Report on field quality in the main LHC dipole collared coils: November-December 2002

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This report gives data relative to field quality measured in collared coils during the period November 1– December 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.

EDMS n. **369375**

The dashboard

- Available measurements: 68 collared coils, 34 cold masses, 17 cryodipoles.
- In these two months, 12 collared coils: 4 from Firm1, 5 from Firm 2 and 3 from Firm 3.

What's new

- **Holding point, closed case**: Collared coil 1027 has been decollared after the detection of a spike in the field harmonics giving a strong indication of a missing shim in the outer layer of one pole. The missing shim has been found (0.8 mm) along one meter, exactly in the position foreseen by the analysis; this has been also a check of the consistency of signs and reference systems used for magnetic measurements. More information available at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/1027.html and in Section 10.
- **Holding point, open case**: Field quality variation after a recollaring: we now have data of four coils that have been collared two times. For a 'hard' decollaring (with change of insulation and coil disassembly) there is some indication of a systematic change in field harmonics. This is not negligible for the b_5 (0.25 to 0.65 units) and for the b_7 (-0.04 to –0.28 units). This is not explained. More information can be found in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/2013.html and in Section 10, pg. 16.
- **Communication**: LHC project report 625 has been issued. It contains best estimates of the expected systematic and random components based on the available measurements at 300 K and at 1.9 K. These values are now used by AB division to carry out tracking studies.
- **Communication**: At http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/crisis.html we have activated a web page with informations about the bad cases (both open and closed) met during the production.
- **Measuring system**: The new system developed by J.Billan and V. Remondino has been installed in Firm 1 for the collared coils measurement. A systematic offset between the old and the new system in magnetic length and main field has been found and is under investigation (see Section 10, pg. 16).
- **Special experiments**: the dedicated experiment on the effect of the midplane insulation on field harmonics has been started under the supervision of D. Tommasini and H. Kummer. First results (a change of 50 micron on inner layer) agree with the coupled magneto-mechanical model within 10% for c_1, b_3 and b_7 and within 25% for b_5. On-line information available at http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/midpl_insul.html. Six more tests are planned. This solution could be implemented, if necessary, on the series to improve b_3 b_5 and b_7.
- **Trends in integrated main field**: We start to have a strong evidence of a systematic difference in integrated main field of around 20 units between Firm 1-2 and Firm 3. 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 systematic harmonics**: New data confirm the previous ones.
- **Trends in randoms**: large random a_2 and b_2 observed in X-section 2 (see previous report) were due to poor statistics and have disappeared. Everything is within specifications (see Section 9, pg. 15).

1. Measured magnets and assembly data

- 12 collared coils have been measured (collared coils 57th to 68th)
  - 4 of Firm 1 (1020, 1029-1031)
  - 5 of Firm 2 (2015 and 2019-2022)
  - 3 of Firm 3 (3010, 3014 and 3015)

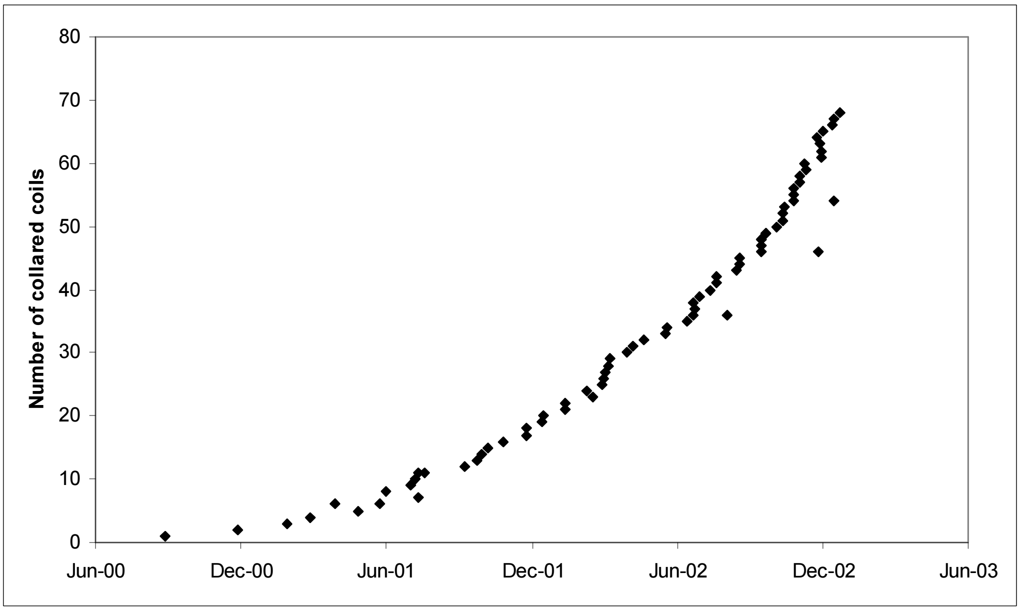


Fig. 1: Number of measured collared coils versus time. Dots out of the main trend are relative to collared coils measured more than one time.

- Cross section: collared coil 3010, i.e. the 57th, has X-section 1 (the old one); all the others have X-section 2. This is the last magnet with X-section 1. The total number of magnets with X-section 1 is 35; in the previous report we gave a different number (34), which was based on erroneous information given by Firm 3.
- Shims are all nominal, with the exception of a 0.05 mm more on the inner layer for 1029 (collared coil 58th in Fig. 2). In particular, azimuthal coil length in Ansaldo is now within specifications, allowing using nominal shims.

