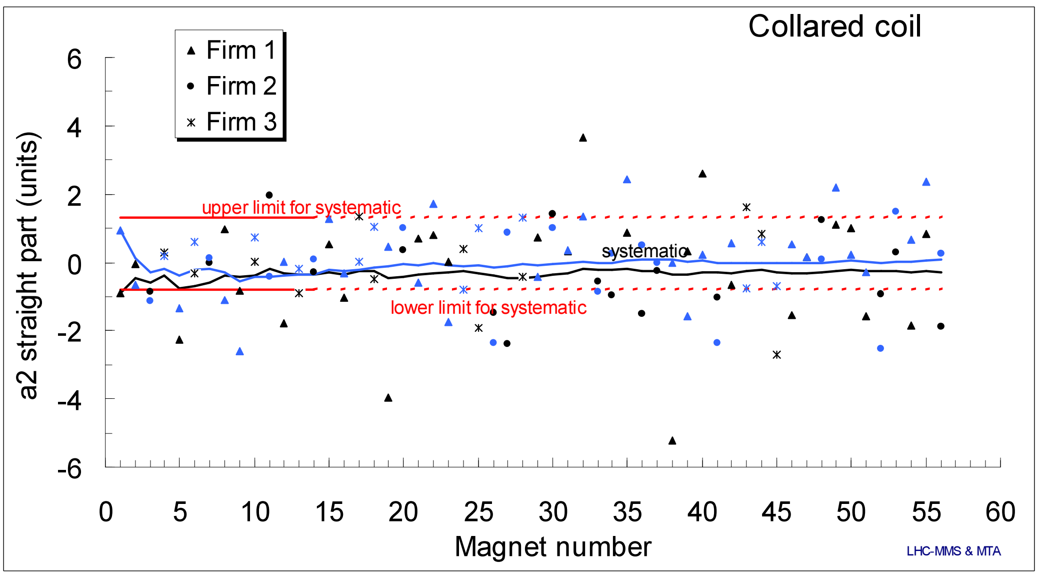

Fig. 11: Average a_2 in the straight part of the collared coils (dots), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

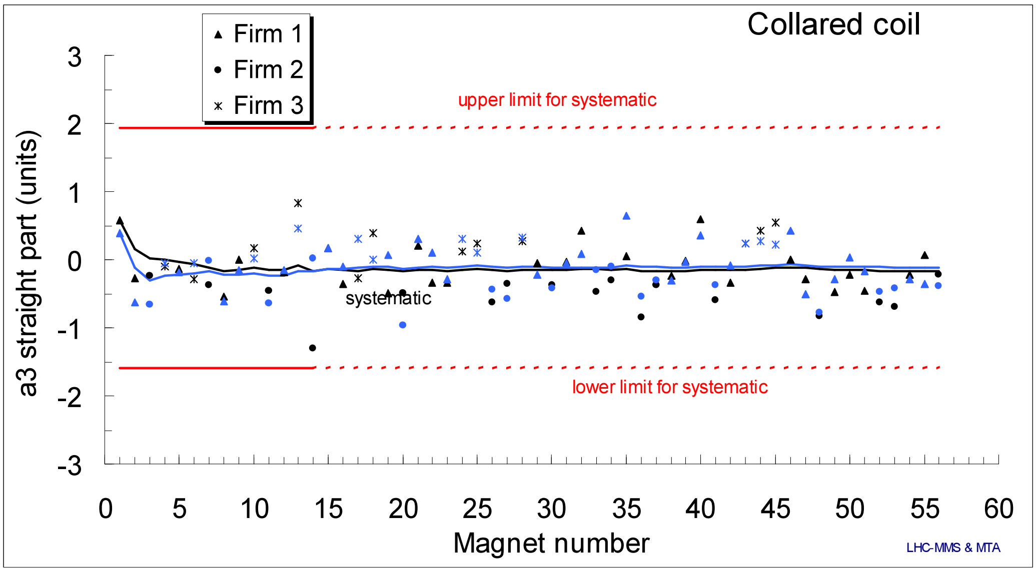

Fig. 12: Average a_3 in the straight part of the collared coils (dots), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

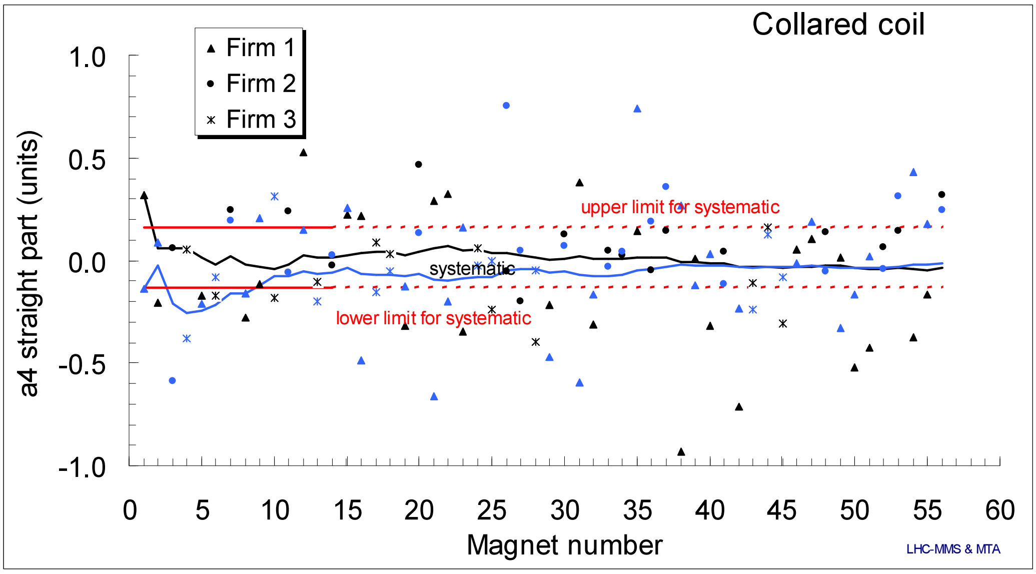

Fig. 13: Average a_4 in the straight part of the collared coils (dots), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

