Report on field quality in the main LHC dipole collared coils: March-April 2003

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This report gives data relative to field quality measured in collared coils during the period March 1– April 30 2003, 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.

EDMS n. **385783**

The dashboard

- Available measurements: 100 collared coils, 58 cold masses, 24 cryodipoles.
- In these two months, 20 collared coils: 6 from Firm 1, 6 from Firm 2 and 8 from Firm 3.

What's new

- **Production rate**: we observe a strong increase in the rate of collared coil production, from 6 per month (September 2002 to February 2003) to 10 per month (March and April 2003).
- **Field quality workshop**: it has been held at CERN in March to discuss field quality steering in the production of the LHC dipoles. Presentations and conclusions are available in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/fqwrkshp/fqwrkshp.html.
- **Corrective actions:** a pre-series collared coil with additional mid-plane insulation to correct b_3 b_5 and b_7 will be assembled in Firm2 in May. Steps to perform the tuning of iron laminations to minimize systematic differences in integrated main field are in progress.
- **Trends in integrated main field**: The systematic difference main field in the last two months between manufacturers is 20 units between Firm 2 and Firm 3; values of Firm 1, that where close to Firm 2, are now in between. More information in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/bdl.html and in Section 3, pg. 4-5.
- **Trends in b_2**: The systematic difference in integrated b_2 between Firm 1-2 and Firm 3 of about 1.5 units observed in the previous reports is decreasing. This feature is under investigation. More information in Section 7, pg. 9-10.
- **Trends in systematic and random harmonics**: New data confirm the previous ones.
- **Field quality variation after a re-collaring**. Collared coil 2002 has been re-collared for the third time. We observe a field quality variation with respect to the second de-collaring that is similar to what observed in the other cases. The first measurement of a re-collared magnet at Firm 3 has been done on collared coil 3010, but unexpectedly no field quality variation has been measured. More information on http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/2013.html). Both re-collared coils have been accepted.
- **Special experiments**: the dedicated experiment on the effect of the midplane insulation on field harmonics is being completed in building 927 under the supervision of D. Tommasini and H. Kummer. Information at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/mid_ins.html.

- **Communication**: We recall the web sites available for monitoring field quality in the production:
  - The AT-MAS **field quality observatory** contains plots relative to multipole trends in the production and comparison to beam dynamics. Now, also plots separated according to the manufacturer are available. At the end of the web page the links with these bimonthly field quality letters are given. Web address: http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs.html
  - The AT-MAS **repository** contains the measurement files of each collared coil or cold mass. Web address: http://lhc-div-mms.web.cern.ch/lhc-div-mms/tests
  - The **field quality crisis unit** contains the information about bad cases (both open and closed), trends and corrective actions that are met during production. Web address: http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/crisis.html

  You need a Nice password to retrieve information from these web sites. Comments and suggestions to improve the communication of field quality data are welcome.

1. Measured magnets and assembly data

- 20 'new' collared coils have been measured (collared coils 81st to 100th), plus two old ones (2002 and 3010 that have been re-collared)
  - 6 of Firm 1 (1036-1039, 1041 and 1045)
  - 6+1 of Firm 2 (2026-31, plus 2002)
  - 8+1 of Firm 3 (3022-25 and 3027-30, plus 3010)

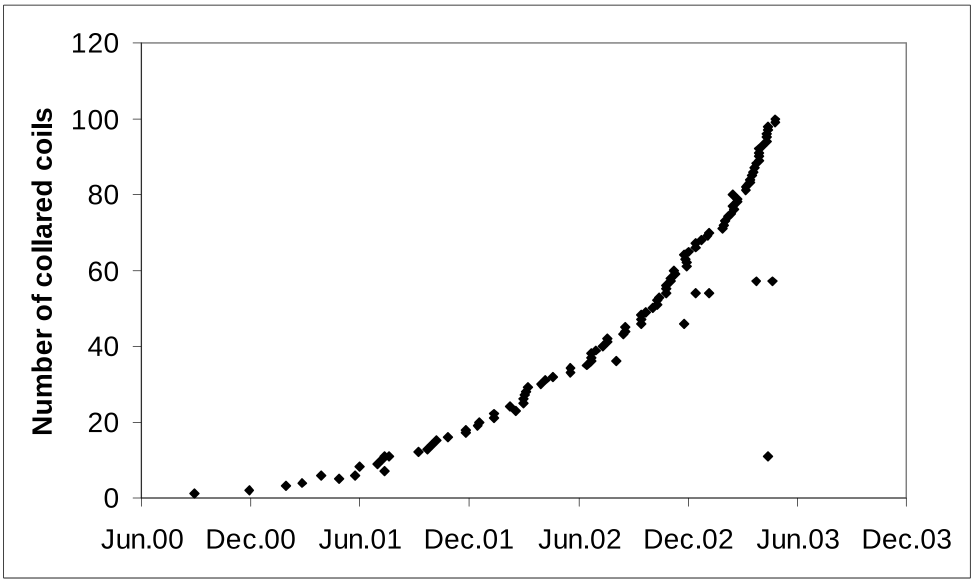


Fig. 1: Number of measured collared coils versus time. Dots out of the main trend are relative to collared coils measured more than one time.

- Cross section: from now on, all magnets with cross section 2.
- All shims are nominal, with the exception of three Firm 3 collared coils, featuring 0.05 mm more on the outer layer (outer coil too small); one collared coil has also 0.05 mm less on the inner layer (inner coil too large) [see Fig. 2]. This has a small impact on field quality.

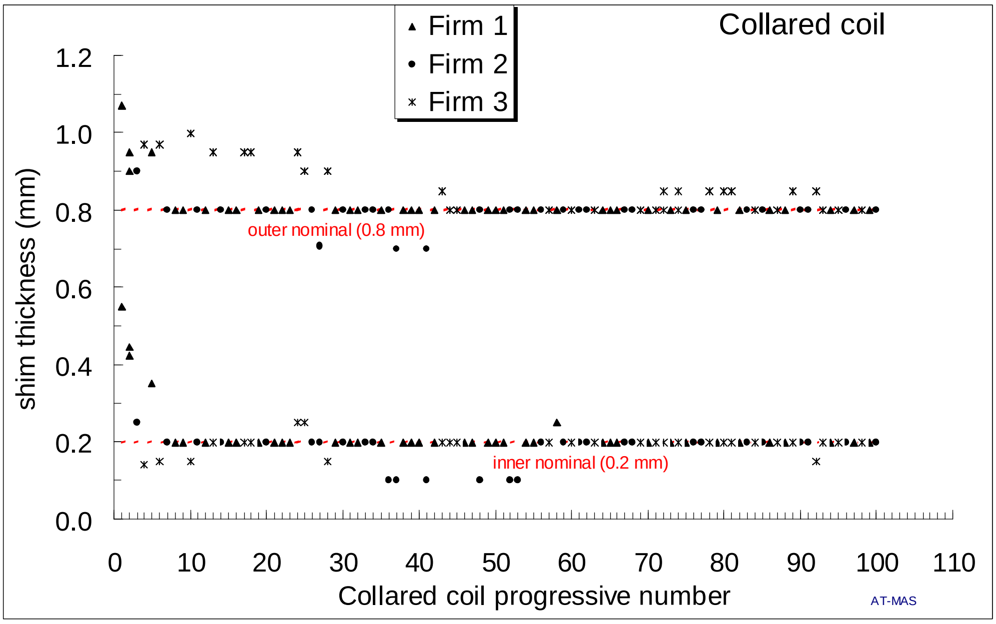


Fig. 2: Thickness of the polar shims used in the collared coils

2. Estimated coil waviness

- Coil waviness estimated from the variation of the multipoles along the axis is getting better in all Firms (among 15 and 25 microns, see Fig. 3).

