Report on field quality in the main LHC dipole collared coils: January-February 2003

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This report gives data relative to field quality measured in collared coils during the period January 1– February 28 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. **375564**

The dashboard

- Available measurements: 80 collared coils, 41 cold masses, 18 cryodipoles.
- In these two months, 12 collared coils: 4 from Firm 1, 2 from Firm 2 and 6 from Firm 3.

What's new

- **Open case**: Field quality variation after a recollaring: collared coil 2023 has been decollared for electrical problems**.** Even though it has not been measured before the decollaring, magnetic measurements relative to the second collaring show a clear increase of b_5 (0.5 units) with respect to previous and following Firm 2 collared coils. This is consistent with has been already observed (see http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/2013.html). The collared coil has been accepted.
- **Trends in integrated main field**: The systematic difference in integrated main field between Firm 1-2 and Firm 3 has been decreased from about 20 units to about 17 units in the collared coils manufactured in the last two months. Data, origins of the problem and possible cures are under analysis. More information in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/bdl_firm3.html and in Section 3, pg. 4-5.
- **Trends in b_2**: We start to observe a systematic difference in integrated b_2 between Firm 1-2 and Firm 3 of about 1.5 units. 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.
- **Special experiments**: the dedicated experiment on the effect of the midplane insulation on field harmonics is going on in building 927 under the supervision of D. Tommasini and H. Kummer. The linearity of the dependence of multipoles on insulation thickness of the inner layer has been successfully checked. Moreover, a change of 50 micron on the outer layer has given a change of multipoles in agreement with the model. On-line information available at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/midpl_insul.html. Two more tests are planned.
- **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

- 12 collared coils have been measured (collared coils 69th to 80th)
  - 4 of Firm 1 (1032-1035, plus a third measurement of 1027)
  - 2 of Firm 2 (2023 and 2025)
  - 6 of Firm 3 (3016-21)

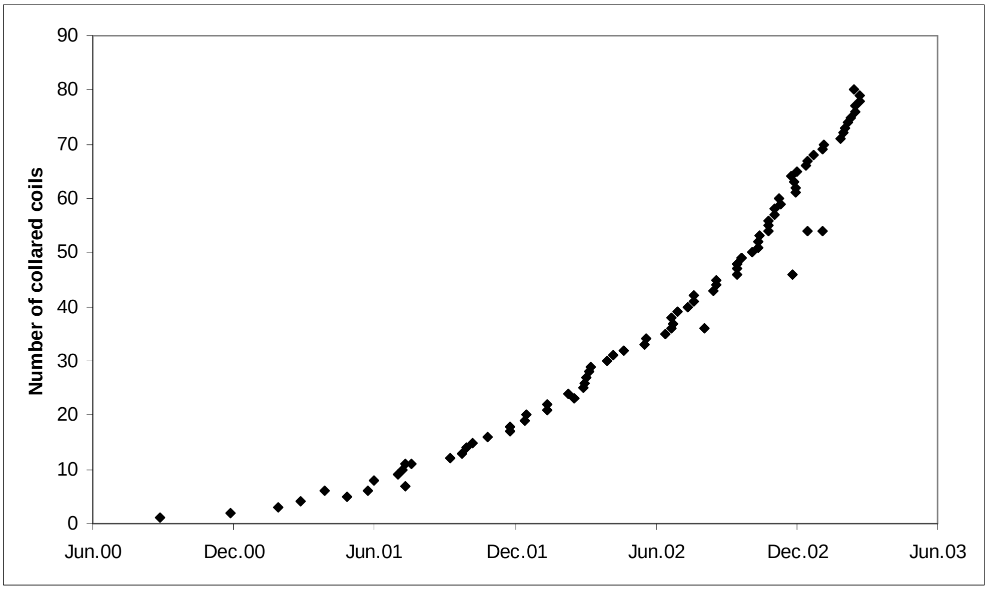


Fig. 1: Number of measured collared coils versus time. Dots out of the main trend are relative to collared coils measured more than one time.

- Cross section: from now on, all magnets with cross section 2.
- All shims are nominal, with the exception of a 0.05 mm more on the outer layers for four Firm 3 collared coils (see Fig. 2). This has a very limited impact on field quality.

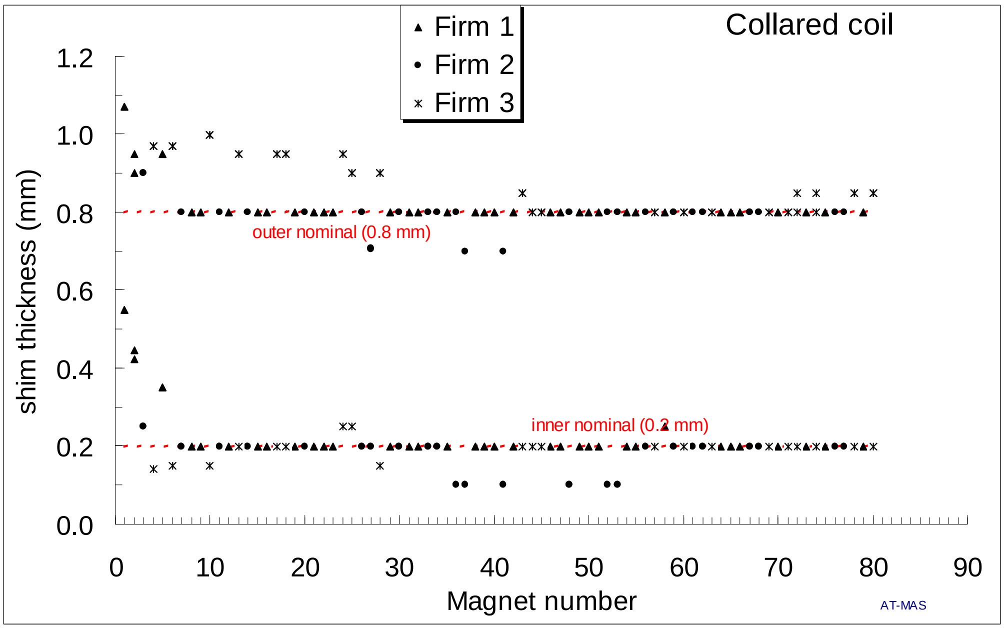


Fig. 2: Thickness of the polar shims used in the collared coils

2. Estimated coil waviness

- Coil waviness estimated from the variation of the multipole along the axis is getting better at Firm 1 and is slightly deteriorating at Firm 2 and 3 (see Fig. 3). Now all the firms are among 20 and 30 microns.