6. Systematic even multipoles

For each multipole subject to beam dynamics specifications, we present two separated plots for the systematic per aperture, and a plot of the systematic per beam, i.e. the average of both apertures (that should be zero due to two-in-one symmetry).

6.1 Normal quadrupole

- The systematic per aperture is within specifications in both apertures (see Figs. 14 and 15).

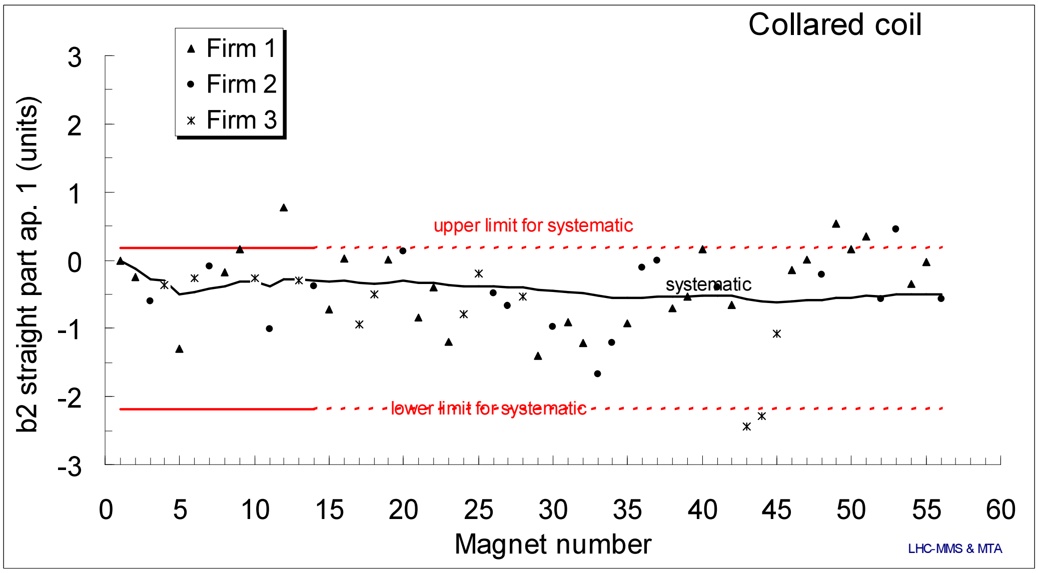

Fig. 14: Average b_2 in the straight part of the aperture 1 collared coils (dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

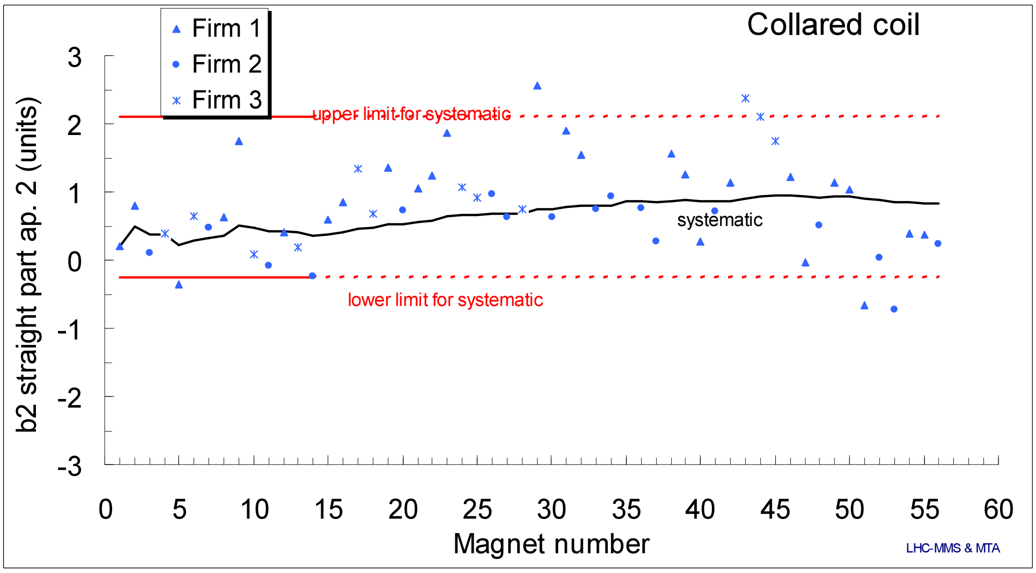

Fig. 15: Average b_2 in the straight part of the aperture 2 collared coils (dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

- The systematic per beam normal quadrupole is within specifications (see Fig. 16).