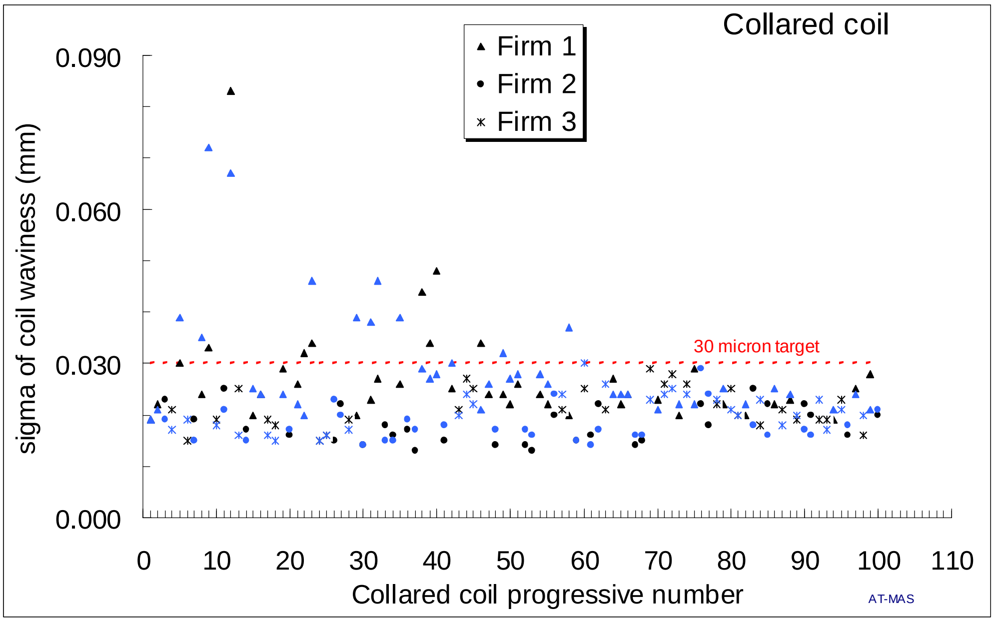


Fig. 3: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

3. Magnetic length and transfer function

- Magnetic lengths of collared coils 81st to 100th are well within targets (see Fig. 4). A small systematic difference between Firm3 and Firm1-2 of less than 5 units can be observed.

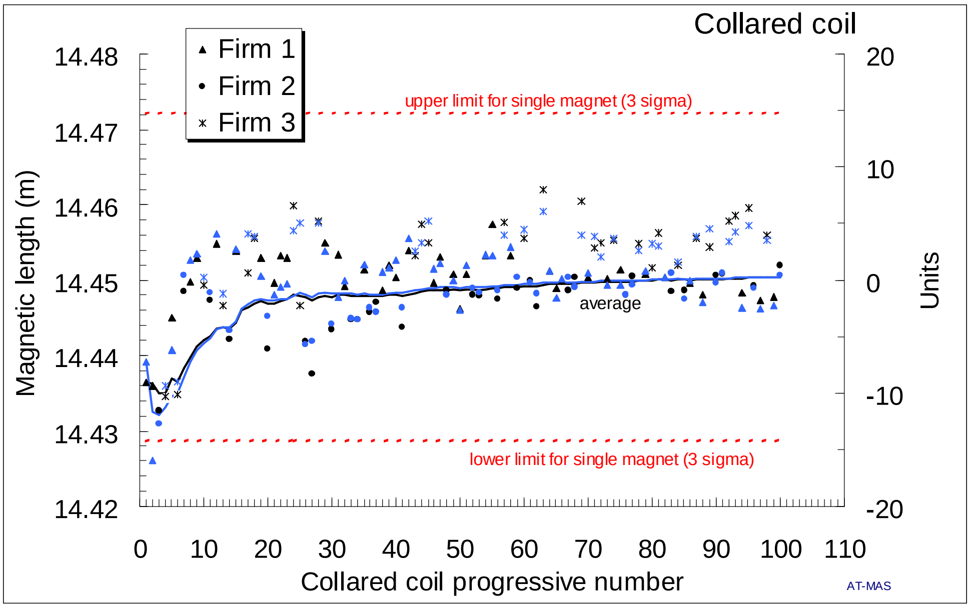


Fig. 4: Magnetic length of the measured collared coils (black dots: aperture 1, blue dots: aperture 2)

- The systematic difference of 17-20 units between Firm 3 and Firm 1-2 in the main field observed in the previous reports is changing. The situation at Firms 2 and 3 is stable, but 3 out of 6 Firm1 collared coils measured in these two months show a higher main field with respect to previous data (see 99th, 94th and 88th in Fig. 5-6). This is pushing up the main field at Firm1. We now observe 20 units between Firm2 and Firm 3, Firm1 being in between.
- This feature is not related to the new cross section: note in Fig. 6 that collared coil 57th has the old cross section, whilst 60th and 63rd have the new one.
- We point out that 20 units of main field could be given by a 0.2 % difference in the radius of the coil, i.e. 56 microns on the inner layer. We do not see related effects on allowed field harmonics.
- The induced sigma is 7.7 units over all collared coils, and of 8.9 units over the last 33 collared coils (11 per manufacturer). This is above the specification (5 units in the cold mass, 6 in the collared coils).
- We remind that the integrated main field (see next page) is the quantity relevant to beam dynamics.

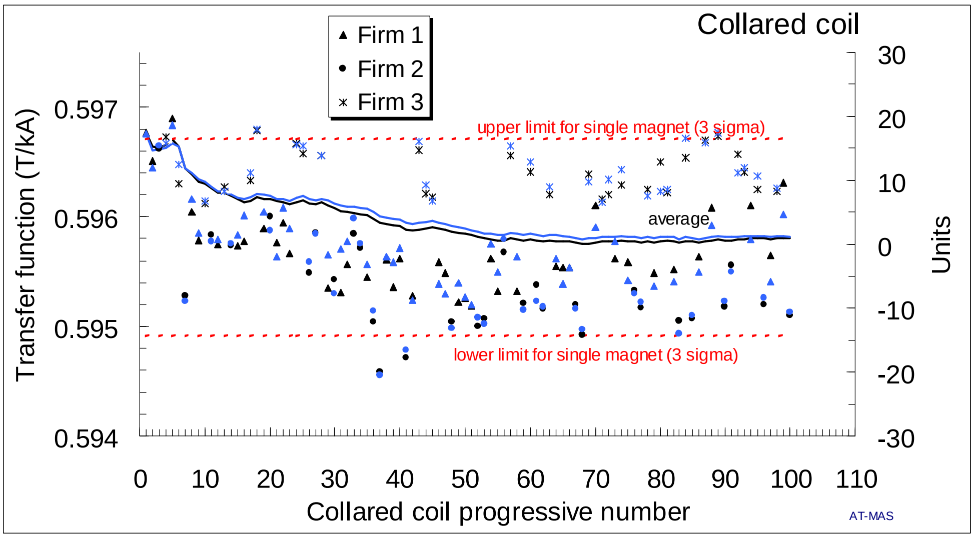


Fig. 5: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

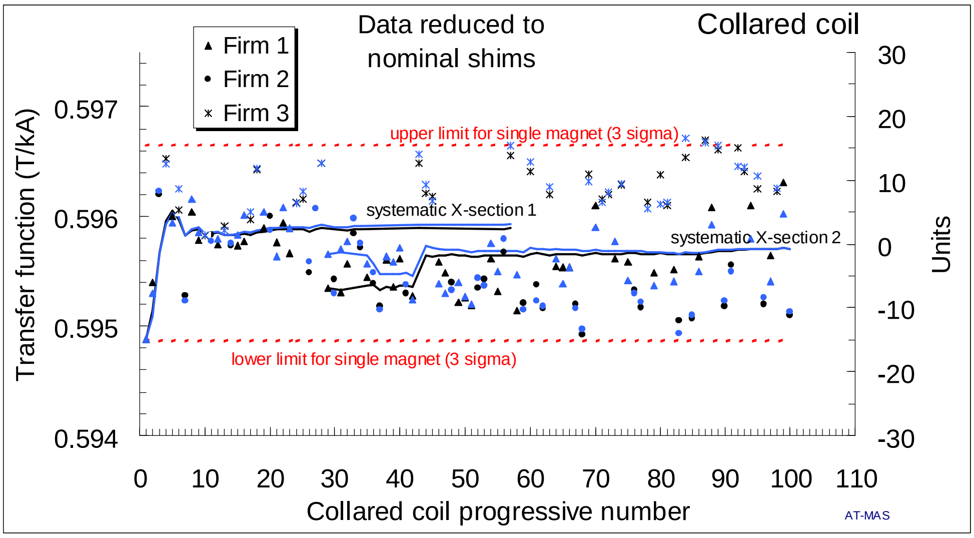


Fig. 6: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

- Integrated transfer function in the last 33 collared coils (11 per firm) has a sigma of 11 units. This is larger than the spec (9.6 in the collared coil, 8 units in the cold mass). Data relative to all collared coils and reduced to nominal shims give a sigma of 9.7 units, at the limit of the specification.
- Origins of the problem and possible cures are under analysis. A procedure for adding magnetic laminations in Firms showing low field and reducing their number in Firm3 has been started. This could cure up to 14 units of systematic difference. The impact of adding ferromagnetic laminations on magnetic length has been tested on two cold masses at Firm2, confirming the expected results (see web page http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/lamin.html for more information).