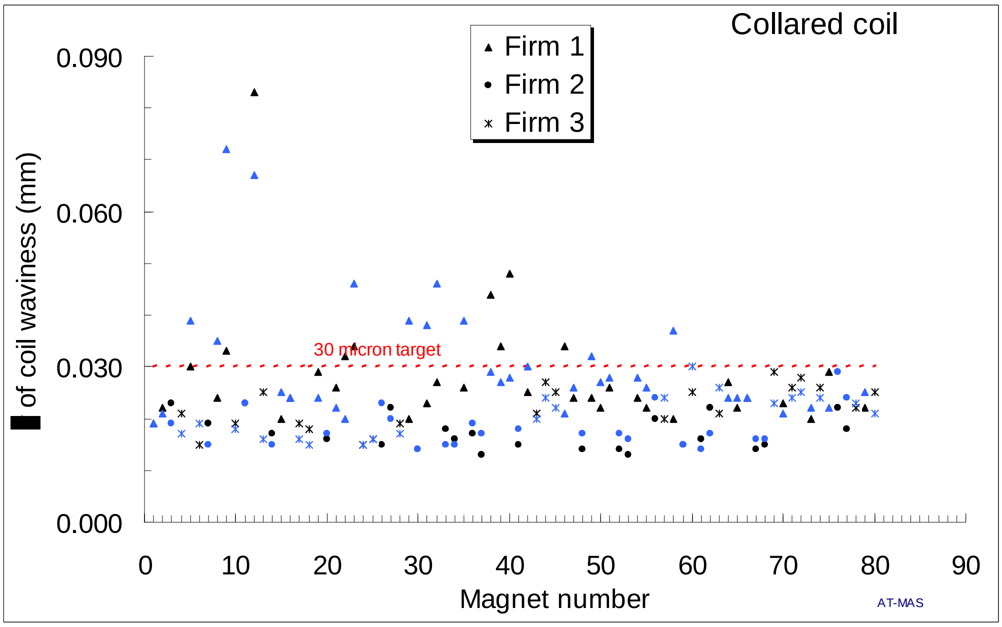


Fig. 3: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

3. Magnetic length and transfer function

- Magnetic lengths of collared coils 69th to 80th are within targets (see Fig. 4). Differences between firms are decreasing in the data of the last 12 collared coils. All data are by far within specifications.

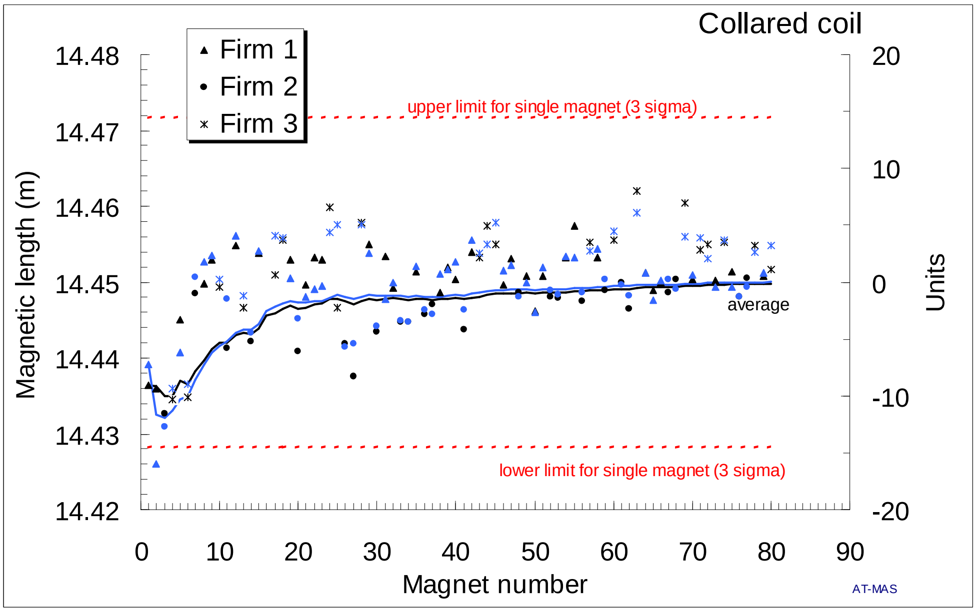


Fig. 4: Magnetic length of the measured collared coils (black dots: aperture 1, blue dots: aperture 2)

- The systematic difference of 20 units between Firm 3 and Firm 1-2 in the main field observed in the previous report seems to decrease in the last 12 collared coils (see Fig. 5 and Fig. 6 for data reduced to nominal shims). In particular, the collared coil 1032 (70th in figs. 5 and 6), produced at Firm 1, shows a rather high value of the field, comparable with the Firm 3 coils.
- 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 field harmonics.
- The last 12 collared coils feature a systematic difference of about 17 units. The induced sigma is 7 units over all collared coils, and of 8 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).
- The very low spread observed in the magnetic length helps reducing the spread in the integrated main field (see next page), which is the quantity relevant to beam dynamics.

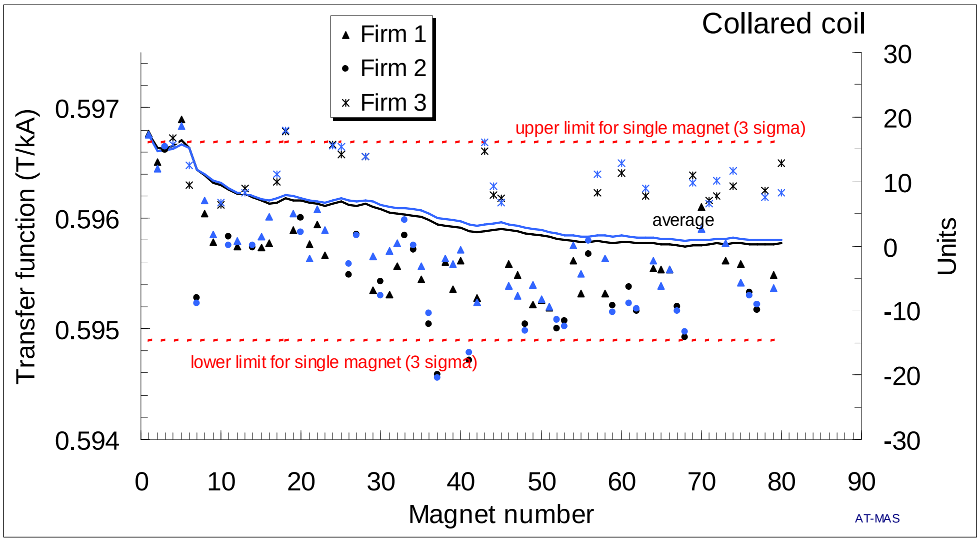


Fig. 5: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

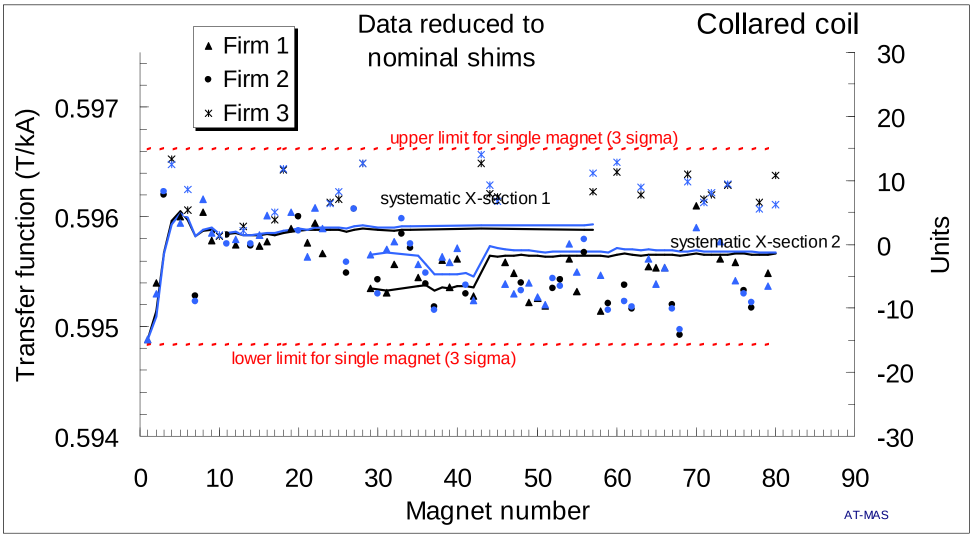


Fig. 6: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

- Integrated transfer function in the last 33 collared coils (11 per firm) has a sigma of 10 units. This is at the limit of the spec (8 units in the cold mass, 9.6 in the collared coil). Data relative to all collared coils and reduced to nominal shims give a sigma of 9 units, at the limit of the specification.
- Origins of the problem and possible cures are under analysis (see web page http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/bdl_firm3.html for more information).