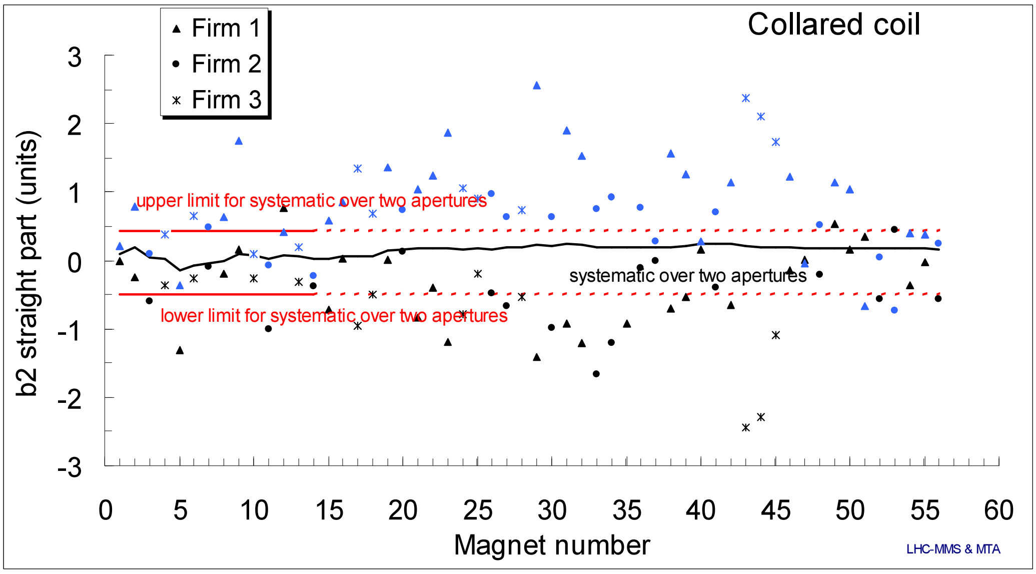

Fig. 16: Average b_2 in the straight part of collared coils (dots), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

6.2 Normal octupole

- The systematic per aperture is within specifications in both apertures (see Figs. 17 and 18).
- The systematic per beam is also within specifications (see Fig. 19).

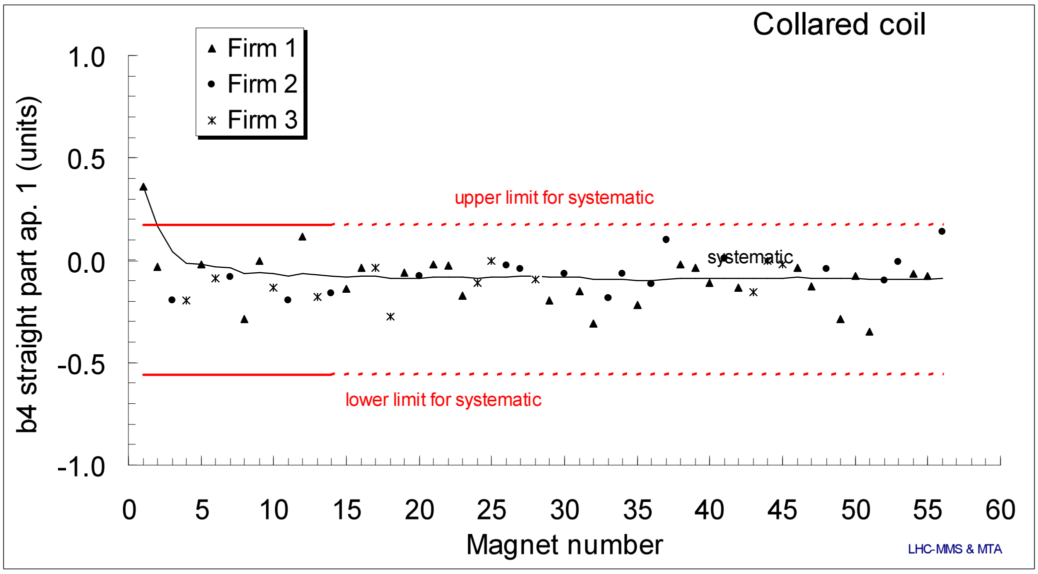

Fig. 17: Average b_4 in the straight part of the aperture 1 collared coils (dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

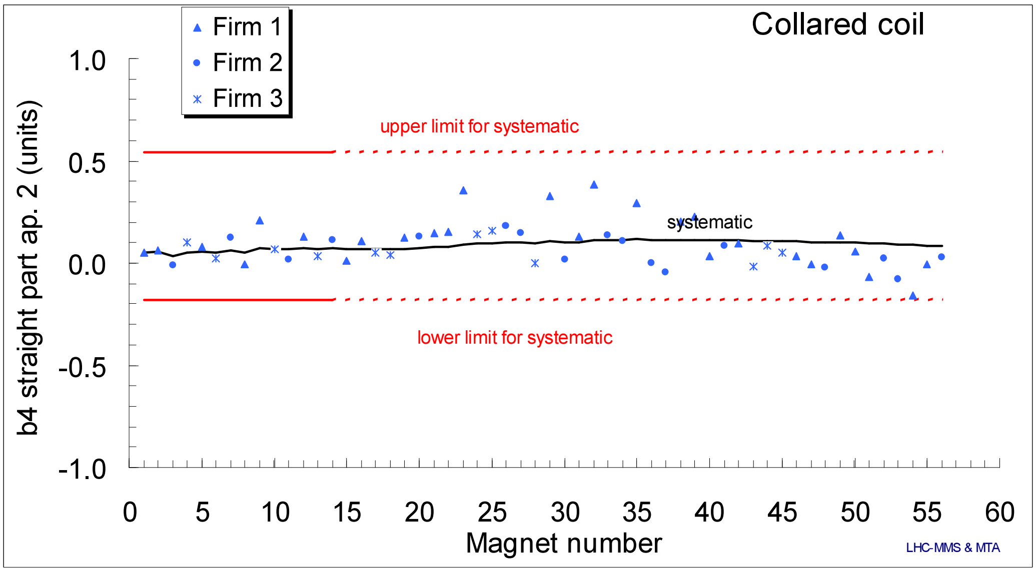

Fig. 18: Average b_4 in the straight part of the aperture 2 collared coils (dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