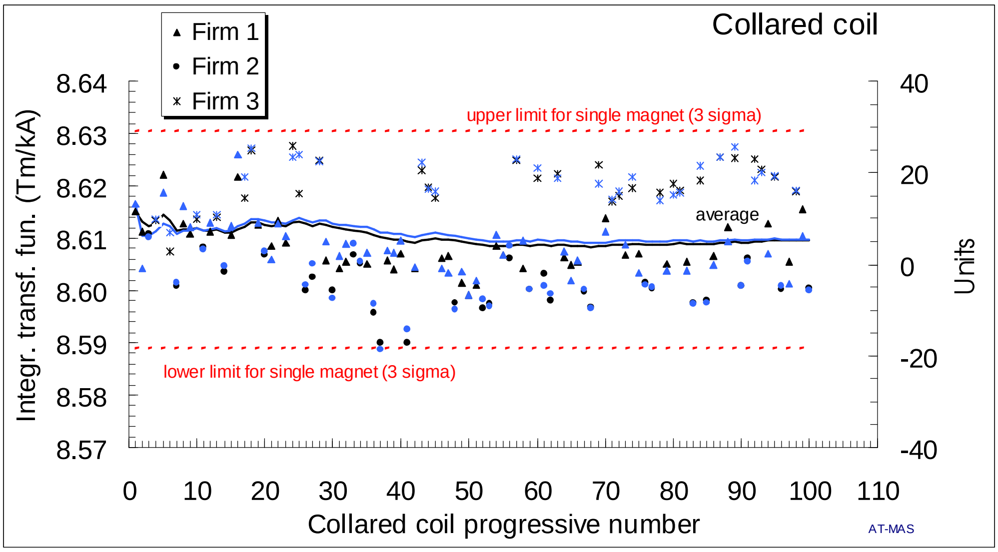


Fig. 7: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

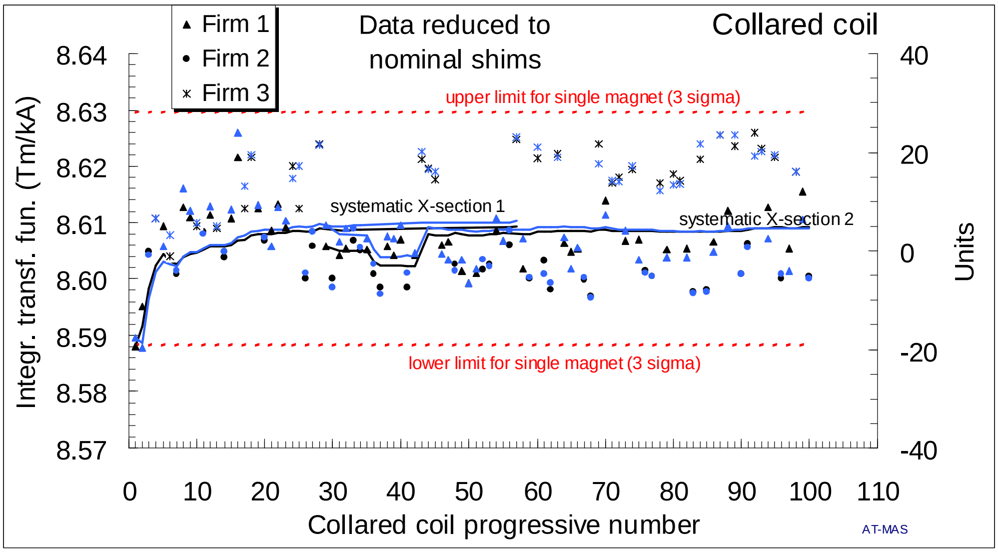


Fig. 8: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

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 6 and 7.

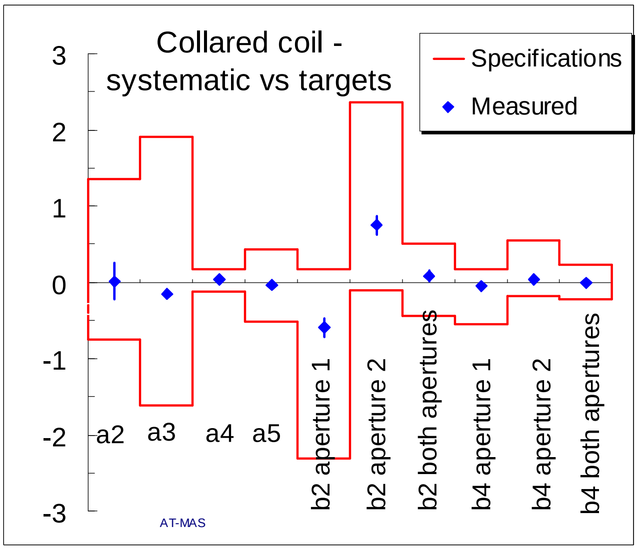
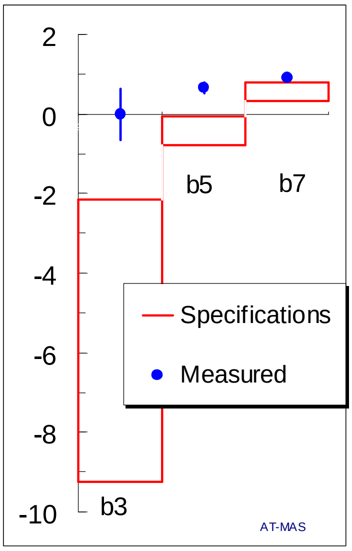


Fig. 9: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics.

- 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 2.15 and 0.71 units respectively.
- In the right part of Fig. 10, data are reduced to nominal shims and separated according the two cross-sections (35 collared coils have cross-section 1, 65 have cross-section 2). With the new X-section, b_3 b_5 and b_7 are larger than the specification of 1.07, 0.42 and 0.30 units respectively.



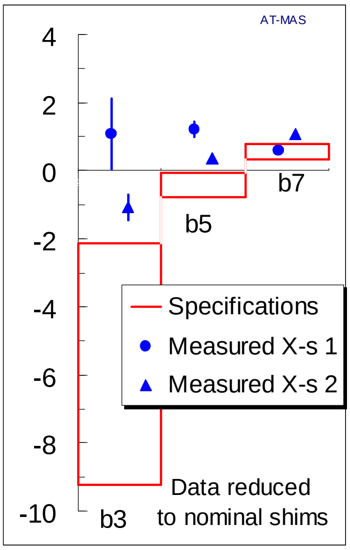


Fig. 10: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections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

5. Summary of systematic differences between firms

From the last two reports, we started to make a preliminary analysis of what are the main systematic differences between firms in collared coil data. We observe a relevant systematic difference between firms only for the main field:

- Main field: Firm 3 is higher than Firm 2 of around 20 units, Firm1 being in between (see Fig. 5). The global sigma (i.e. the sigma of all collared coils, with a complete mixing of manufacturers) is 10 units.

In other cases, we observe a small systematic difference between firms.

- Normal decapole b_5: Firm 1 is higher than Firm 2-3 of 0.6 units. Global sigma: 0.4 units. This is not negligible compared to the allowed range (0.7 units).
- Normal 14th pole b_7: Firm 1 b_7 is 0.25 units higher than Firm 2, Firm 3 being in between. Global sigma: 0.14 units. This is rather small if compared to the allowed range (0.5 units).
- Normal sextupole b_3: Firm 1 is higher than Firm 3 of 1.2 units, Firm 2 being in between. Global sigma: 1.2 units. This is completely negligible compared to the allowed range (7 units).