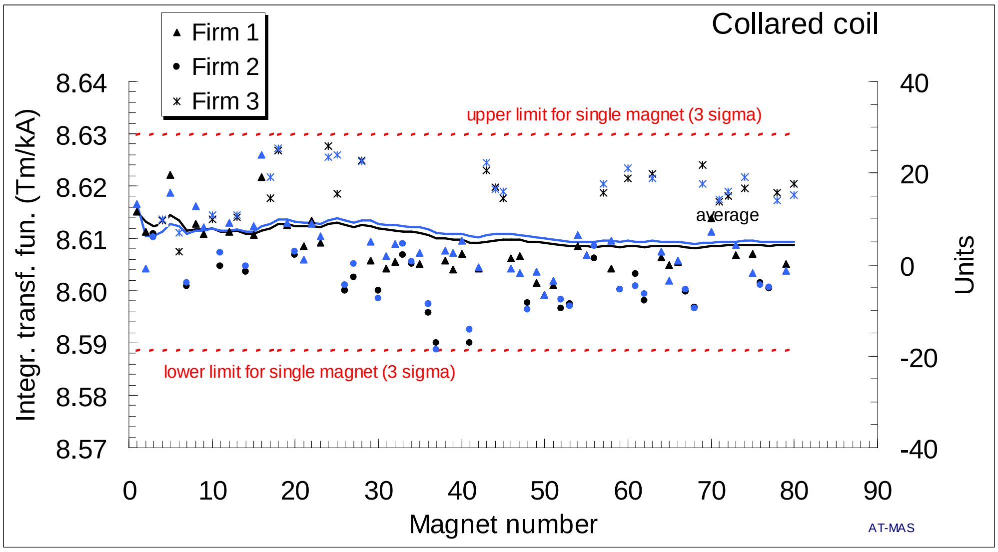


Fig. 7: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

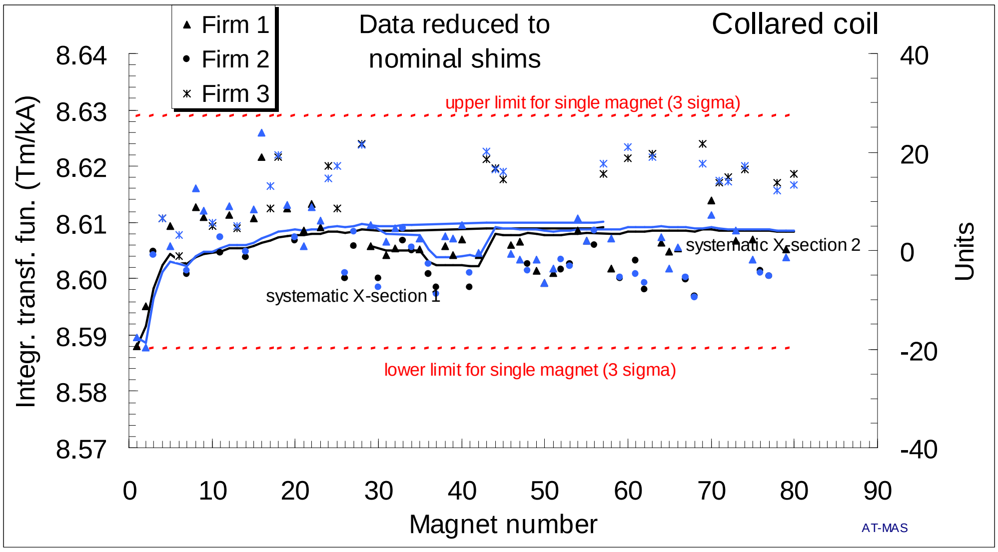


Fig. 8: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

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.

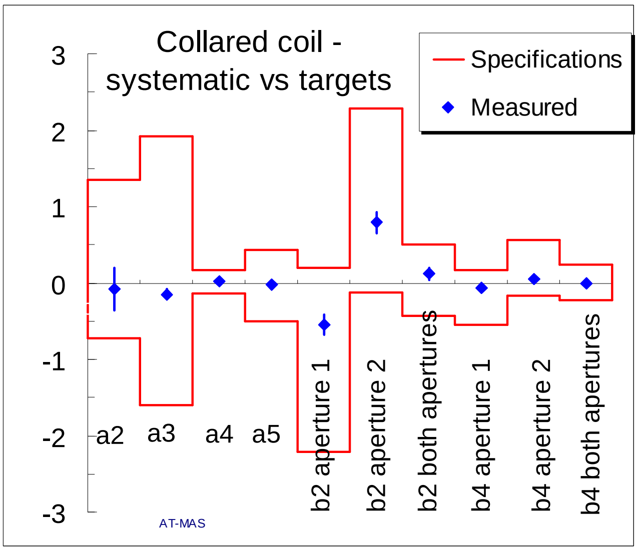
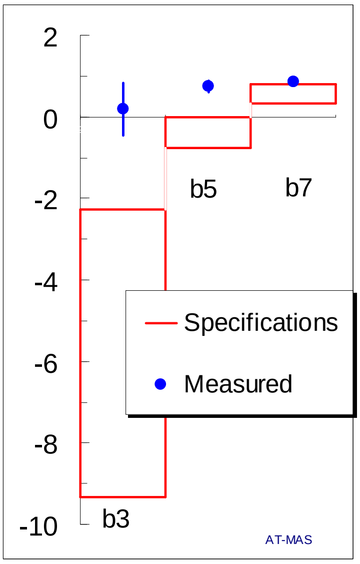


Fig. 9: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics.

- 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 2.35 and 0.75 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, 45 have cross-section 2). With the new X-section, b_3 b_5 and b_7 are larger than the specification of 0.9, 0.40 and 0.28 units respectively.



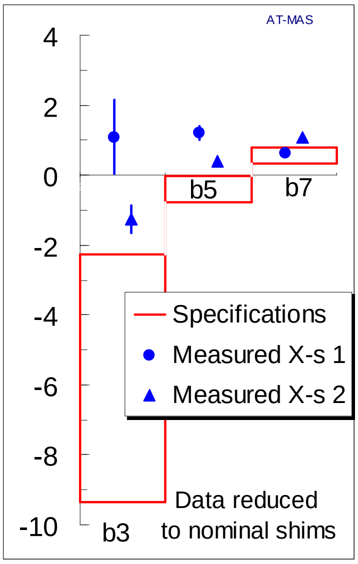


Fig. 10: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections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

5. Summary of systematic differences between firms

From the last report, we started to make a preliminary analysis of what are the main systematic differences between firms in collared coil data. We observe a non-negligible systematic differences between firms in the following cases:

- Main field: Firm 3 is higher than Firm 1-2 of around 17 units (see Fig. 5)
- Normal decapole b_5: Firm 1 is higher than Firm 2 of 0.8 units, and is higher than Firm 3 of 0.4 units. This is a large difference compared both to the allowed range (0.7 units) and to the natural random component (0.5 units) (see Fig. 23).
- Normal quadrupole b_2: The last 40 collared coils show a systematic difference of 1.5 units between Firm 3 and Firm 1-2 (see Figs. 14 and 15). Indeed, this difference helps to keep the systematic in the centre of the allowed range.
- Normal 14th pole b_7: Firm 1 is 0.10 higher than Firm 3 and 0.15 higher than Firm 2 (see Fig. 25). This is rather small if compared both to the allowed range (0.5 units) and to the random component (0.2 units). Indeed, the two collared coils from Firm 2 measured in these two months have a much lower b_7. The same negative trend in Firm 2 was observed in the first cross-section.