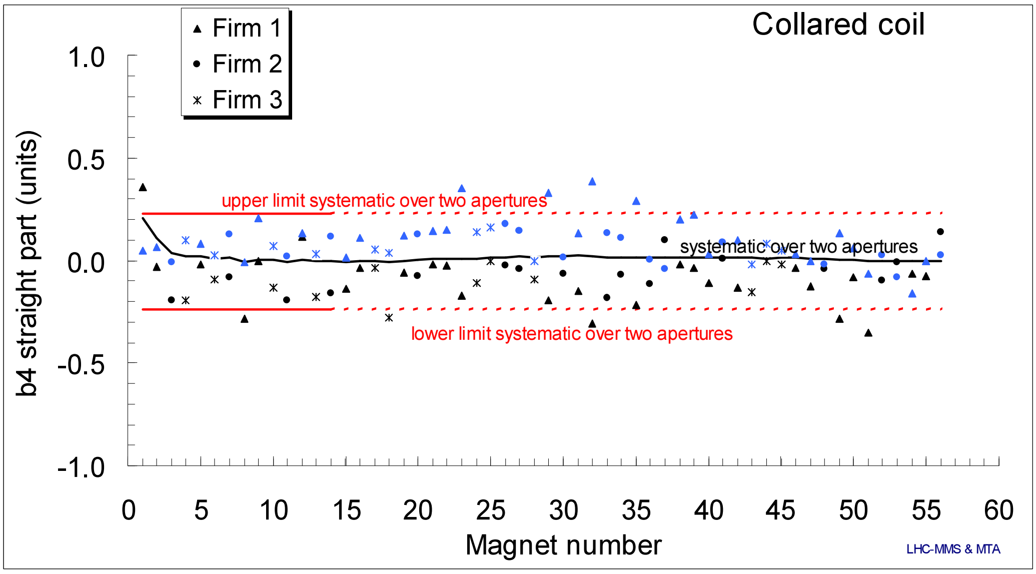

Fig. 19: Average b_4 in the straight part of collared coils (dots), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

7. Systematic odd multipoles

7.1 Normal sextupole

- The cross section correction shifted down the normal sextupole from around 2.2 units (excluding the data from collared coil 1 to 15 that experienced an upward trend) to –1.3 units, i.e. –3.5 units (see fig. 21). This has to be compared to what expected from simulations (-3.9 units). Therefore, the correction worked at 90%.
- Due to the positive trend, our estimate for systematic in X-section 2 is 0.9 units out of the limit (see fig. 21). The associated error is 0.6 units (95% confidence level, see Fig. 10).
- Alstom 27 and 28 (collared coil 54th and 55th in Fig. 21) feature a higher b_3 with respect to previous cases.
- Cryodipoles with the new X-section should feature 3.7 units of b_3 at high field; this is outside the specification but within the hard limit of 4.2 units given by chromaticity correctors.