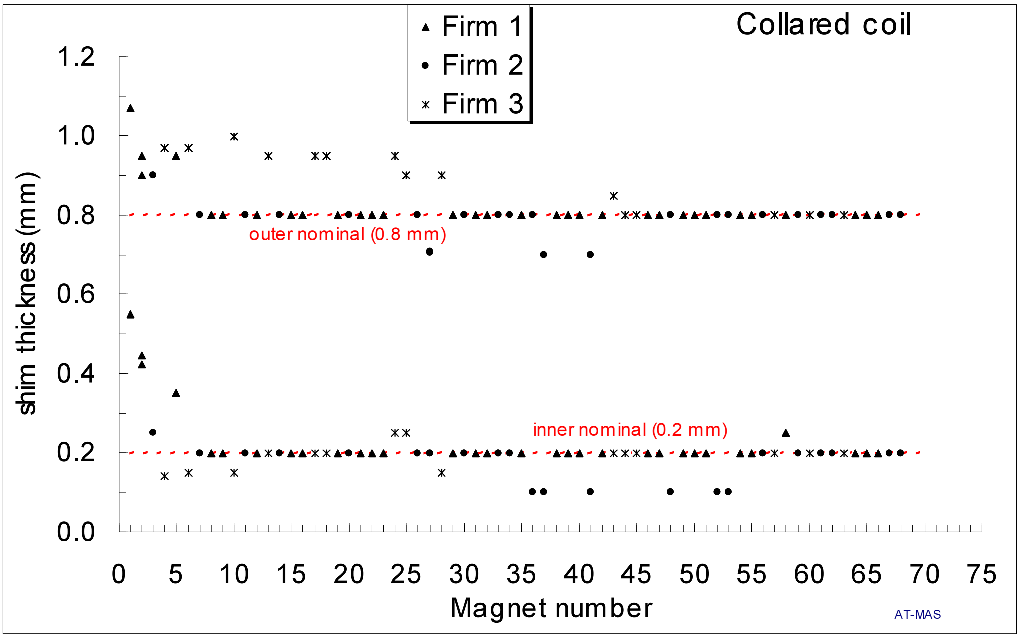


Fig. 2: Thickness of the polar shims used in the collared coils

2. Estimated coil waviness

- Coil waviness estimated from the variation of the multipole along the axis is getting better at Firm 1 (see Fig. 3). Corrective actions on the curing mould seem to be effective.
- The other Firms have coil waviness below 30 microns, Firm 2 showing the best results (15 microns).

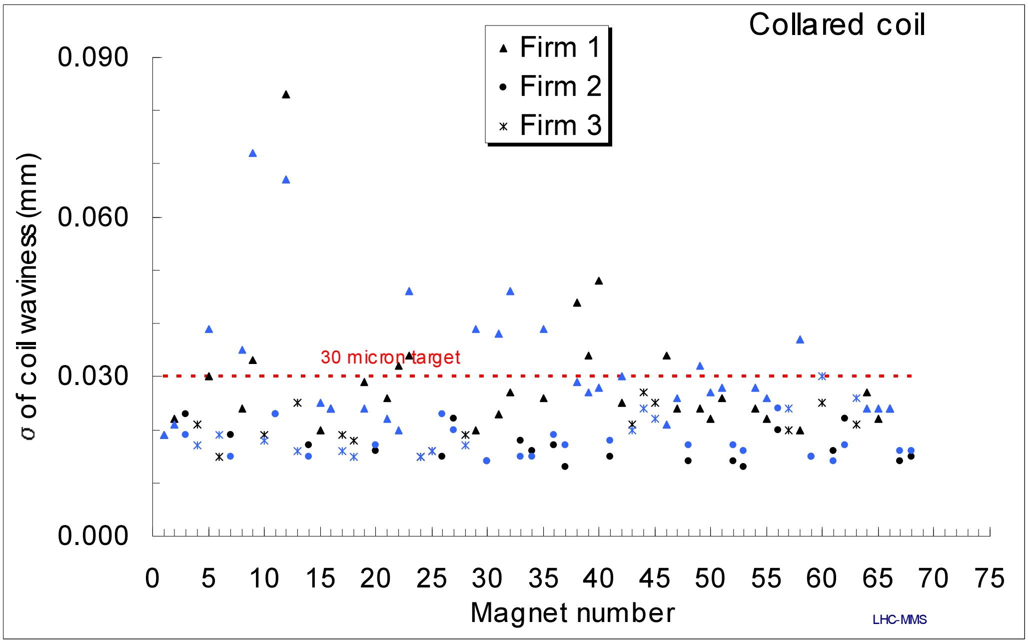


Fig. 3: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

3. Magnetic length and transfer function

- Magnetic lengths of collared coils 57th to 68th are within targets (see Fig. 4). Collared coils of Firm 3 feature a slightly longer magnetic length (10 mm more, i.e. around 7 units). All data are well within specifications.

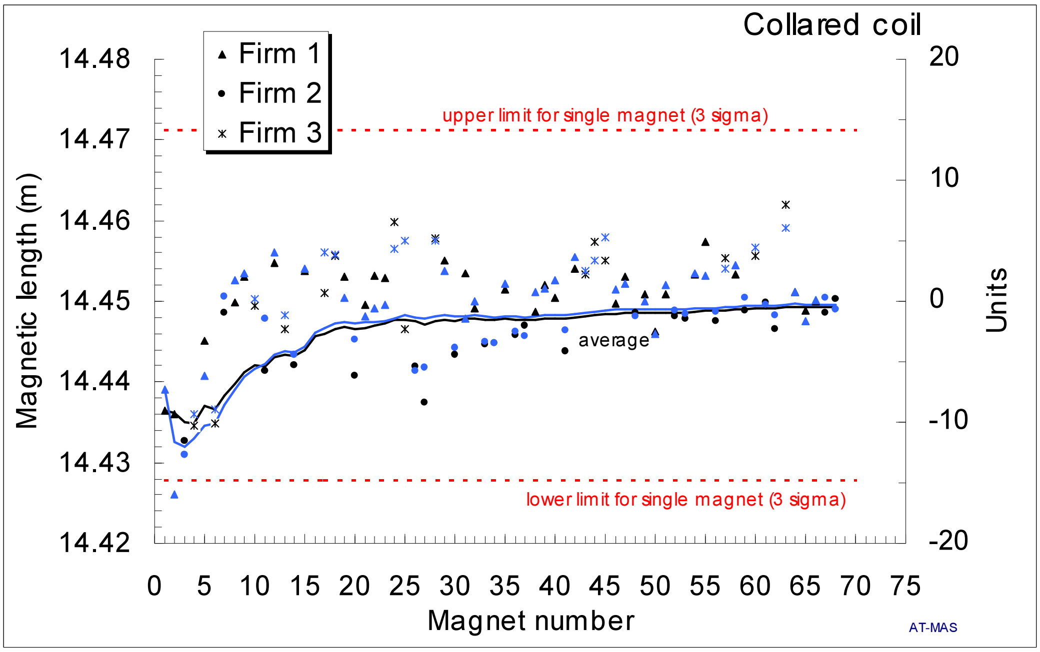


Fig. 4: Magnetic length of the measured collared coils (black dots: aperture 1, blue dots: aperture 2)

- There is a strong evidence of a systematic difference of 20 units between Firm 3 and Firm 1-2 in the main field (see Fig. 5). This is particularly evident when data are reduced to nominal shims (see Fig. 6). 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. 50 microns. We do not see related effects on field harmonics.
- Collared coil 68th features a rather low main field. This is under investigation.