No systematic differences between firms are visible in a_2, a_3, a_4 and b_4. The previously reported systematic difference in a_3 has been strongly reduced in the last 12 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.
- The small differences of about 0.8 unit in systematic a_3 between Firm 3 and Firm 1-2 observed in collared coils 40 to 70 is disappearing (see Fig. 12).

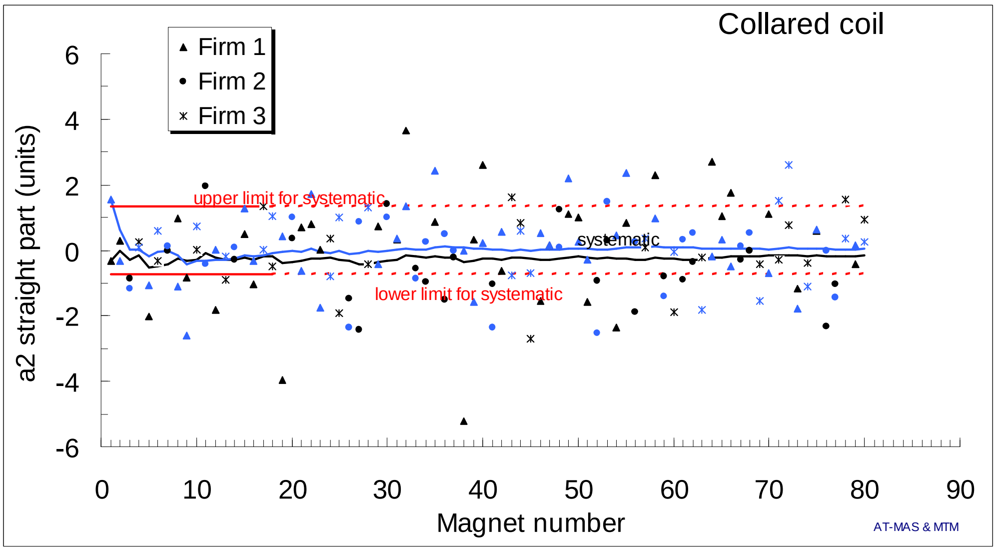


Fig. 11: Average a_2 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

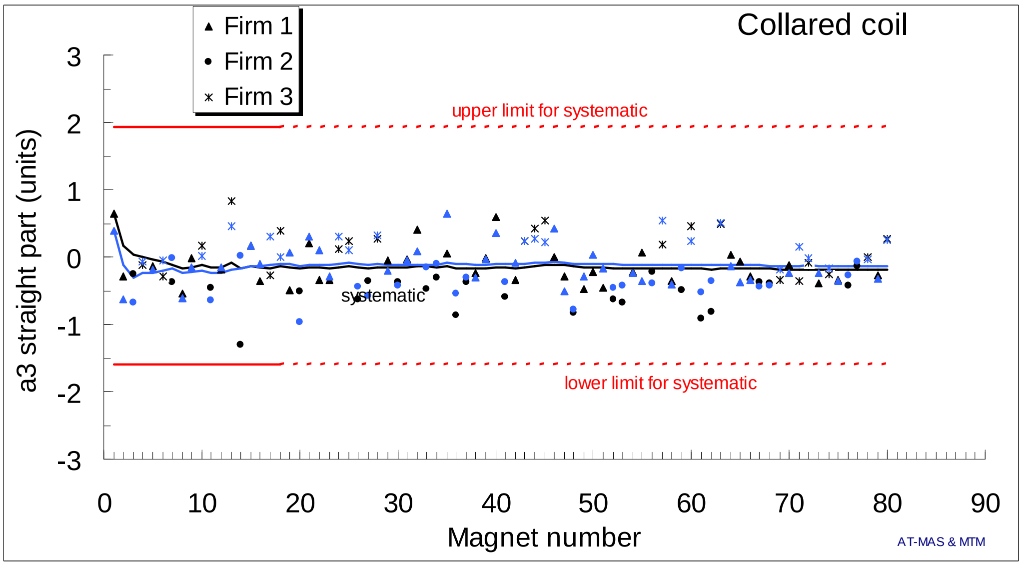


Fig. 12: Average a_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

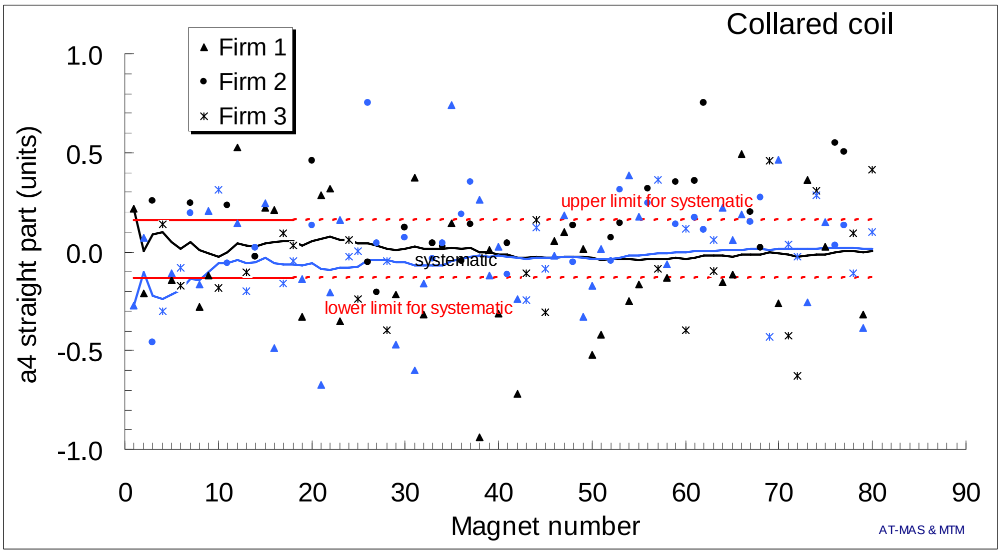


Fig. 13: Average a_4 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

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 per aperture is within specifications in both apertures (see Figs. 14 and 15).
- We observe a systematic difference between Firm 1-2 and Firm 3 of about 1.5 units in the last 50 collared coils. First analysis by W. Scandale, A. Schiappapietra, I. Vanenkov and C. Vollinger show that this could be related to the collars. Indeed, this feature is helping in keeping the average in the centre of the allowed range.