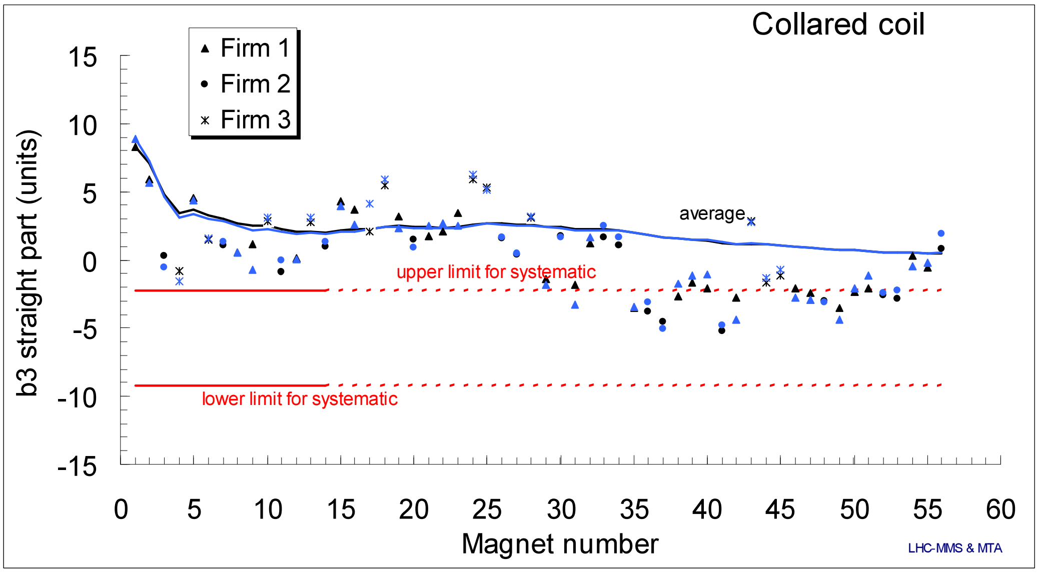

Fig. 20: Average b_3 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

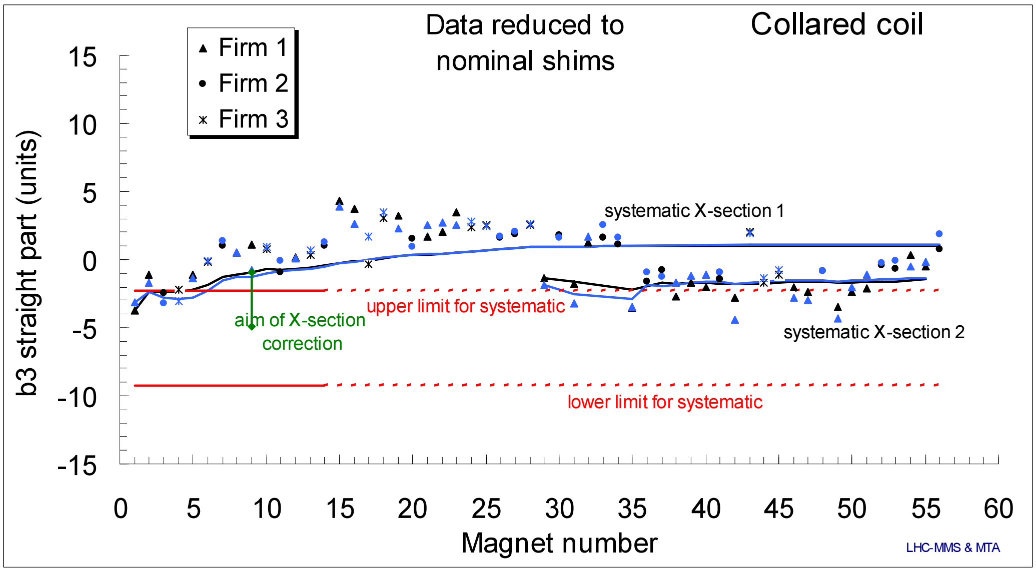

Fig. 21: Average b_3 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles. Data reduced at nominal shims and separated according to X-section type.

7.2 Normal decapole

- Alstom 21 to 28 (collared coils 43rd, 46th, 47th, 49th, 50th, 51st, 54th and 55th in Figs. 22 and 23) feature a higher b_5 with respect to previous Alstom with the new X-section (0.9 units instead of 0.4 units). An intervention carried out in the polymerisation press ([1]) could be the cause of this jump. The shift goes in the wrong direction with respect to beam dynamics limits.
- Best estimate for systematic b_5 in new X-section is 0.32 units larger than the upper allowed limit. Ansaldo collared coils are within limits, but both Alstom and Noell are out. These preliminary data show that the new cross-section features a large difference in systematic b_5 between firms, as the previous one.
- Ansaldo 11 (collared coil 56th), i.e. the last collared coil with old cross-section, has a very high b_5 (1.7 units) compared to previous ones (around 1 unit).