No systematic differences between firms are visible in a_2, a_3, a_4 and b_4. The previously reported systematic difference in b_2 has been strongly reduced in the last 20 collared coils.

6. 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.
- Four collared coils from Firm3 show an anomalous a_3 (see Fig. 12); this is not worrying for beam dynamics since margins are large.

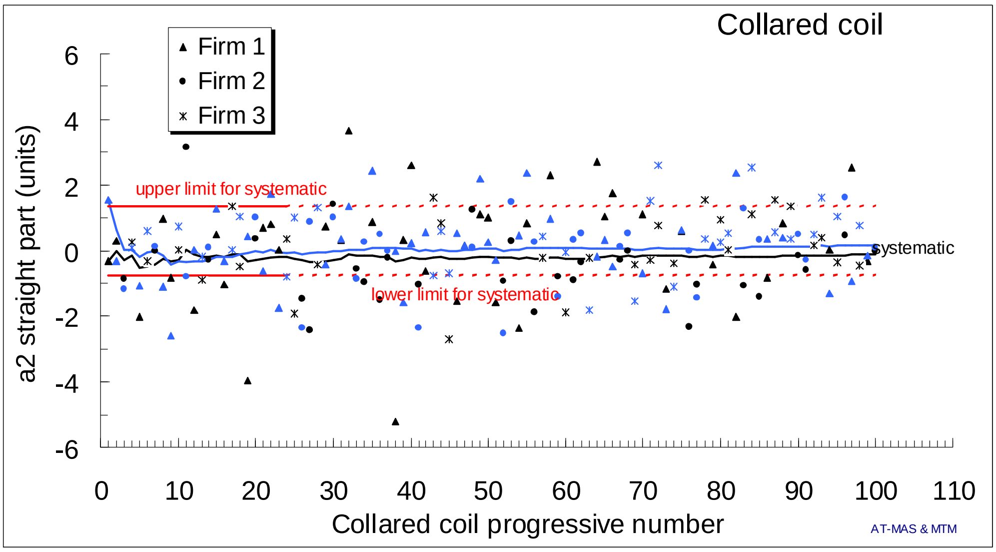


Fig. 11: Average a_2 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

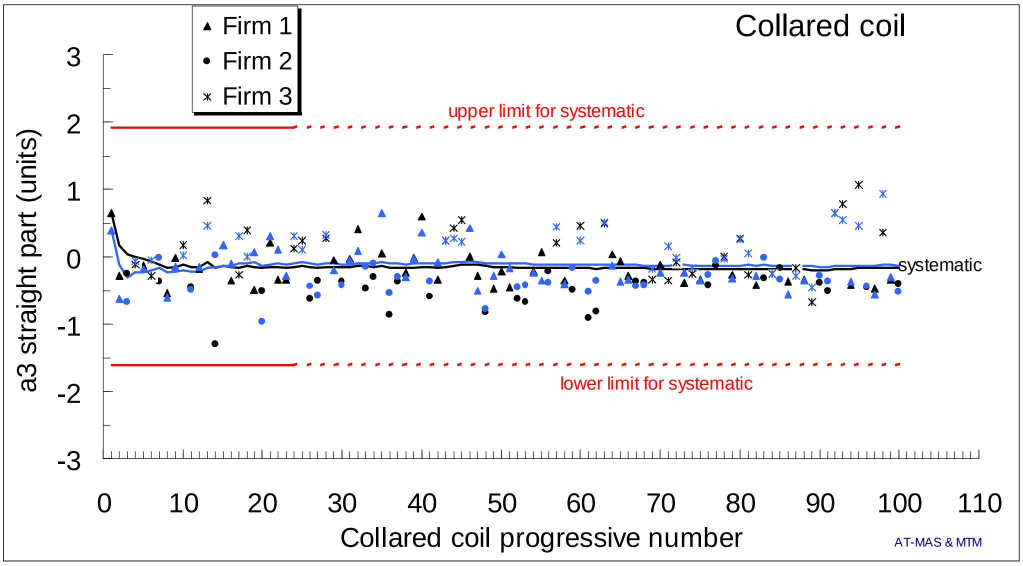


Fig. 12: Average a_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

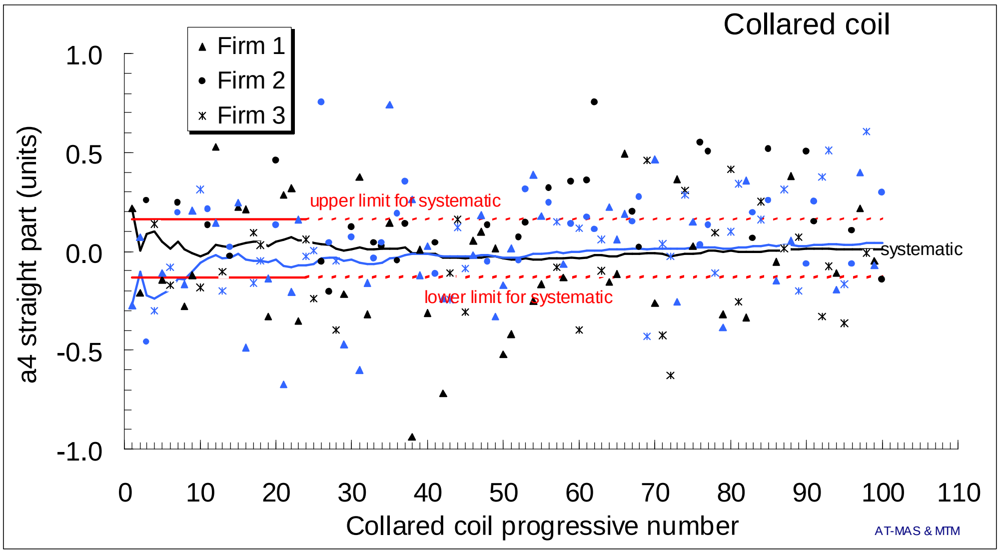


Fig. 13: Average a_4 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

7. 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).

7.1 Normal quadrupole

- The systematic difference between Firm 1-2 and Firm 3 of about 1.5 units observed in collared coils 40-80 is disappearing. Relations with collar manufacturer are under analysis.
- The systematic per aperture is within specifications in both apertures (see Figs. 14 and 15).