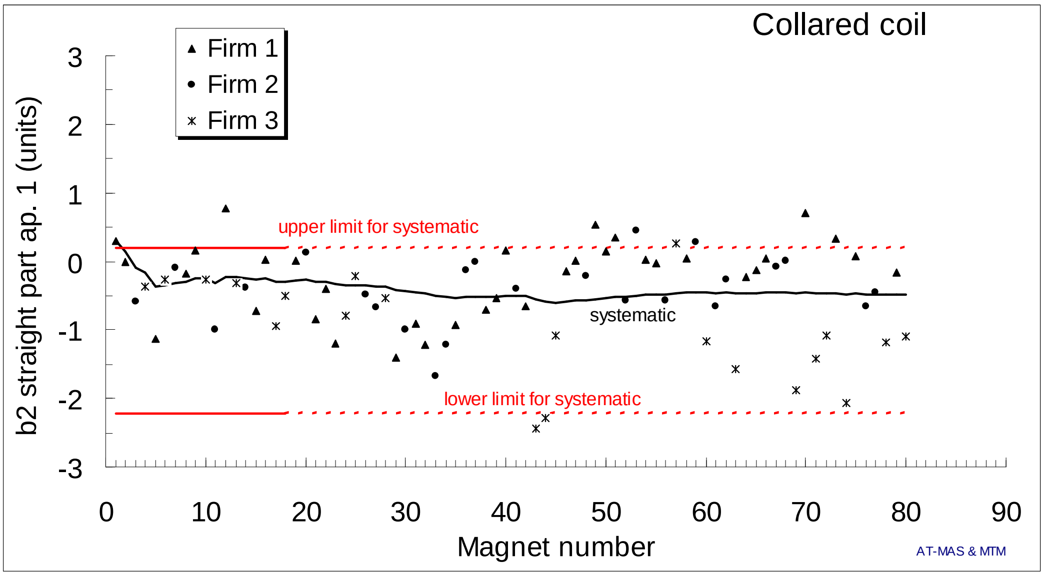


Fig. 14: Average b_2 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

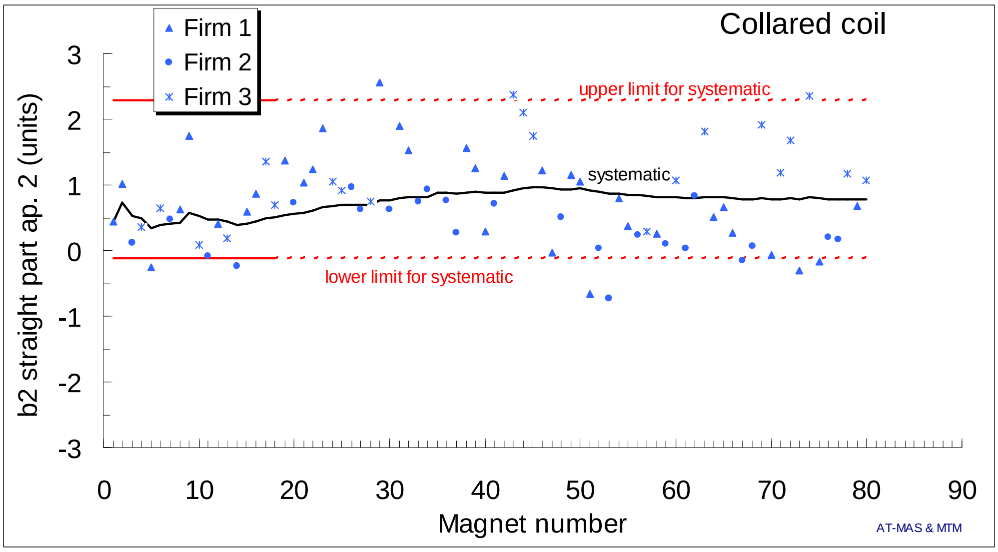


Fig. 15: Average b_2 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (blue line) and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

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

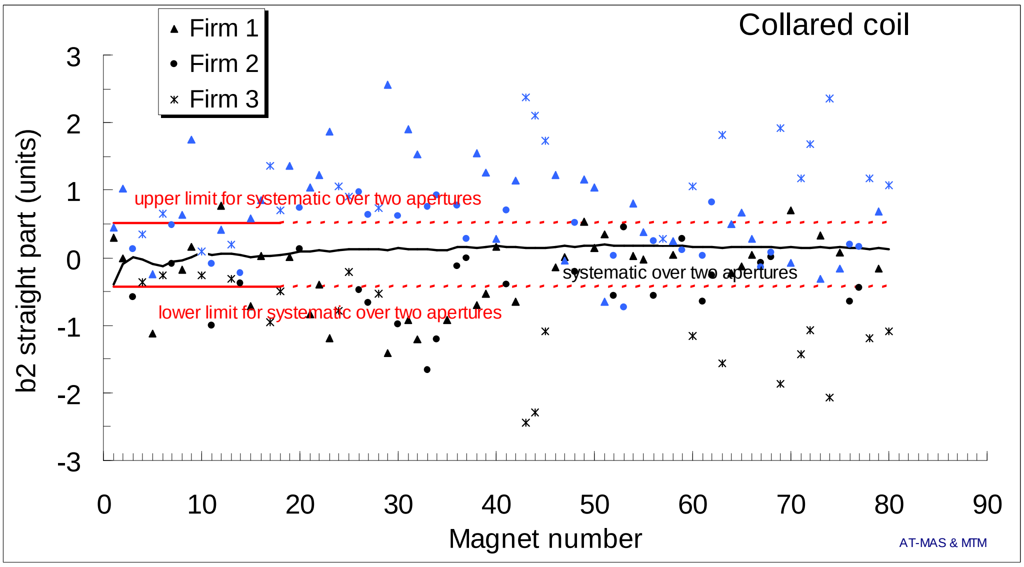


Fig. 16: Average b_2 in the straight part of collared coils ((black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (soild line) and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

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).