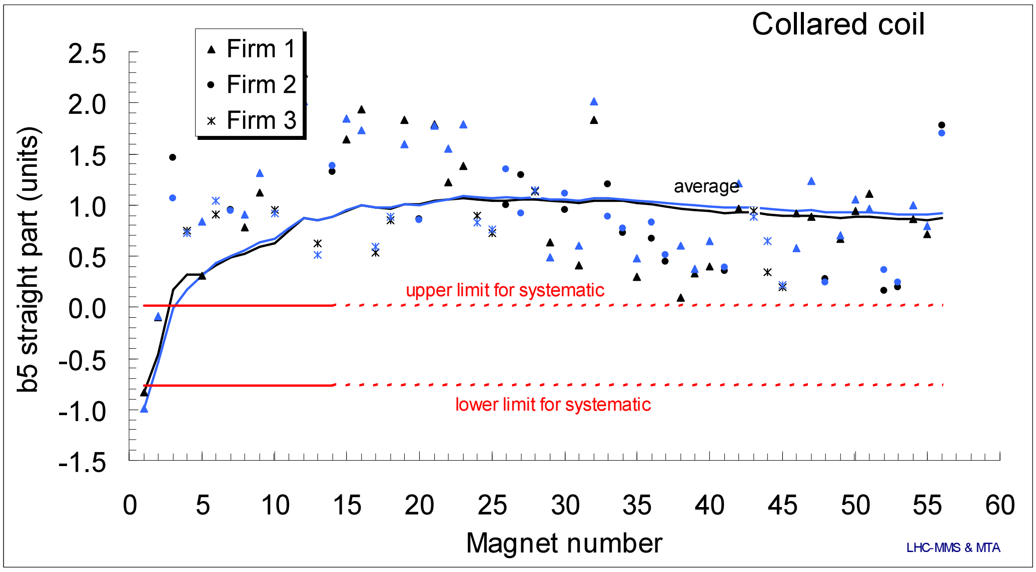

Fig. 22: Average b5 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

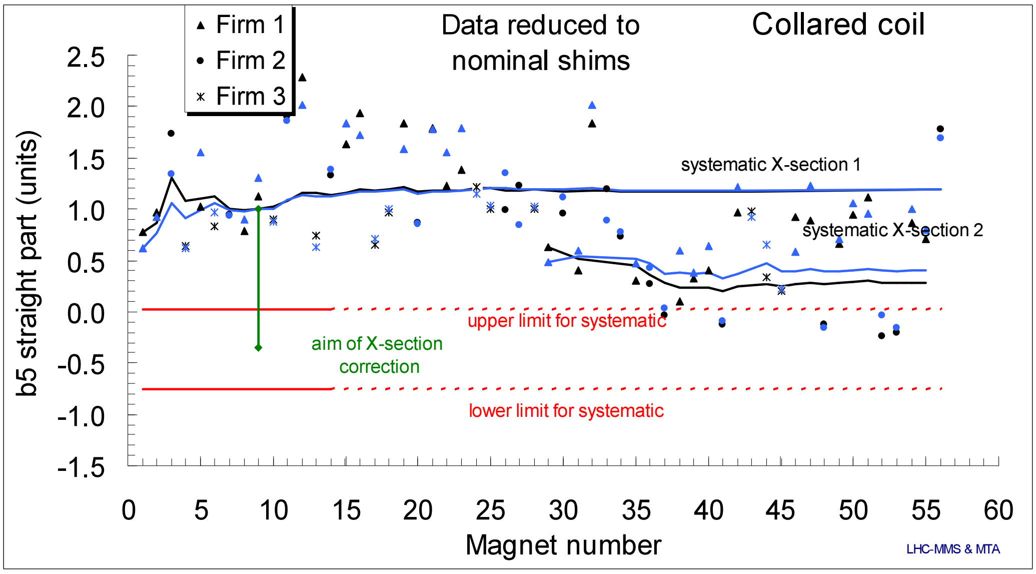

Fig. 23: Average b5 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

[1] A. Devred, private comunication

7.3 Normal 14-th pole

- New data confirm previous trends: new X-section collared coils have a systematic b_7 of around 1.1 units, i.e. 0.3 units more than the upper limit. The associated error is small (0.04 units at 95% confidence level, see Fig. 10).
- The b_7 of the last magnet with the old cross-section (Ansaldo 11, i.e. 56th in Figs. 24 and 25) is around 0.15, i.e. 0.2 units less of the previous values measured in Ansaldo. The strong systematic difference (0.4 units) between Ansaldo and other firms that was observed in X-section 1 is reduced in X-section 2 (around 0.2 units).

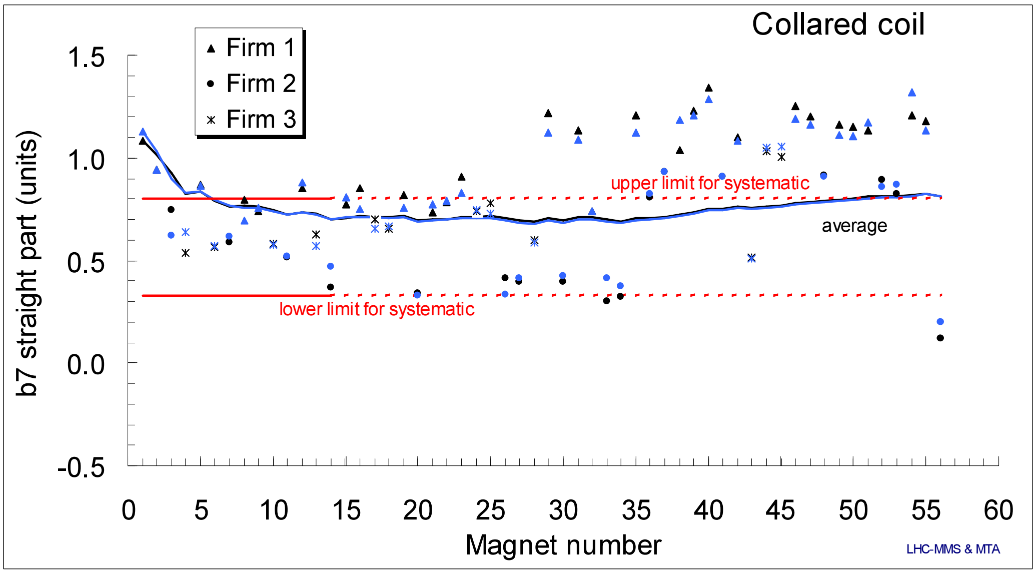

Fig. 24: Average b_7 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles.