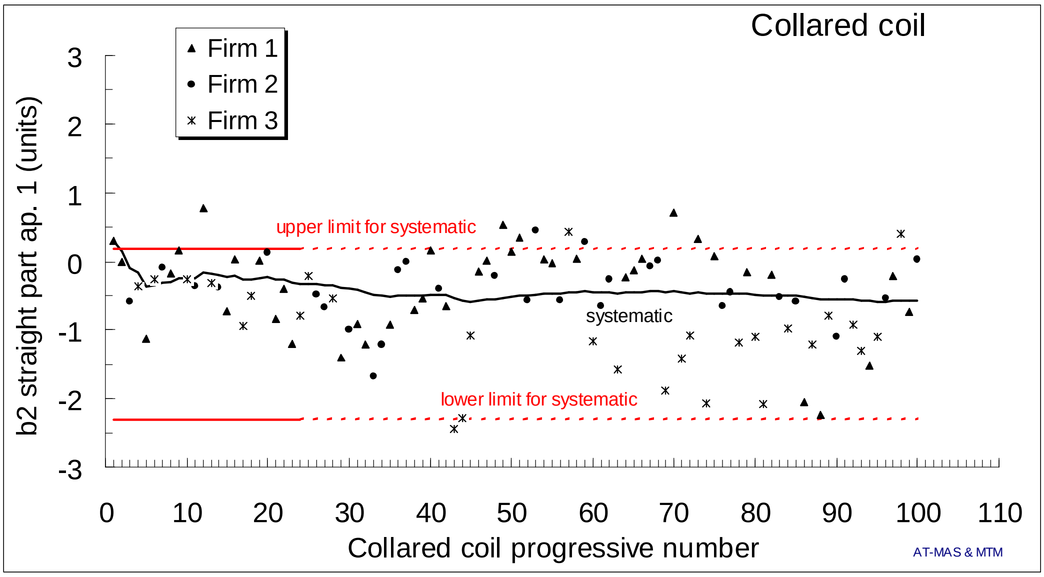


Fig. 14: Average b_2 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

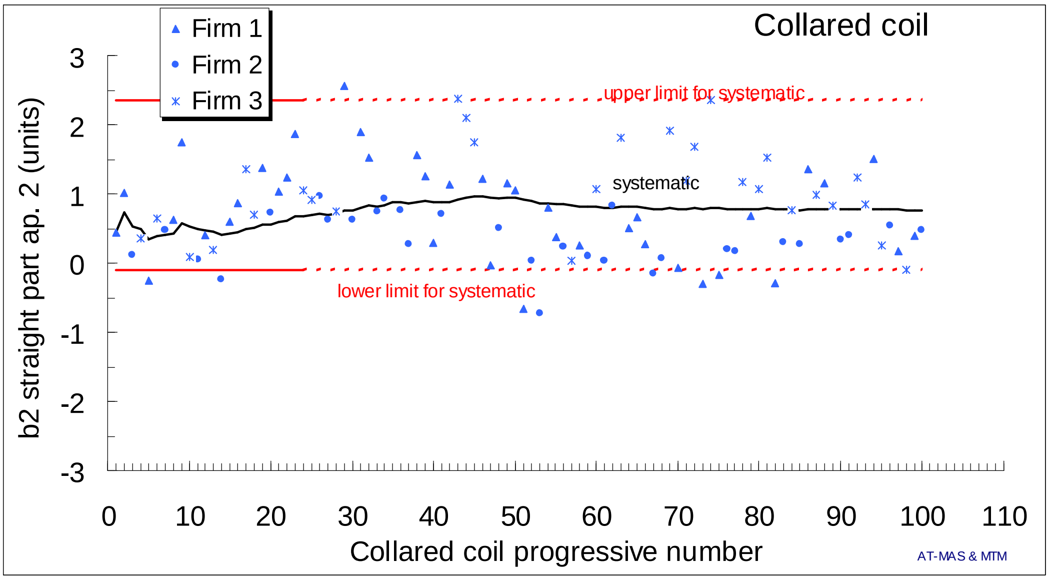


Fig. 15: Average b_2 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (blue line) and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

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

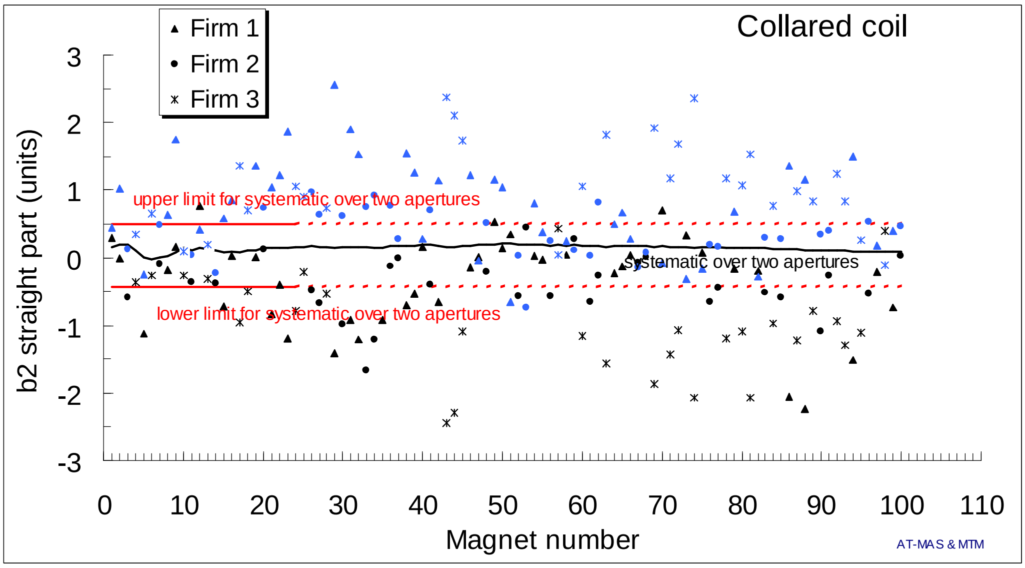


Fig. 16: Average b_2 in the straight part of collared coils ((black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (soild line) and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

7.2 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).