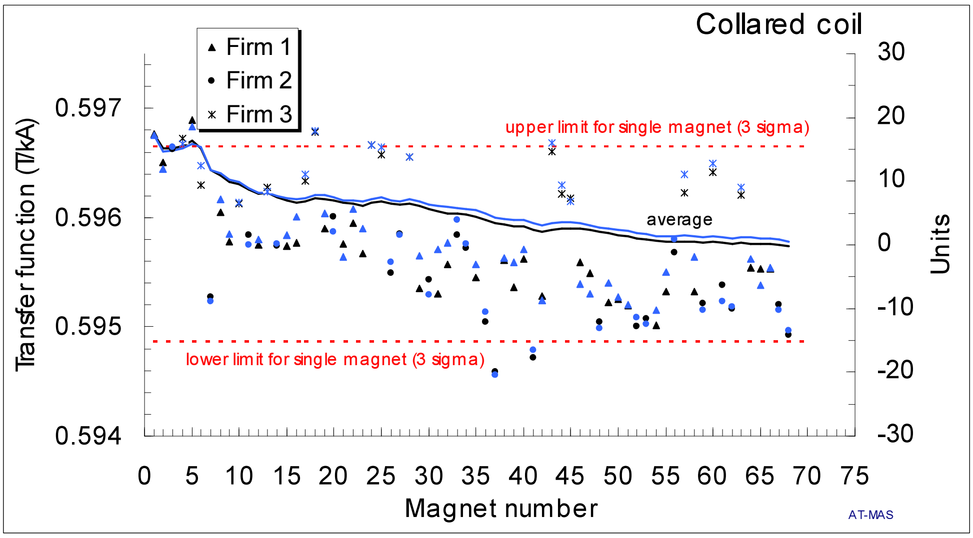


Fig. 5: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

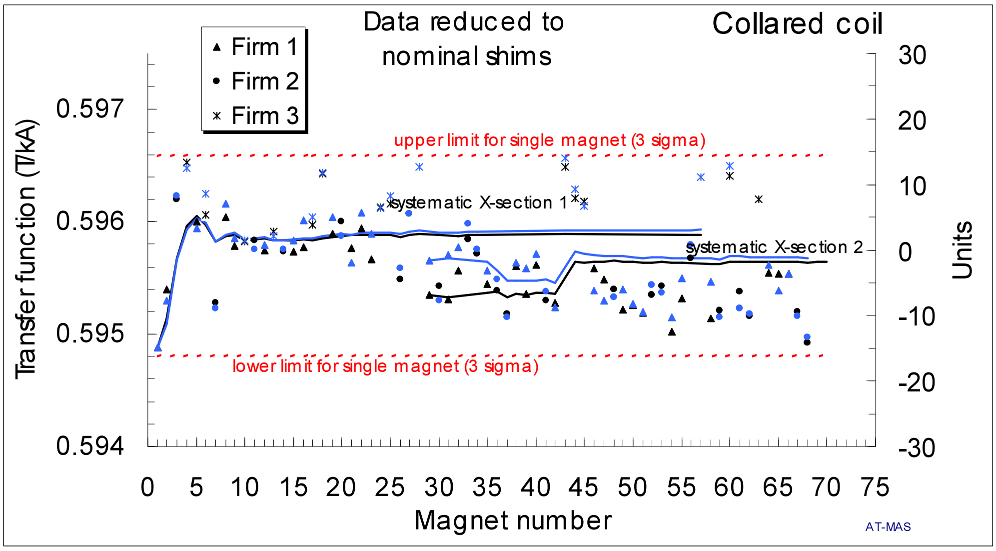


Fig. 6: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

- Integrated transfer function has a systematic difference between Firm 3 and Firm 1-2 of about 20 units (see Figs. 7 and 8). This gives a random component in the hypothesis of a complete mixing of 9 units, i.e. slightly more than the specified value of 8 units. Nevertheless, a reduction of 20% is expected in the cold mass. 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).