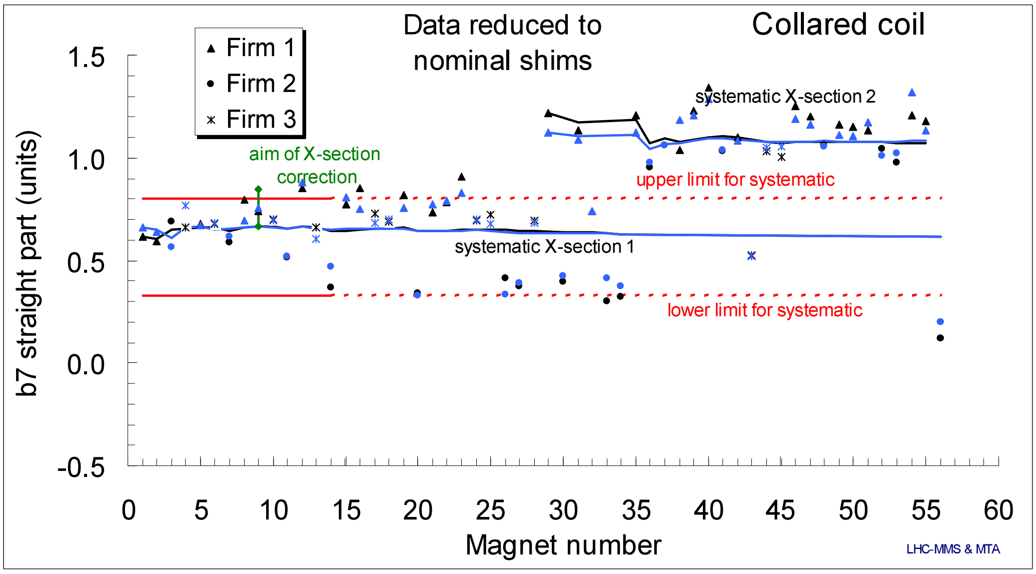

Fig. 25: Average b_7 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 14 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

8. Random multipoles

- Random per manufacturer and global random (i.e., the standard deviation of the distribution of all magnets) are shown in Figs. 26 and 27.
- Raw data (see Fig. 26) show an out of tolerance for b_3 and b_5. This is mainly due to the change of cross-section that shifted down these multipoles of 3 units and 1 unit respectively. The other parameters are within specifications, also in the hypothesis of a complete mixing.
- When data are reduced to nominal shims and split according to the cross-section type, one observes a random b_3 out of tolerance in the old X-section: this is due to the upward trend (see Section 7.1, Fig. 21). This is the only out of tolerance in the old X-section.

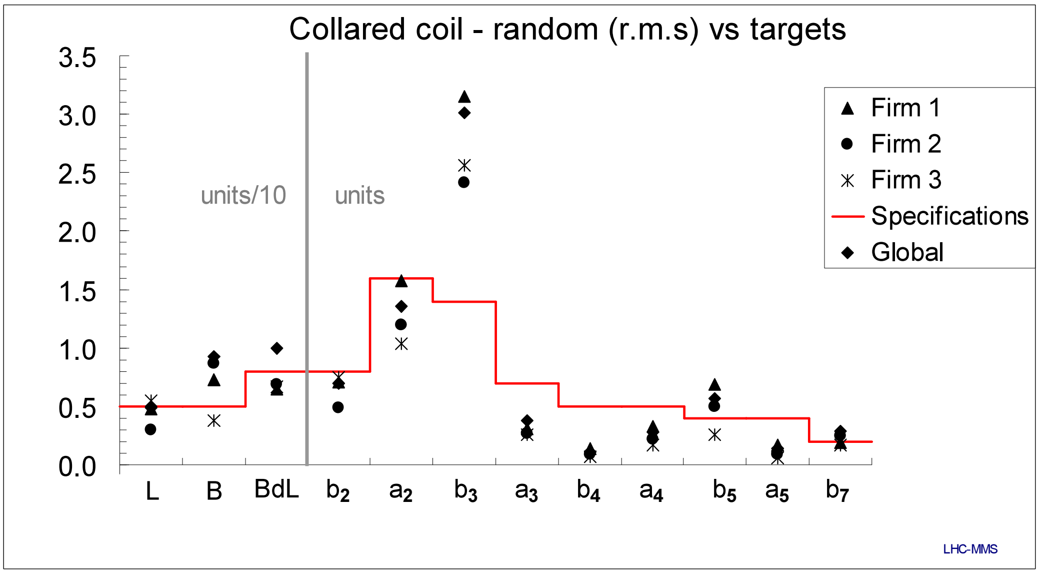

Fig. 26: Random component in the measured collared coils

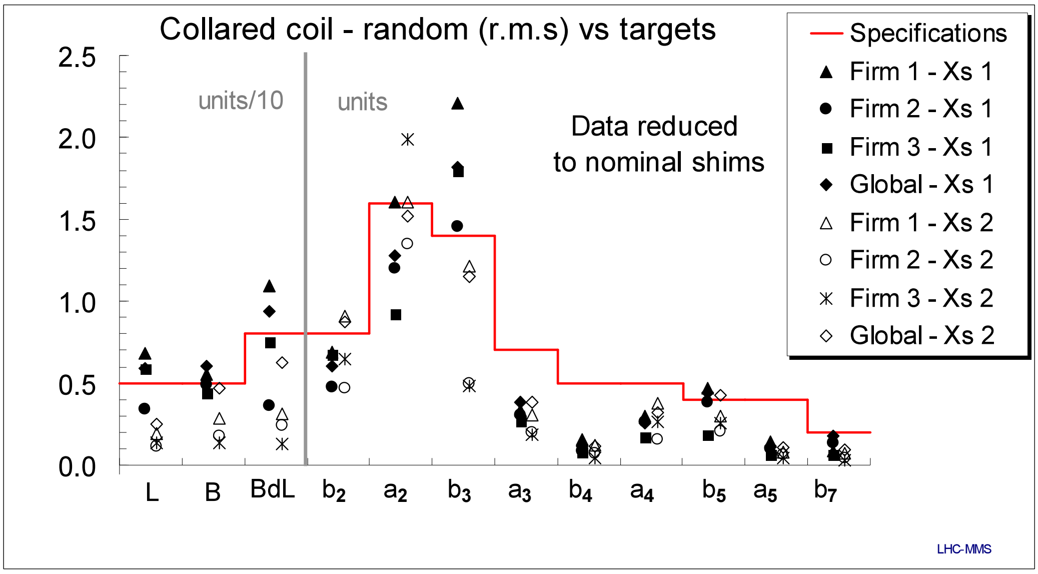

Fig. 27: Random component in the measured collared coils. Data reduced to nominal shims and split according to different cross-sections.