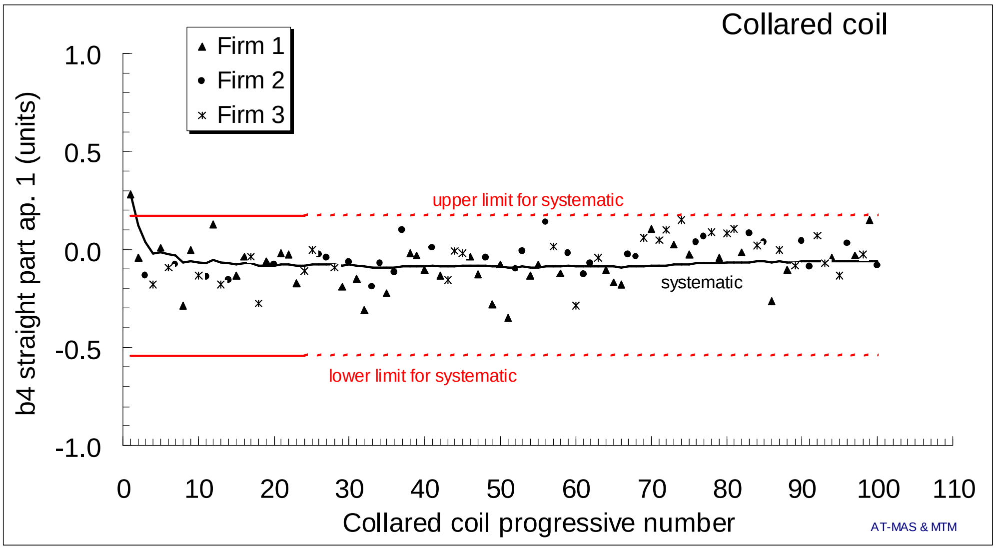


Fig. 17: Average b_4 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

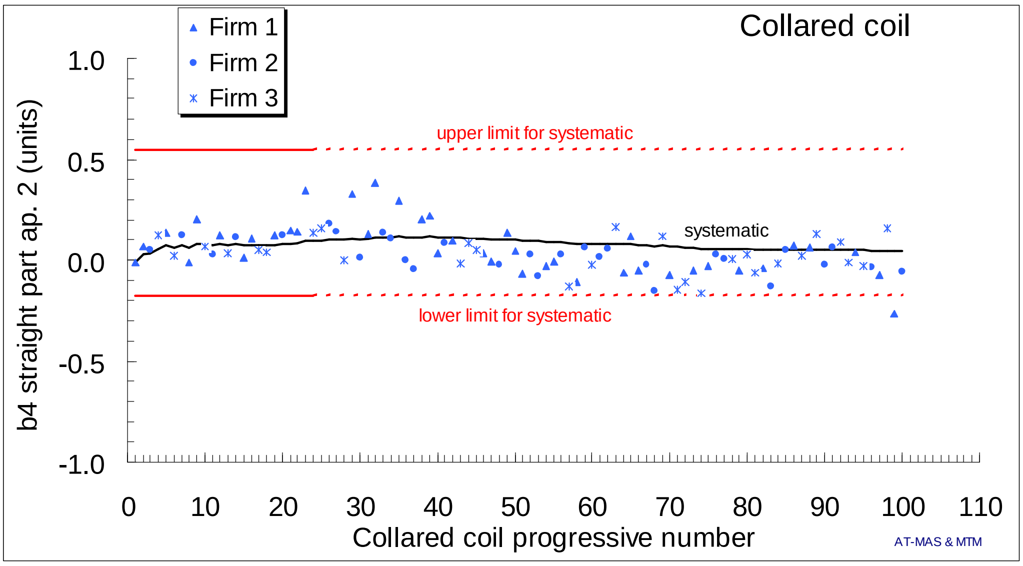


Fig. 18: Average b_4 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

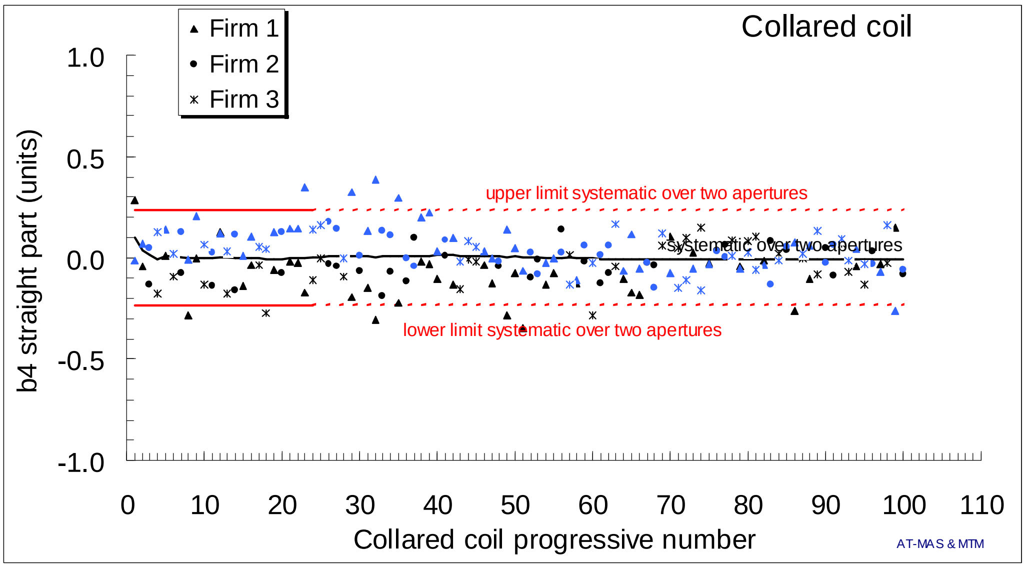


Fig. 19: Average b_4 in the straight part of collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

8. Systematic odd multipoles

8.1 Normal sextupole

- New data confirm the previous ones, with a small upward trend: the systematic in X-section 2 is 1.07 units larger than the limit (see fig. 21).
- Systematic differences between firms are small.
- Cryodipoles with the new X-section should feature 3.9 units of b_3 at high field; this is outside the specification but within the hard limit of 4.35 units given by the correction of chromaticity.

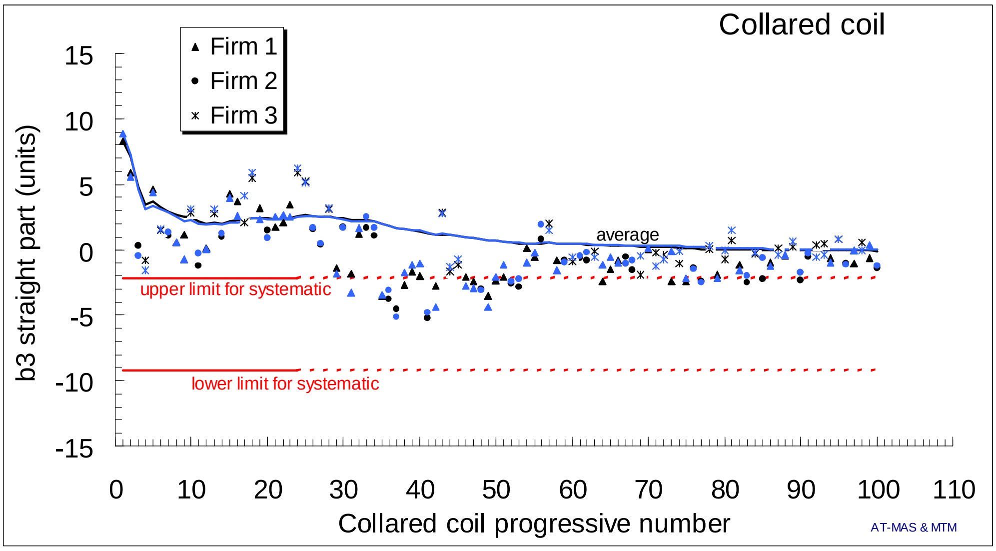


Fig. 20: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

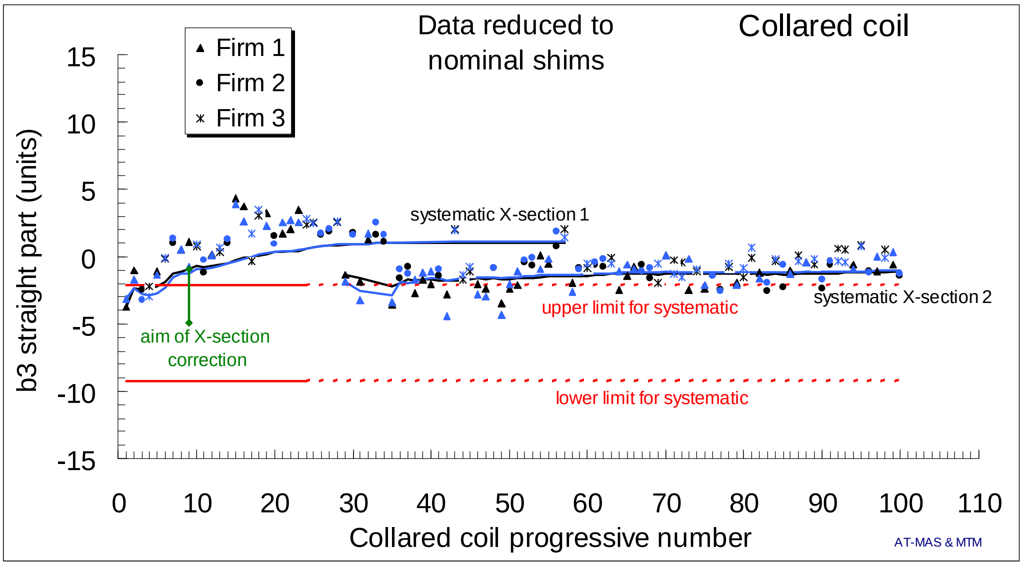


Fig. 21: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: ap. 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles. Data reduced at nominal shims and separated according to X-section type.

8.2 Normal decapole

- The average normal decapole is stable in Firm1 (around 0.7 units), increasing from around 0.2 to 0.4 units at Firm2, and decreasing from 0.3 to 0.0 units in Firm3. The best estimate for the systematic is stable at 0.37, i.e. 0.4 more than the limit for the collared coil.