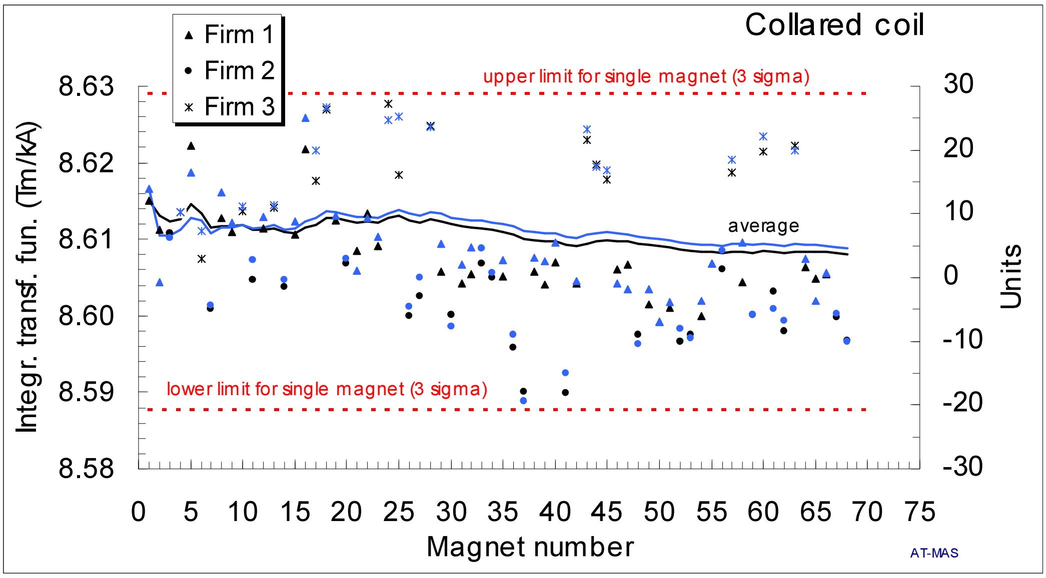


Fig. 7: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

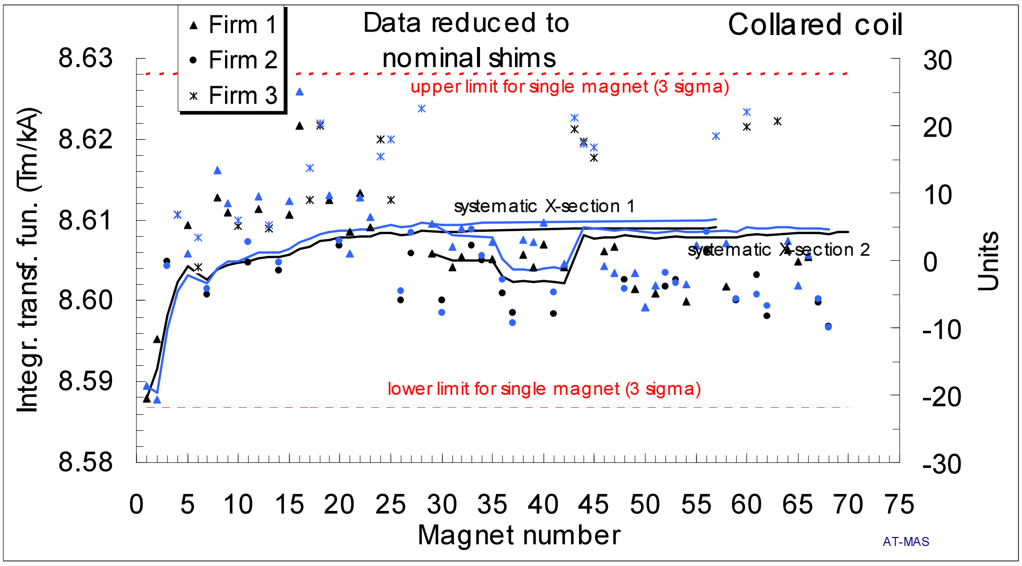


Fig. 8: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

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.

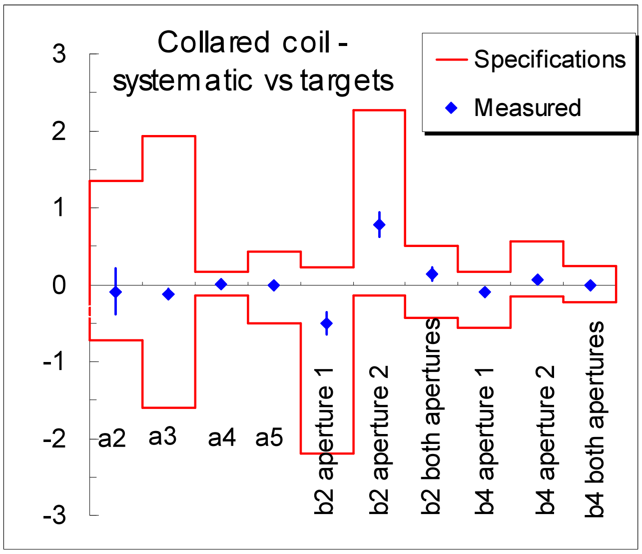
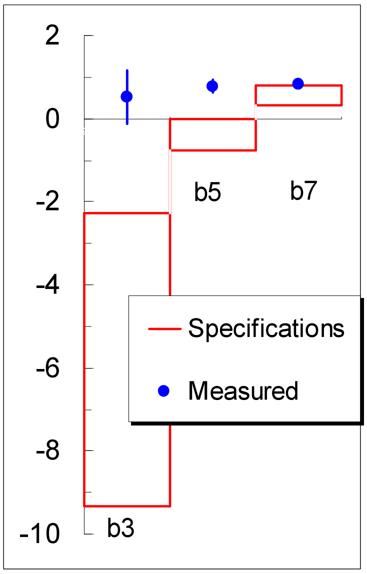


Fig. 9: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics.

- 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 2.8 and 0.80 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, 33 have cross-section 2). With the new X-section, b_3 b_5 and b_7 are larger than the specification of 1.0, 0.35 and 0.3 units respectively.



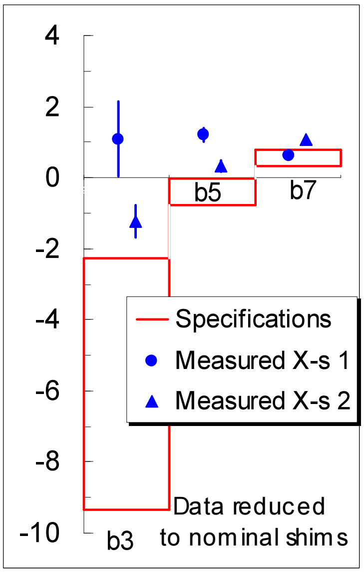


Fig. 10: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections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

5. Summary of systematic differences between firms

We can start to make a preliminary analysis of what are the main systematic differences between firms in collared coil data. We observe a non-negligible systematic difference between firms in the following cases:

- Main field: Firm 3 is higher than Firm 1-2 of 20 units (see Fig. 5)
- Normal decapole b_5: Firm 1 is higher than Firm 2 of 0.75 units, and is higher than Firm 3 of 0.5 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).
- Coil waviness: Firm 2 shows a better quality in the coil winding and curing, with a waviness of 15 microns (see Fig. 8 in Section 3). A deterioration of waviness is visible at Firm 3, which started at 15 microns and now is around 25-30 microns. Firm 1 showed in the past bad waviness (above 30 microns), but now is getting better.

On the other hand, we observe small differences between firms in the following field harmonics:

- Normal sextupole b_3: Firm 1 is lower than Firm 2-3 of 1.2 units (see Fig. 21). This is small if compared both to the allowed range (7 units) and to the random compoment (1 to 1.5 units).
- Normal 14th pole b_7: Firm 1 is 0.15 higher than Firm 2 and 0.10 higher than Firm 3. This is rather small if compared both to the allowed range (0.5 units) and to the random component (0.2 units).
- Skew sextupole a_3: From collared coil 40 to 68, we observe that Firm 3 systematic a_3 is around 0.5 units, whilst in Firm 1-2 is around –0.3 units (see Fig. 12). This has no practical implications on the follow-up since the allowed range for a_3 is very large (3.5 units).

No systematic differences between firms are visible in a_2, a_4, b_2 and b_4.

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.
- Small differences of about 0.8 unit in systematic a_3 between Firm 3 and Firm 1-2 are observed in the last 30 collared coils.