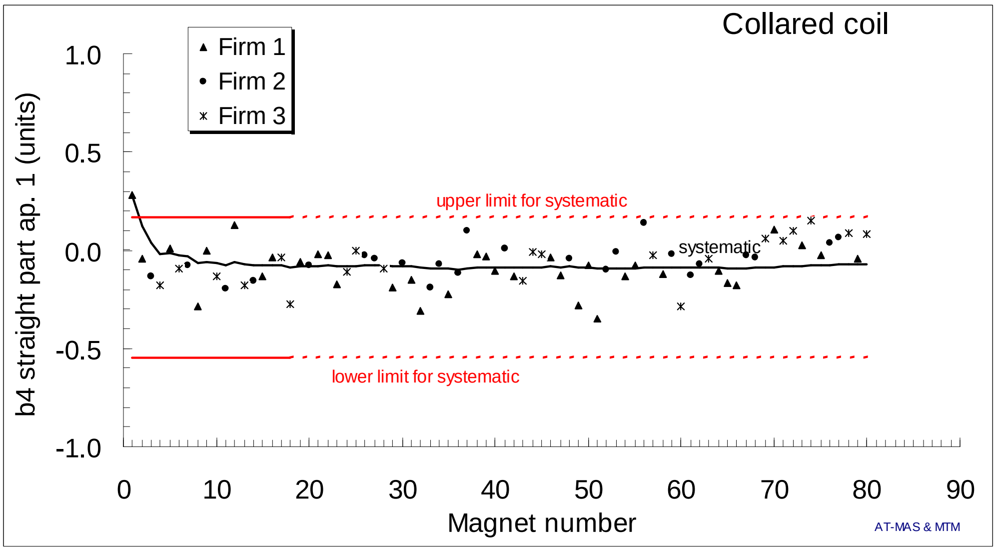


Fig. 17: Average b_4 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

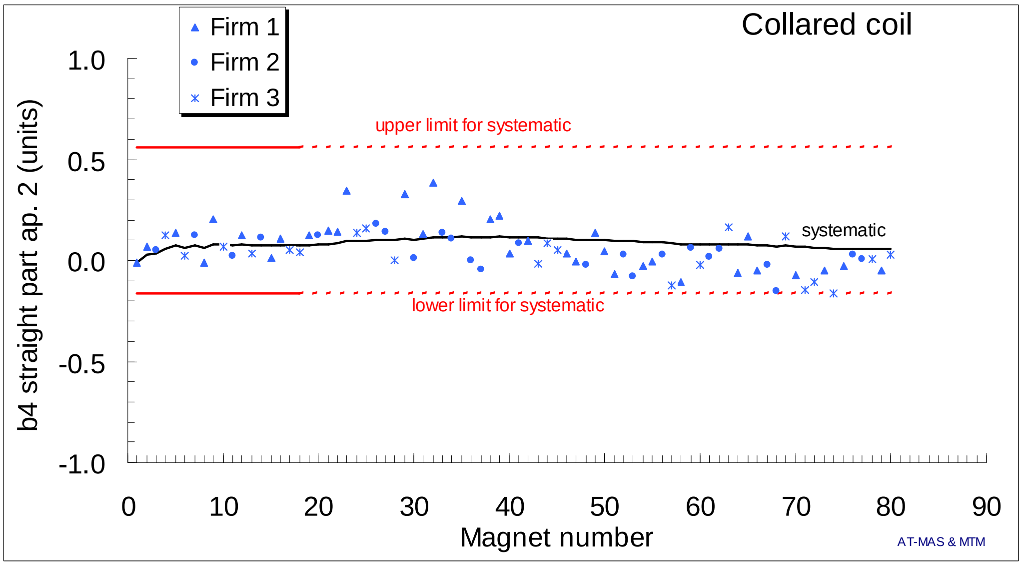


Fig. 18: Average b_4 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

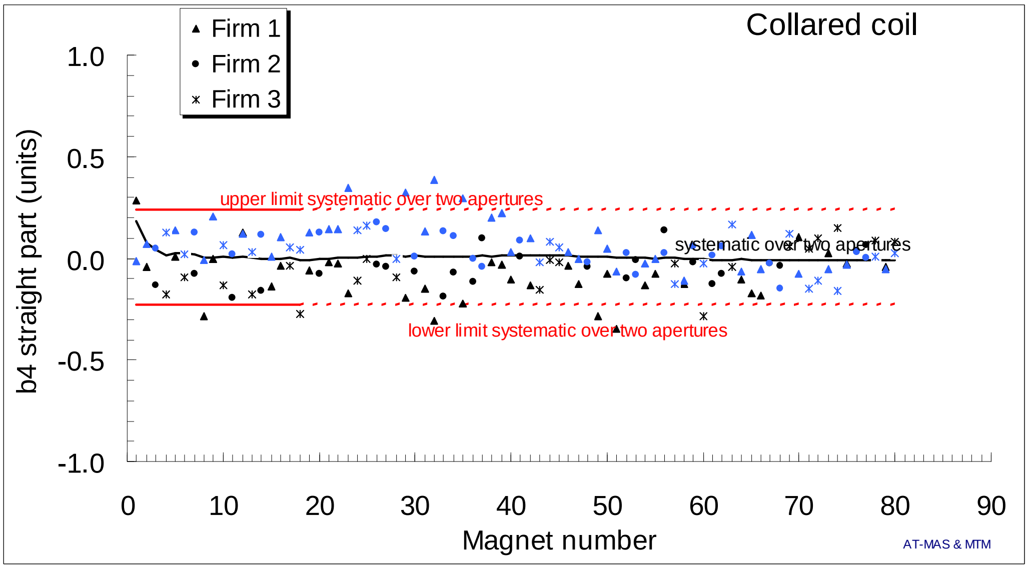


Fig. 19: Average b_4 in the straight part of collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

8. Systematic odd multipoles

8.1 Normal sextupole

- New data confirm the previous ones: the systematic in X-section 2 is 0.9 units larger than the limit (see fig. 21). The associated error is 0.6 units (95% confidence level, see Fig. 10).
- Systematic differences between firms are negligible.
- 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 4.35 units given by the correction of chromaticity.

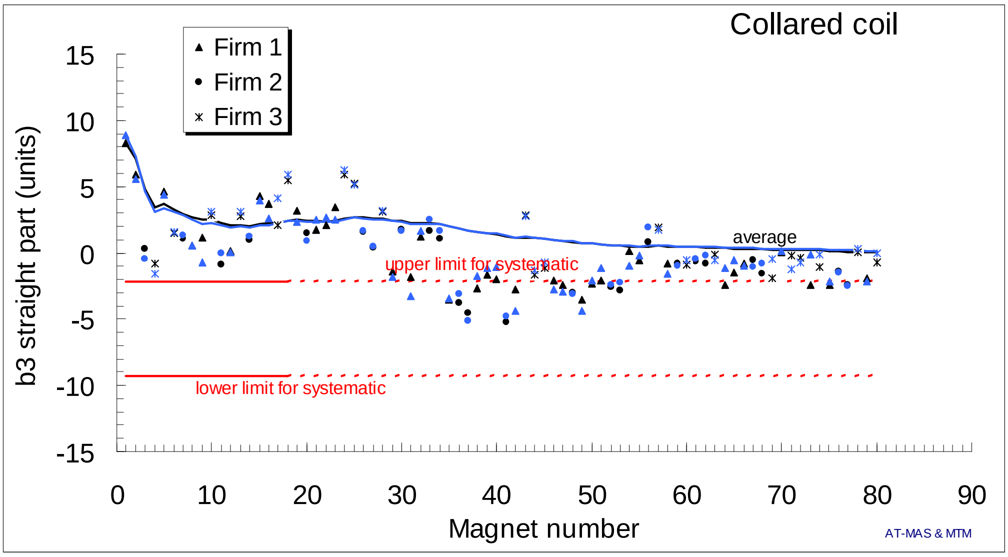


Fig. 20: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

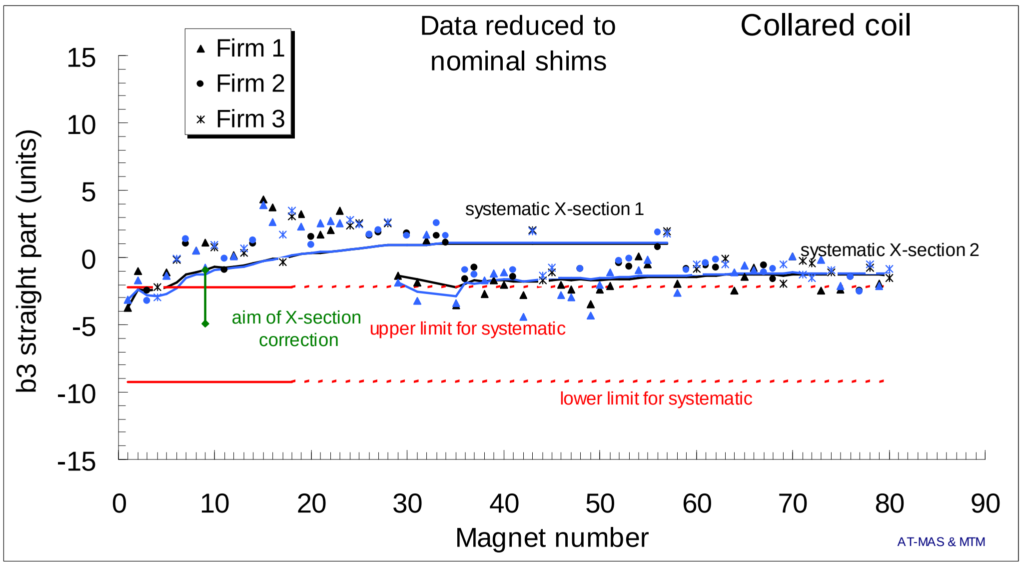


Fig. 21: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: ap. 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles. Data reduced at nominal shims and separated according to X-section type.