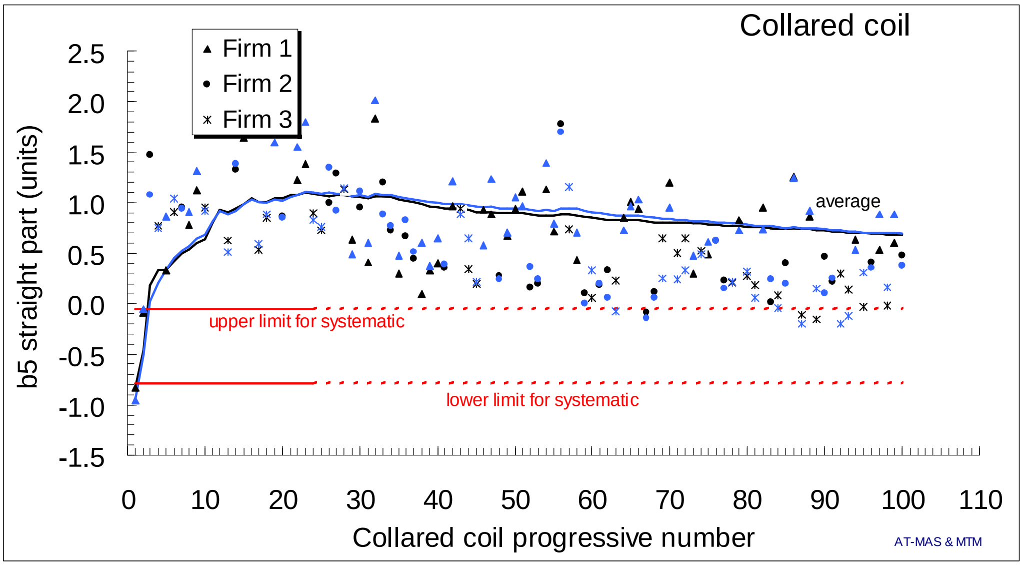


Fig. 22: Average b_5 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

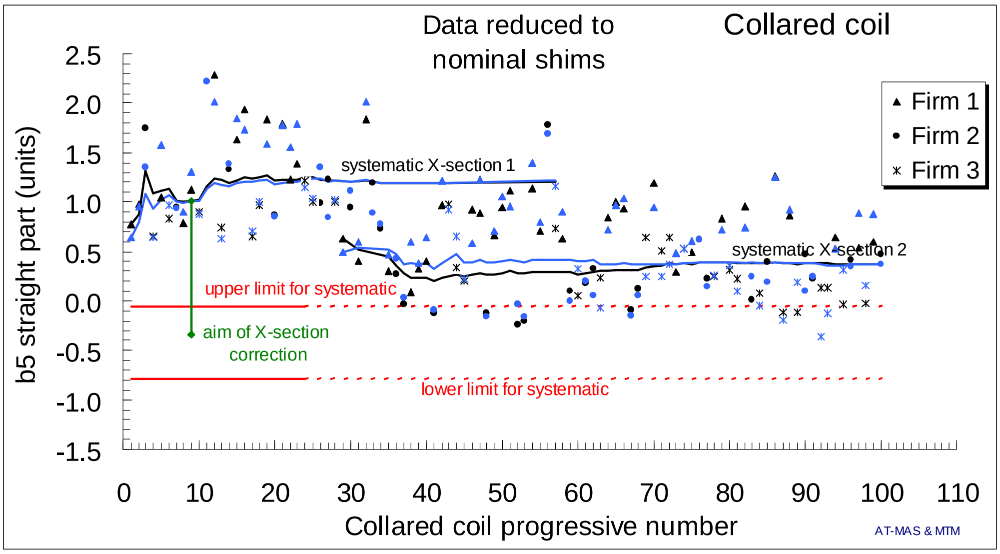


Fig. 23: Average b_5 in the straight part of the collared coil (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

8.3 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).
- Firm1 has an average of 1.20 units, but latest coils are around 1.30 units. Firm2 and Firm3 are stable at 1.0 and at 1.1 respectively. The negative trend in Firm2 has disappeared.
- The best estimate for the systematic is 1.07 units, which corresponds to 0.34 units at injection.

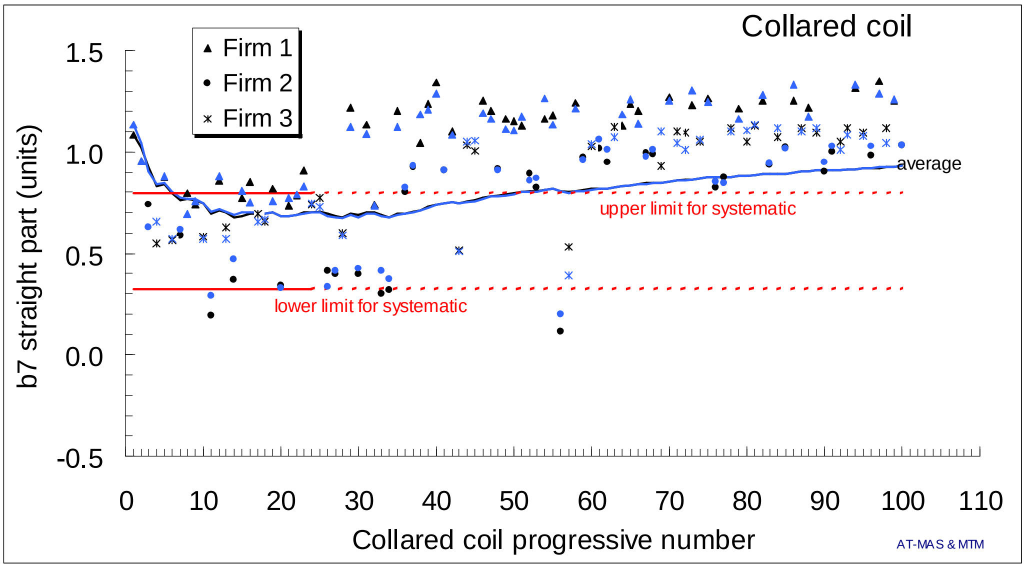


Fig. 24: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles.

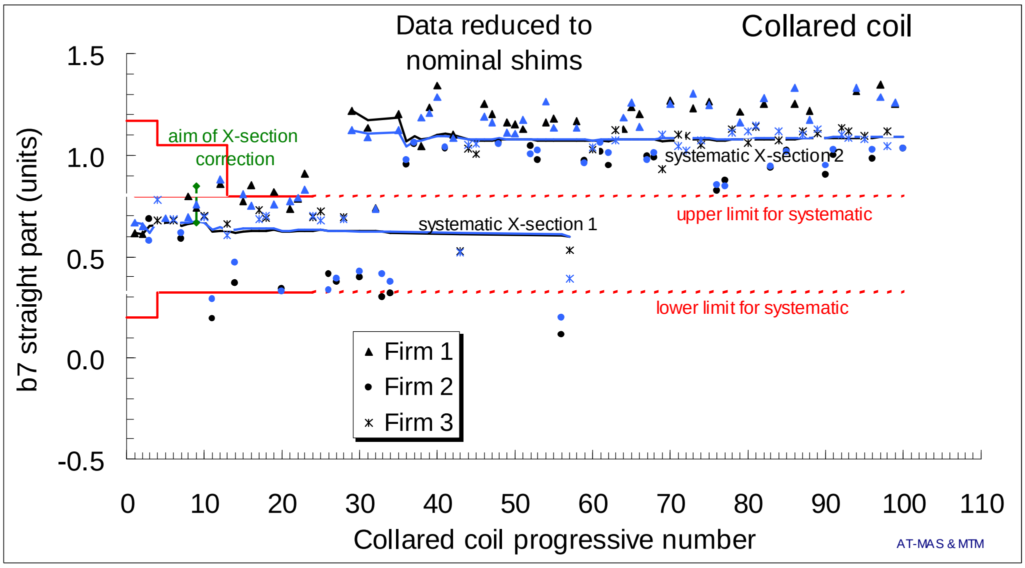


Fig. 25: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 24 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

9. Random multipoles

We repeat the same considerations made in the previous report.

- 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.
- We now have a good statistics for the new cross-section: all the multipoles are within specifications, global integrated main field BdL being slightly above the specification.