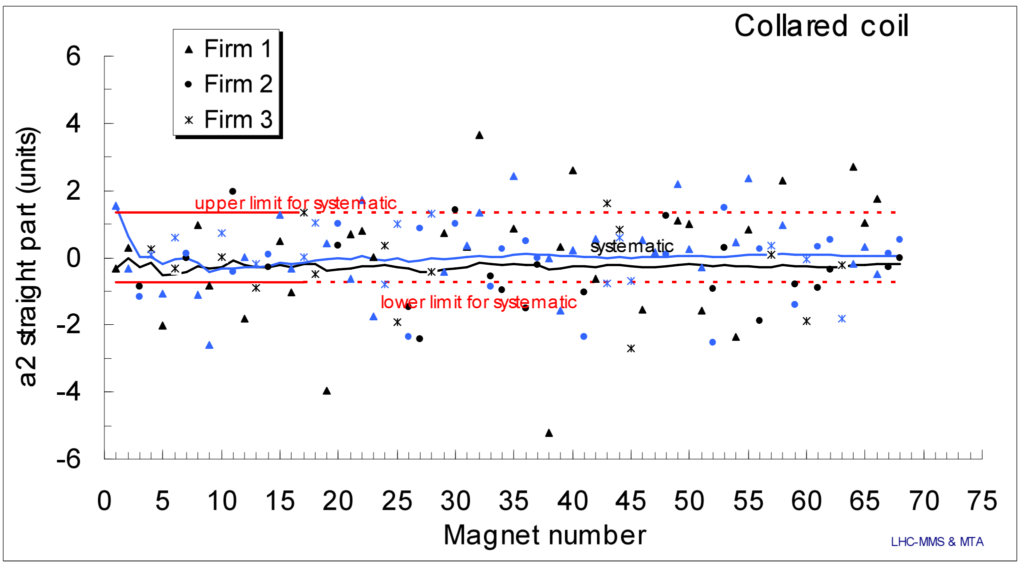


Fig. 11: Average a_2 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

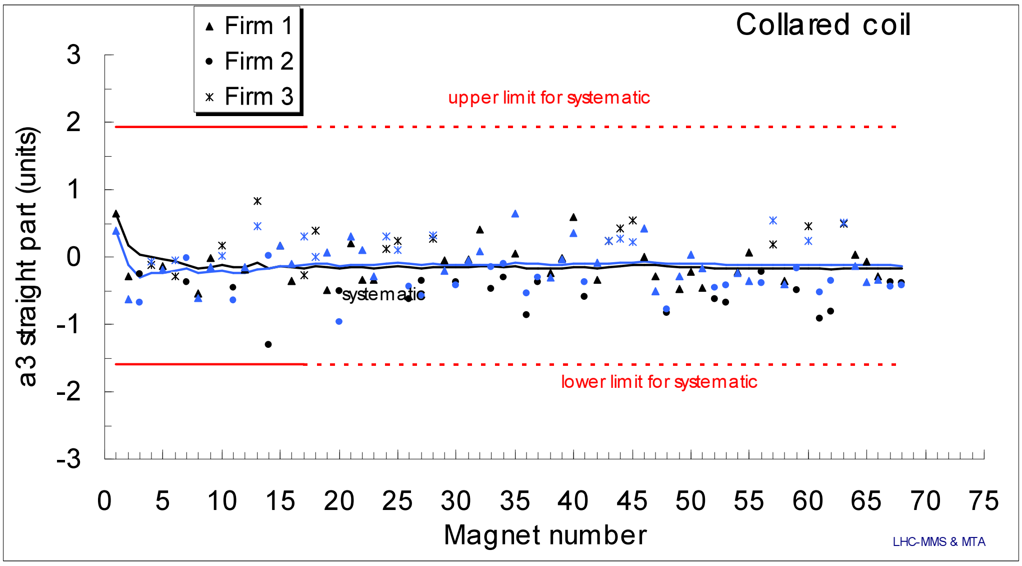


Fig. 12: Average a_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

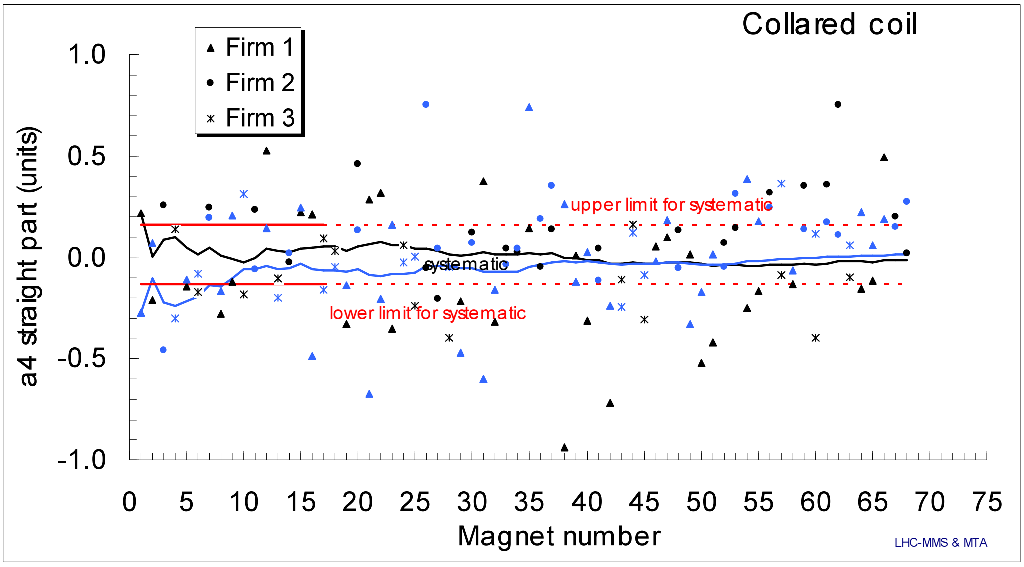


Fig. 13: Average a_4 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

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).