8.2 Normal decapole

- New data from Firm 1 show that two collared coils (73th and 75th in Figs. 22 and 23) have a b_5 of 0.5 units instead of the previous collared coils (0.9 units). This unexplained shift goes in the right direction with respect to beam dynamics limits.
- Best estimate for systematic b_5 in new X-section is 0.40 units larger than the upper allowed limit. Firm 2 collared coils are close or at the edge of the limits, but Firm 1 and Firm 3 are definitely out. These preliminary data show that the new cross-section features a large difference in systematic b_5 between firms, as the previous one.

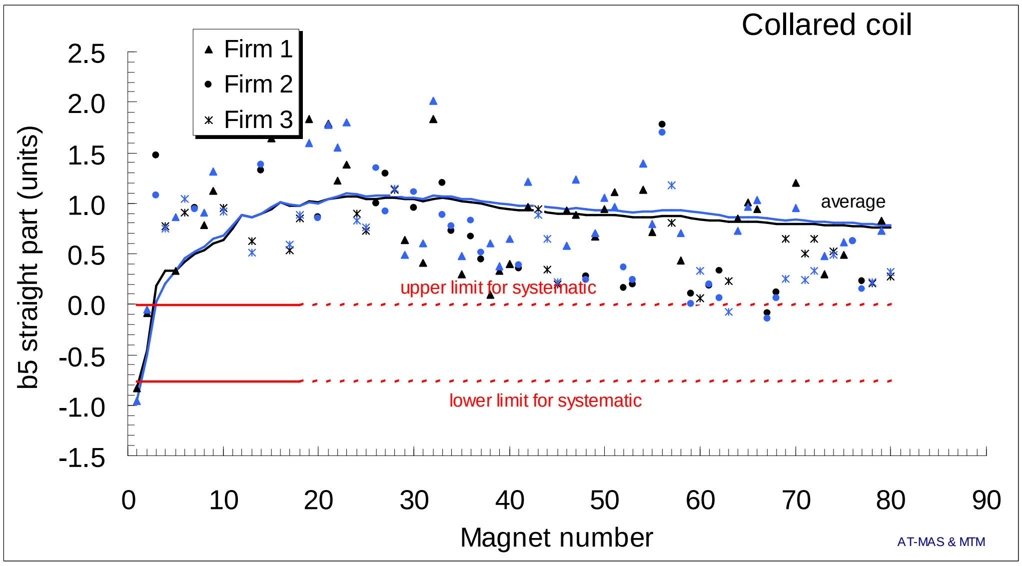


Fig. 22: Average b_5 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

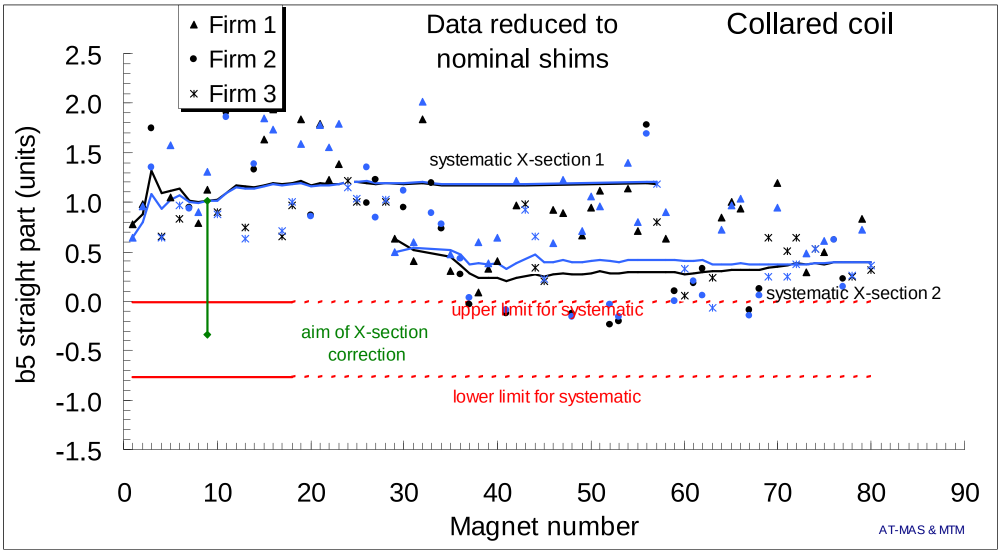


Fig. 23: Average b_5 in the straight part of the collared coil (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles. Data are reduced to nominal shims and separated 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).
- Collared coils manufactured at Firm 1 have a systematic b_7 of around 1.2 units and Firm 3 around 1.1 units (see Fig. 25). Firm 2 collared coils had a systematic b_7 of around 1.0 units, but the last two collared coils (76th and 77th) are around 0.85 units. This can be explained by the two collarings performed on 76th, but no explanations are available for 77$^{th.}$ A similar negative trend has been observed in X-section 1.
- In Fig. 25 we show the evolution of the beam dynamics specifications at the beginning of the pre-series. Acceptance ranges at injection went from [-0.4,0.4] to [-0.3,0.3], and finally to [-0.1,0.3] given in LHC Project Report 501.

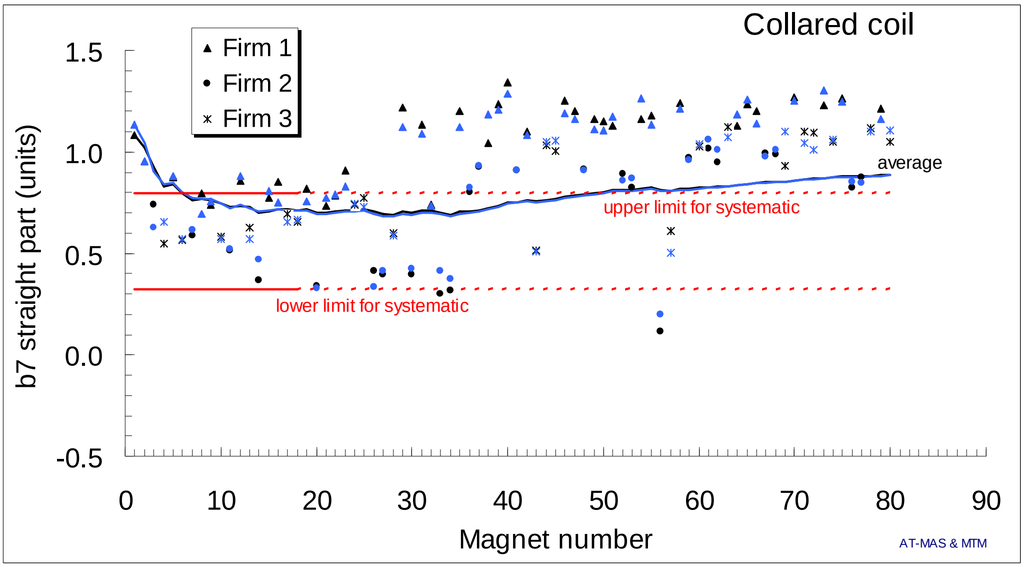


Fig. 24: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles.