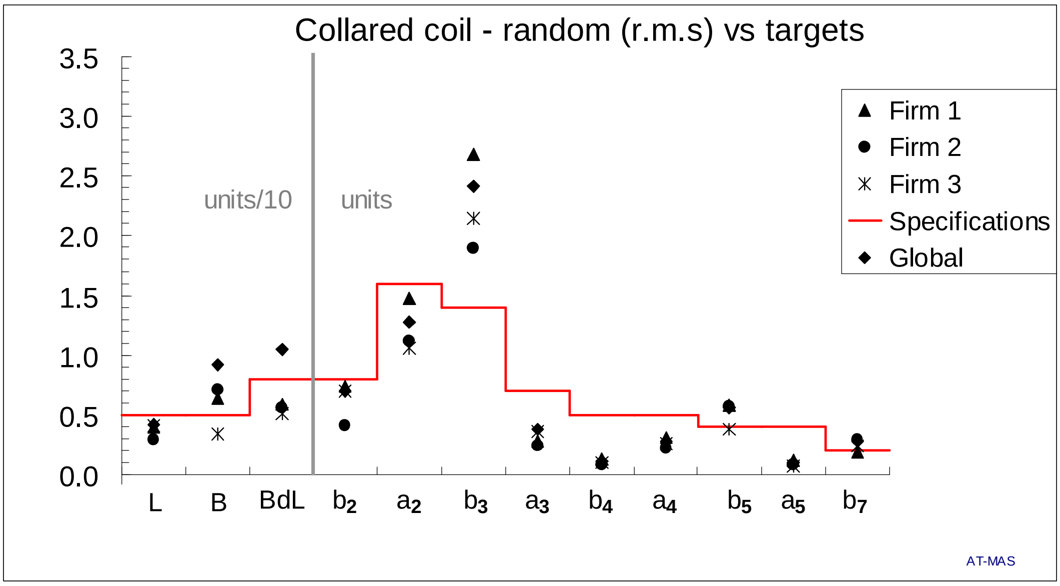


Fig. 26: Random component in the measured collared coils

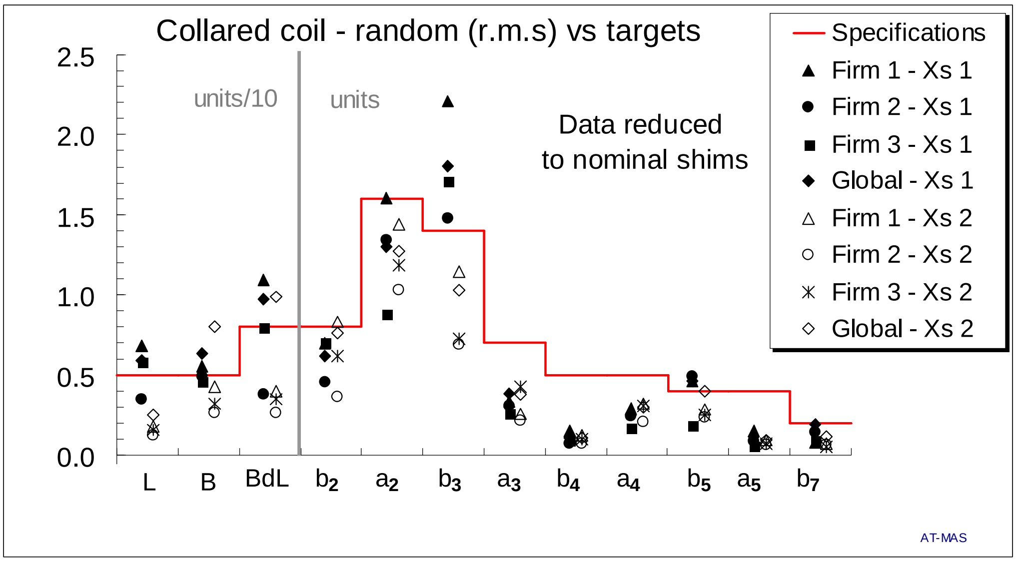


Fig. 27: Random component in the measured collared coils. Data reduced to nominal shims and split according to different cross-sections.

10. Holding point results

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

	Magnet name	Collared coil measure	Result	Comments
81st	3022	12/03/03	OK	Non-nominal shims used in the outer layers of both apertures
82nd	1036	12/03/03	OK	
83rd	2026	20/03/03	Ok-W	Yellow alarm on multipole b3 in the heads of both apertures NCS
84th	3023	20/03/03	OK	
85th	2027	21/03/03	Ok-W	Yellow alarm on multipole b3 in the head of aperture 1 NCS, red alarm on multipole b3 in the head of aperture 2 NCS
86th	1037	25/03/03	OK	Measurement with the new system - accepted in the hypothesis of mag len smaller of 20 mm - main field smaller of 2.3 mT/kA
88th	3024	26/03/03	OK	
88th	1038	28/03/03	OK	Measurement with the new system - accepted in the hypothesis of mag len smaller of 20 mm - main field smaller of 2.3 mT/kA
89th	3025	02/04/03	OK	Non-nominal shims used in the outer layers of both apertures
90th	2028	02/04/03	OK	Yellow alarm on b3 in the heads of both apertures NCS
91st	2029	03/04/03	OK	Yellow alarm on b3 in the heads of both apertures NCS
92nd	3027	03/04/03	OK	Non-nominal shims in all layers
93rd	3028	08/04/03	OK	
94th	1045	15/04/03	OK	Measurement with the new system - accepted in the hypothesis of mag len smaller of 20 mm - main field smaller of 2.3 mT/kA
95th	3029	14/04/03	OK	
96th	2030	16/04/03	OK	Yellow alarm on b3 in the heads of both apertures NCS
98th	1039	18/04/03	OK	Measurement with the new system - accepted in the hypothesis of mag len smaller of 20 mm - main field smaller of 2.3 mT/kA
99th	3030	17/04/03	OK	
99th	1041	29/04/03	OK	Measurement with the new system - accepted in the hypothesis of mag len smaller of 20 mm - main field smaller of 2.3 mT/kA
11th	2002	17/04/03	OK	Third collaring – multipole change with respect to second collaring (especially b5)
57th	3010	26/04/03	OK	Second collaring – no multipole variations, main field larger of 5 units
100th	2031	29/04/03	OK	Yellow alarm on multipole b3 in the head of aperture 1 NCS, red alarm on multipole b3 in the head of aperture 2 NCS

- 2002 has been collared for the third time. Also in this case, we observe a field quality variation which is not negligible. Therefore, there is no indication of a saturation of the effect.
- 3010 has been recollared. This is the first measured impact of recollaring on field quality. No effect is found on multipoles, some change is observed in the main field.
- Both collared coil have been released. Summary of the impact of re-collaring on field quality in Table II. Information in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/1027.html

Table II: Multipole variation due to recollaring, measurements on 6 cases.

Magnet	Ap.	c1	b3	b5	b7	b9
2002	1	-2.4	0.39	0.18	-0.04	-0.005
2002	2	-3.0	0.51	0.14	-0.05	-0.003
2011	1	1.0	-0.80	0.65	-0.28	0.016
2011	2	0.6	-0.67	0.50	-0.23	0.009
2013	1	3.4	-0.63	0.54	-0.09	0.024
2013	2	4.7	-0.38	0.50	-0.11	0.028
1027	1	-0.3	-0.43	0.25	-0.04	0.007
1027	2	0.2	-0.46	0.39	-0.05	0.004
2002	1	-0.2	-0.47	0.63	-0.33	0.085
2002	2	0.3	-0.22	0.36	-0.23	0.076
3010	1	5.5	0.06	-0.07	-0.08	0.010
3010	2	4.2	-0.28	-0.02	-0.11	0.014

10. Acknowledgements

Magnetic measurements have been taken through personnel and instrumentation of the LHC-MMS-IF and LHC-MMS-MD section; in particular, G. Brun, G. Busetta, R. Camus, P. Galbraith, G. Molinari, A. Musso. Measurements at one of the Firms performed by M. Zehner and R. Moresi. We wish to acknowledge J. Billan, B. Bellesia, F. Bertinelli, L. Bottura, A. Devred, P. Fessia, S. Pauletta, V. Remondino, L. Rossi, S. Sanfilippo, W. Scandale, A. Schiappapietra, I. Vanenkov, E. Wildner for valuable help and discussions. Thanks to C. Vollinger for collared coil analysis and comments on the manuscript.

Appendix A

The link between the progressive number used in Figures and the official name is given in Table III.

Table III: relation between magnet numbers used in Figs. 2-25 and official names

1st	1001	21st	1010	41st	2014	61st	2015	81st	3022
2nd	1002	22nd	1011	42nd	1021	62nd	2020	82nd	1036
3rd	2001	23rd	1012	43rd	3011	63rd	3015	83rd	2026
4th	3001	24th	3007	44th	3012	64th	1020	84th	3023
5th	1003	25th	3008	45th	3013	65th	1030	85th	2027
6th	3002	26th	2008	46th	1026	66th	1031	86th	1037
7th	2003	27th	2007	47th	1022	67th	2021	87th	3024
8th	1004	28th	3009	48th	2016	68th	2022	88th	1038
9th	1005	29th	1013	49th	1023	69th	3016	89th	3025
10th	3003	30th	2006	50th	1024	70th	1032	90th	2028
11th	2002	31st	1014	51st	1025	71st	3018	91st	2029
12th	1006	32nd	1015	52nd	2017	72nd	3017	92nd	3027
13th	3004	33rd	2010	53rd	2018	73rd	1033	93rd	3028
14th	2005	34th	2009	54th	1027	74th	3019	94th	1045
15th	1007	35th	1016	55th	1028	75th	1034	95th	3029
16th	1008	36th	2013	56th	2011	76th	2023	96th	2030
17th	3005	37th	2012	57th	3010	77th	2025	97th	1039
18th	3006	38th	1017	58th	1029	78th	3021	98th	3030
19th	1009	39th	1018	59th	2019	79th	1035	99th	1041
20th	2004	40th	1019	60th	3014	80th	3020	100th	2031