- The statistics for the new cross-section is still poor for Firm 3 and therefore some features could change when more data will be available.
  - Collared coils with the new cross-section feature a very stable integrated main field BdL and odd multipoles (see Fig. 27).

- Firm 1 has a large random b_2 (12% higher than specifications) .
- Firm 3 have a large random a_2 (see Figs. 27 and 11), but only two magnets have been measured.

- All the random components are expected to decrease by around 20% in the cold mass, due to the main field increase. Therefore, out of tolerances in a_2 and b_2 are likely to disappear in the cold mass.

9. 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
46th	HCMB__A001	1000026	18/09/02	18/09/02	18/09/02	20/09/02	OK-w	Stilll some anomalous coil waviness in aperture 1
47th	HCMB__A001	1000022	19/09/02	19/09/02	19/09/02	20/09/02	OK-w	The third magnet from Alstom (21,22,26) with higher b5 with respect to previous ones (13,14,16,17,18,19) of about 0.5 units
48th	HCMB__A001	2000016	19/09/02	19/09/02	19/09/02	23/09/02	Corr. Act.	Low main field due to non-nominal shim - corrective action on ferrromagnetic laminations in the cold mass to be implemented
49th	HCMB__A001	1000023	25/09/02	25/09/02	25/09/02	26/09/02	OK-w	Coil waviness still slightly above 30 micron in aperture 2
50th	HCMB__A001	1000024	09/10/02	09/10/02	09/10/02	10/10/02	OK	
51st	HCMB__A001	1000025	15/10/02	15/10/02	16/10/02	18/10/02	OK	
52nd	HCMB__A001	2000017	16/10/02	16/10/02	16/10/02	17/10/02	Corr. Act.	Low main field due to non nominal shims to be recovered by adding laminations in the cold mass
53rd	HCMB__A001	2000018	17/10/02	17/10/02	18/10/02	21/10/02	Corr. Act.	More laminations to be added to recover low main field due to non nominal shim on inner layer
54th	HCMB__A001	1000027	29/10/02	30/10/02	01/11/02	06/11/02	HOLD	Spike in position 8 in b2, a2 and b3
55th	HCMB__A001	1000028	30/10/02	31/10/02	01/11/02	01/11/02	OK	
56th	HCMB__A001	2000011	30/10/02	01/11/02	01/11/02		OK-w	The collared coil has been recollared for electric problems - relevant changes in field quality similar to 1013

- We still observe anomalous coil waviness in Alstom 26 and 23.
- A corrective action will be taken on Ansaldo 16-18. It has been agreed to add magnetic laminations to recover an integrated main field within tolerances.
- Alstom 27 shows a large sipke in a_2 (more than 8 sigma) in position 8 that partly affects also position 7. There is a strong numerical evidence that this is due to a missing shim in the outer layer. Measurement has been repeated, confirming previous results. The collared coil will be decollared in early November 2002.
- Ansaldo 13 that has been collared and measured in August 2002 has been de-collared for electric problems and recollared with the same shims. Measurements were carried out to see the effect on field quality. We find a shift in multipoles (see Tab. III) similar to what observed in 2013, mainly in b_5 (see Table IV). Since this effect seems systematic, 2013 (that was held since August 2002, see previous report) has been released; we wait for more statistics on other collared coils that will be decollared.

Table III: Effect of recollaring on field quality, measurements on collared coil 2011

	ΔC_1	Δb_3	Δb_5	Δb_7
2011 Aperture 1	1.0	-0.8	0.65	-0.28
2011 Aperture 2	0.6	-0.7	0.50	-0.23

Table IV: Effect of a shim change of 0.1 mm on the outer layer: model, measurements on 2013, and discrepancy with respect to model

	ΔC_1	Δb_3	Δb_5	Δb_7
Model	4.0	1.6	-0.08	-0.02
2013 Aperture 1	7.4	1.0	0.46	-0.11
2013 Aperture 2	8.7	1.2	0.42	-0.13
2013 Average	8.0	1.1	0.44	-0.12
2013 Av.-model	4.0	-0.5	0.52	-0.10

10. Acknowledgements

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

Appendix A

In Figs. 2 to 25, 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. 2-25 and official names

1st	1001	21st	1010	41st	2014
2nd	1002	22nd	1011	42nd	1021
3rd	2001	23rd	1012	43rd	3011
4th	3001	24th	3007	44th	3012
5th	1003	25th	3008	45th	3013
6th	3002	26th	2008	46th	1026
7th	2003	27th	2007	47th	1022
8th	1004	28th	3009	48th	2016
9th	1005	29th	1013	49th	1023
10th	3003	30th	2006	50th	1024
11th	2002	31st	1014	51st	1025
12th	1006	32nd	1015	52nd	2017
13th	3004	33rd	2010	53rd	2018
14th	2005	34th	2009	54th	1027
15th	1007	35th	1016	55th	1028
16th	1008	36th	2013	56th	2011
17th	3005	37th	2012		
18th	3006	38th	1017		
19th	1009	39th	1018		
20th	2004	40th	1019		