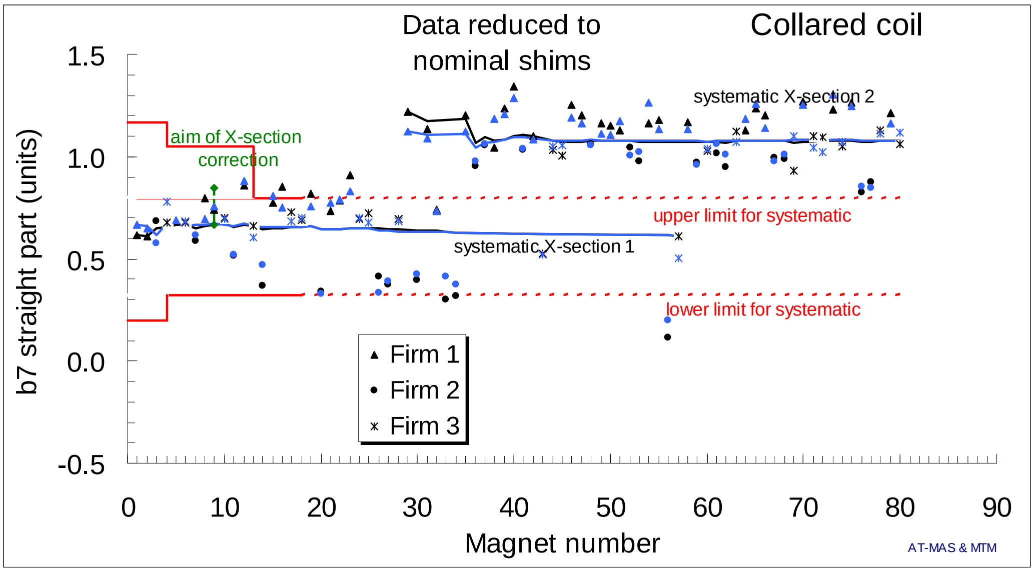


Fig. 25: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 18 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

9. 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.
- 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.

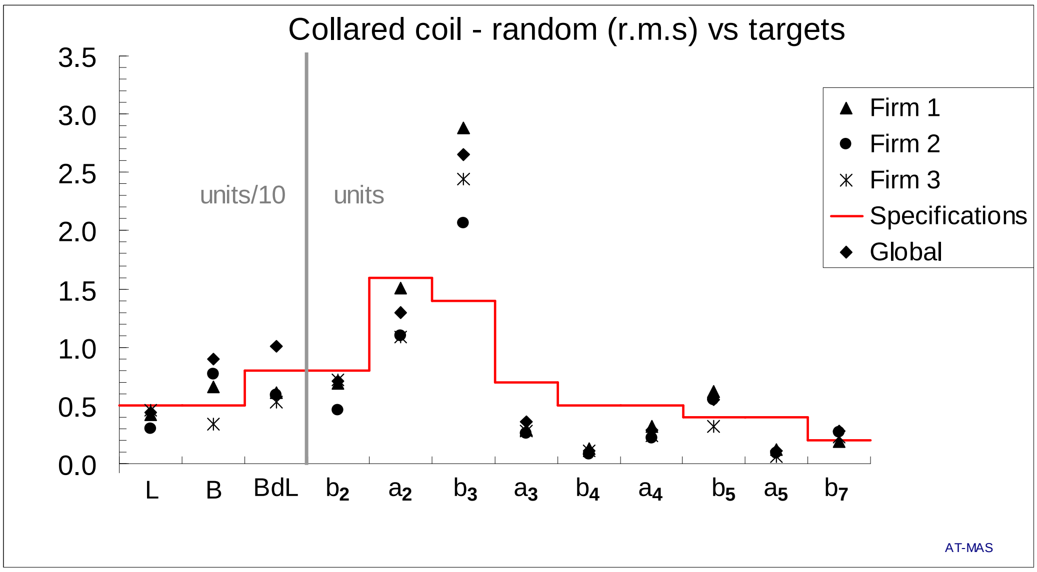


Fig. 26: Random component in the measured collared coils

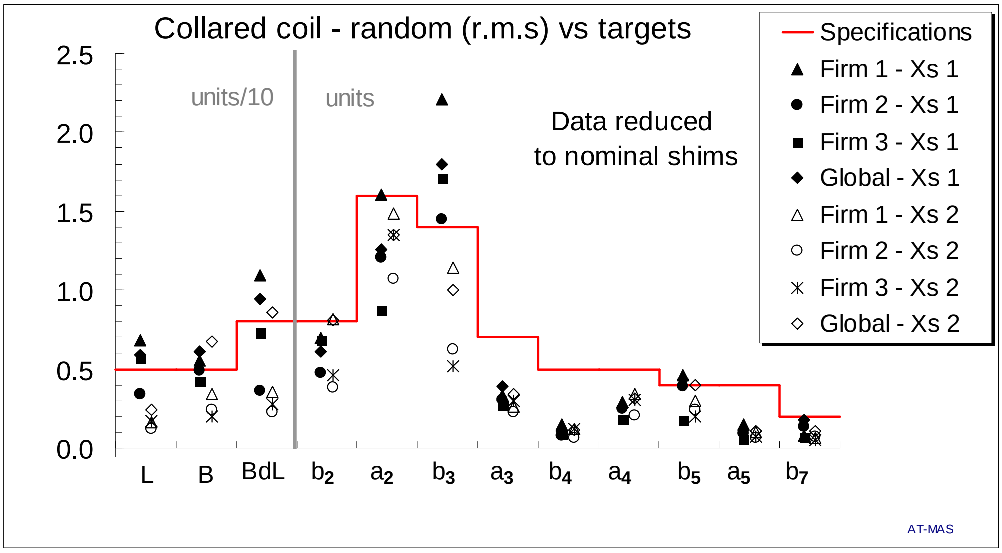


Fig. 27: Random component in the measured collared coils. Data reduced to nominal shims and split according to different cross-sections.

10. Holding point results

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

	Magnet name		Collared coil measure	Result	Comments
69th	HCMB__A001	3000016	07/01/03	OK	
70th	HCMB__A001	1000032	09/01/03	OK	Accepted in the hypothesis of -20 mm diff in mag len and -2.3 mT/KA diff in main field between new and old system (1026 data)
71st	HCMB__A001	3000018	31/01/03	OK	
72nd	HCMB__A001	3000017	03/02/03	OK	Non-nominal shims in aperture 2.
73rd	HCMB__A001	1000033	05/02/03	OK	Accepted in the hypothesis of -20 mm diff in mag len and -2.3 mT/KA diff in main field between new and old system (1026 data)
74th	HCMB__A001	3000019	10/02/03	Ok-W	Non-nominal shims in aperture 2. Warning: a trend in b2 has been detected.
75th	HCMB__A001	1000034	14/02/03	OK	Accepted in the hypothesis of -20 mm diff in mag len and -2.3 mT/KA diff in main field between new and old system (1026 data)
76th	HCMB__A001	2000023	19/02/03	OK	b5 higher of 0.6 units and b7 lower of 0.15 units - due to the fact that this cc has been recollared (electrical problems) - first collaring not measured
77th	HCMB__A001	2000025	18/02/03	OK	
78th	HCMB__A001	3000021	24/02/03	OK	Non-nominal shims in both apertures
79th	HCMB__A001	1000035	25/02/03	OK	Accepted in the hypothesis of -20 mm diff in mag len and -2.3 mT/KA diff in main field between new and old system (1026 data)
80th	HCMB__A001	3000020	17/02/03	OK	Non-nominal shims in both apertures

- 1027, that has been recollared after adding the missing shim, showed an anomalous peak of about 8 units of main field; the repetition of the measurement has shown that this was an error of the measuring system. The collared coil has been released. Information in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/1027.html

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Appendix A

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

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

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