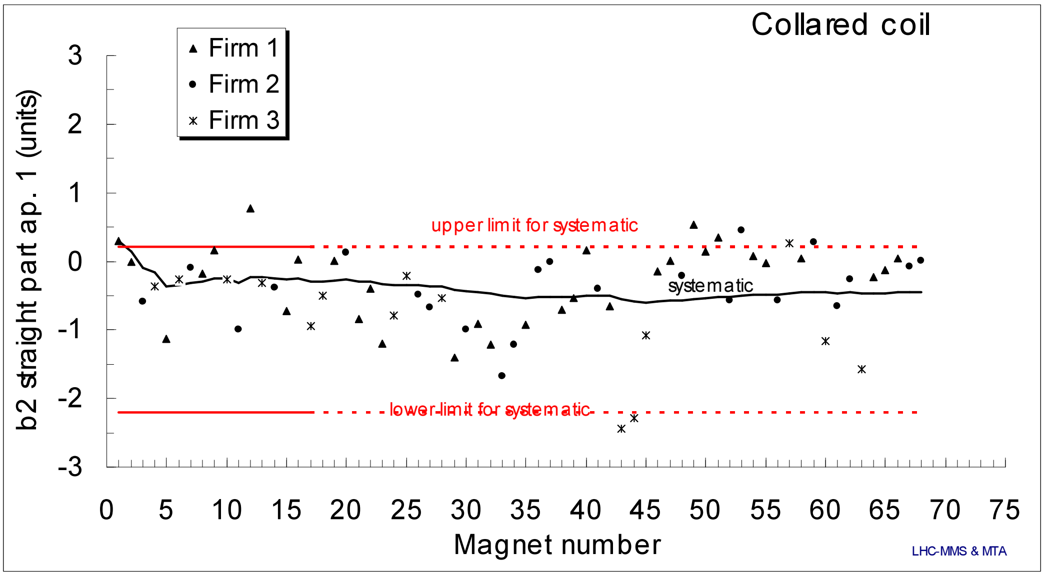


Fig. 14: Average b_2 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

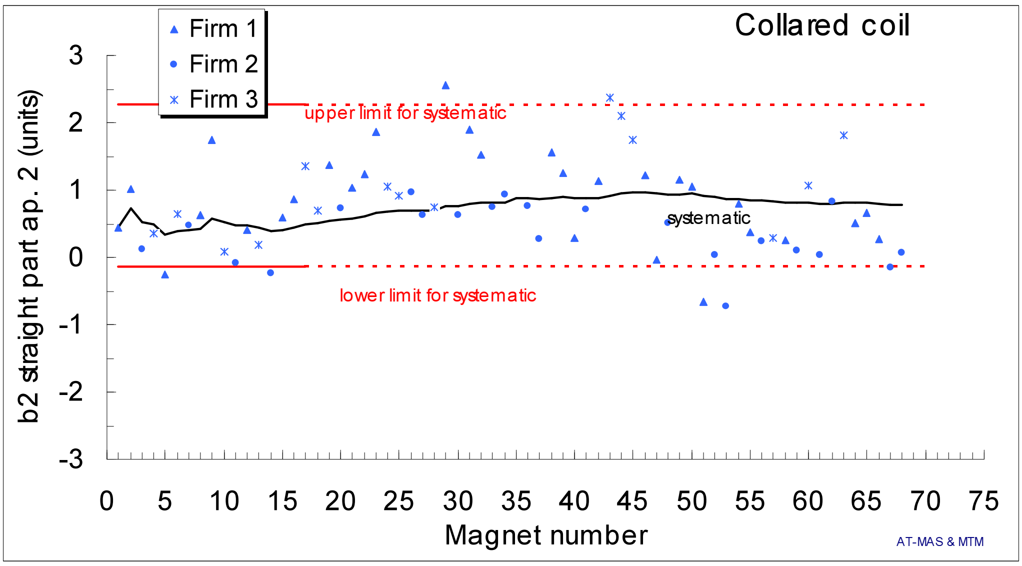


Fig. 15: Average b_2 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (blue line) and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

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

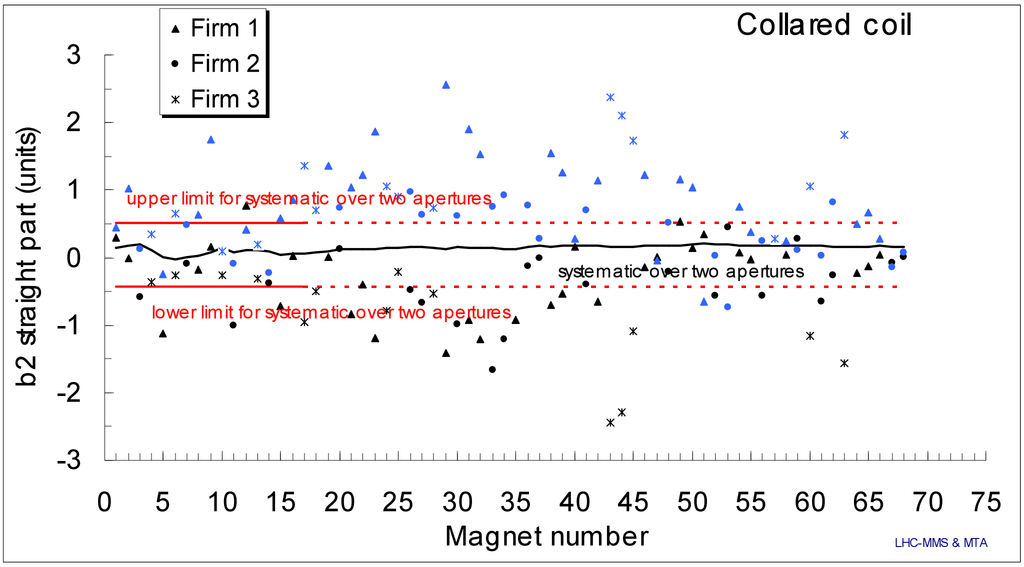


Fig. 16: Average b_2 in the straight part of collared coils ((black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (soild line) and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

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).

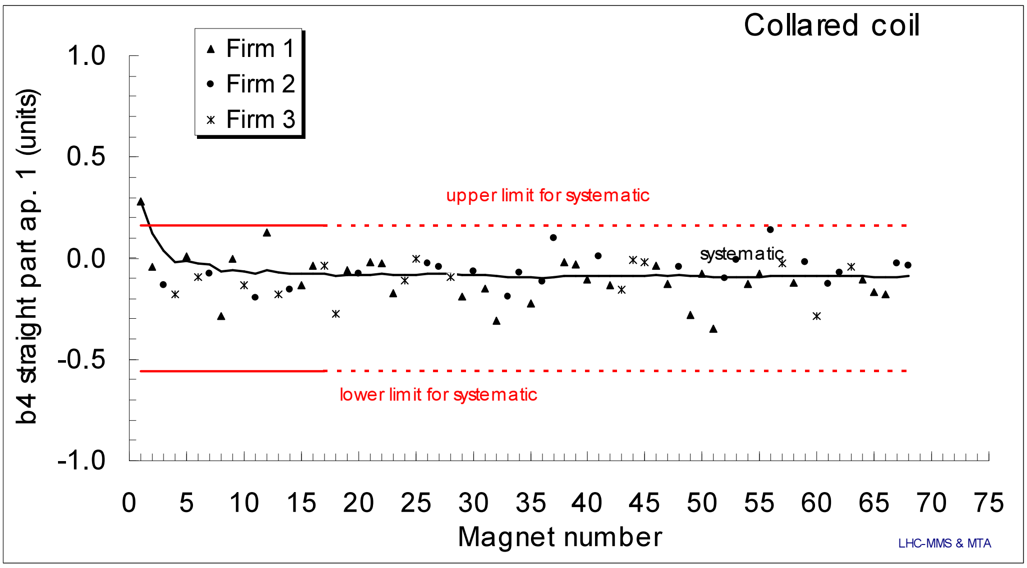


Fig. 17: Average b_4 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

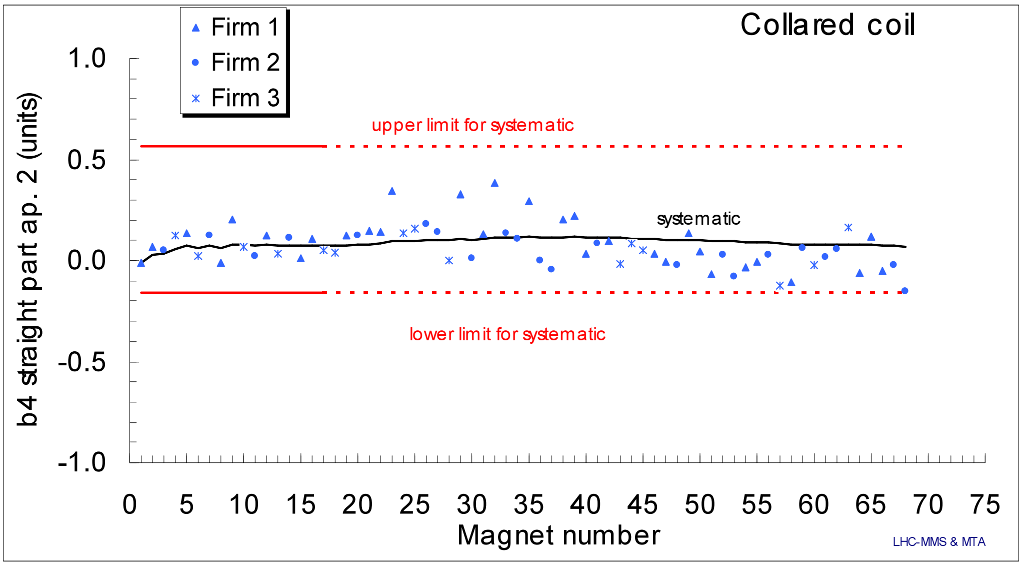


Fig. 18: Average b_4 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

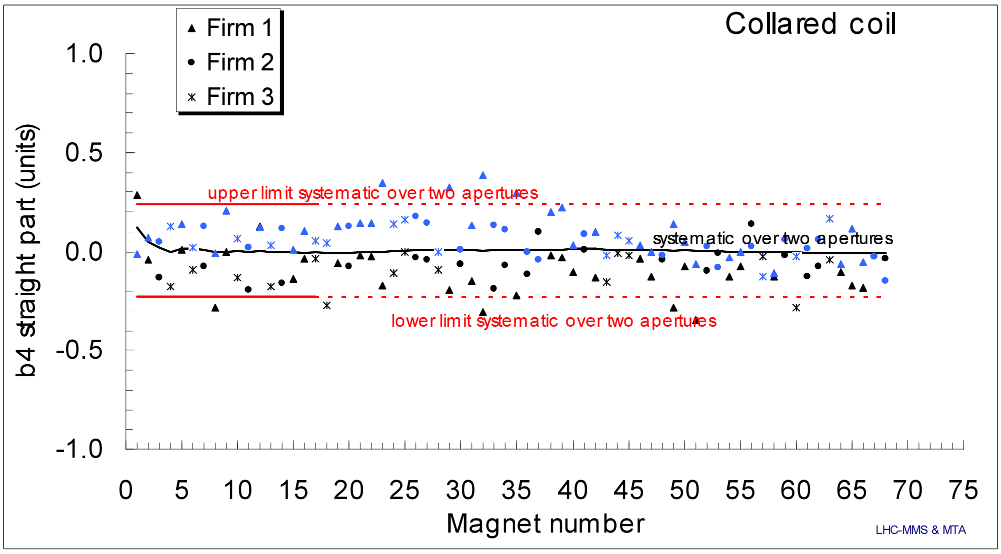


Fig. 19: Average b_4 in the straight part of collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

8. Systematic odd multipoles

8.1 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 –1.2 units, i.e. –3.4 units (see fig. 21). This has to be compared to what expected from simulations (-3.9 units). Therefore, the correction worked at 85%.
- The best estimate for systematic in X-section 2 is 1.0 units out of the limit (see fig. 21). The associated error is 0.6 units (95% confidence level, see Fig. 10).
- A small systematic difference between Firm 2-3 and Firm 1 (around 1.2 units) is observed.
- Cryodipoles with the new X-section should feature 3.8 units of b_3 at high field; this is outside the specification but within the hard limit of 4.2 units given by the correction of chromaticity.

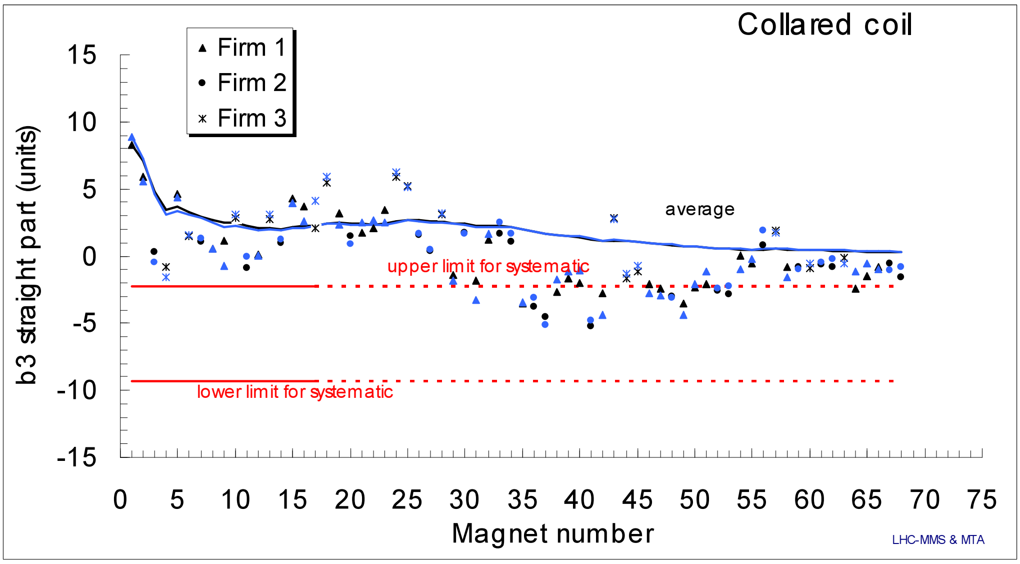


Fig. 20: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

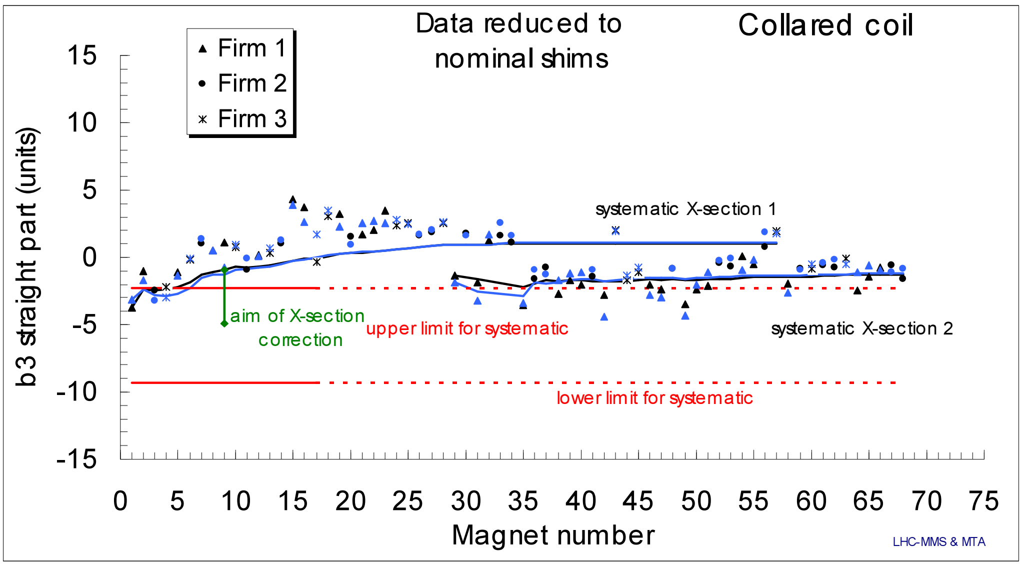


Fig. 21: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: ap. 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles. Data reduced at nominal shims and separated according to X-section type.

8.2 Normal decapole

- Data from Firm 1 (collared coils 58th, 64th to 66th in Figs. 22 and 23) confirm the effect analysed in the previous report: b_5 has been shifted upward by 0.5 units from collared coil 42nd, due to an intervention on the polymerisation mould. The shift goes in the wrong direction with respect to beam dynamics limits.
- Excluding the above discussed effect in Firm 1, the cross-section change shifted down b_5 from 1.20 to 0.25, i.e. of 0.95 units against a foreseen effect of 1.35, i.e. the correction worked at 70 %.
- Best estimate for systematic b_5 in new X-section is 0.36 units larger than the upper allowed limit. Firm 3 and Firm 2 collared coils are close or at the edge of the limits, but Firm 1 is 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.

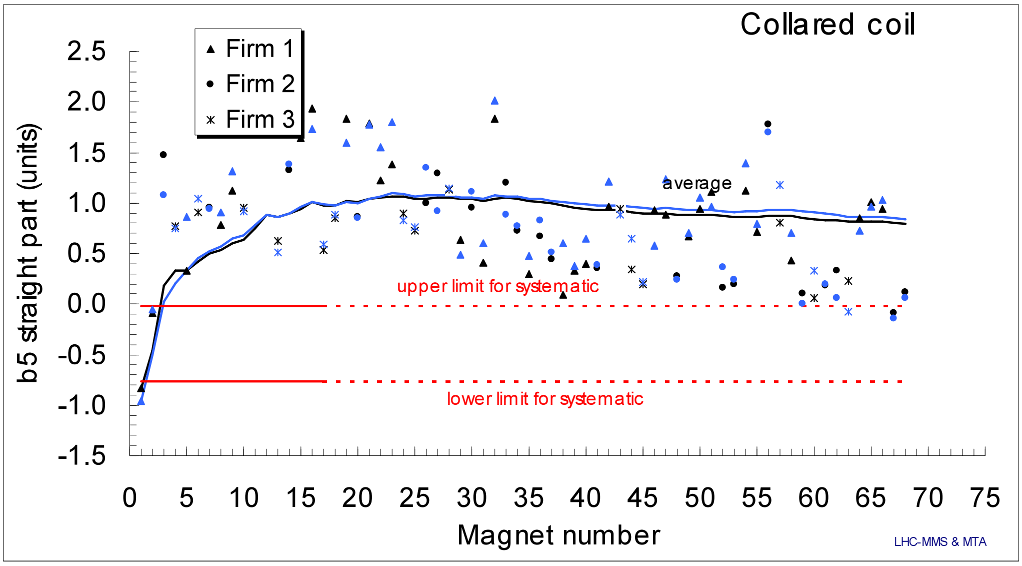


Fig. 22: Average b_5 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

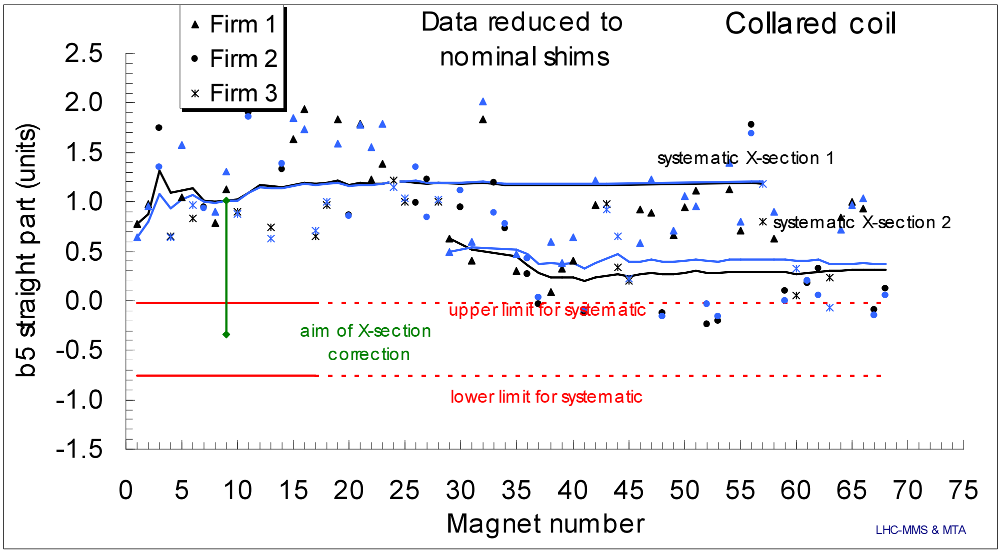


Fig. 23: Average b_5 in the straight part of the collared coil (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles. Data are reduced to nominal shims and separated 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).
- Firm 2 collared coils have a systematic b_7 of around 1.0 units, Firm 1 around 1.2 units, Firm3 being in between (see Fig. 25). This confirms trends observed for the X-section 1, but with a much lower difference between firms.

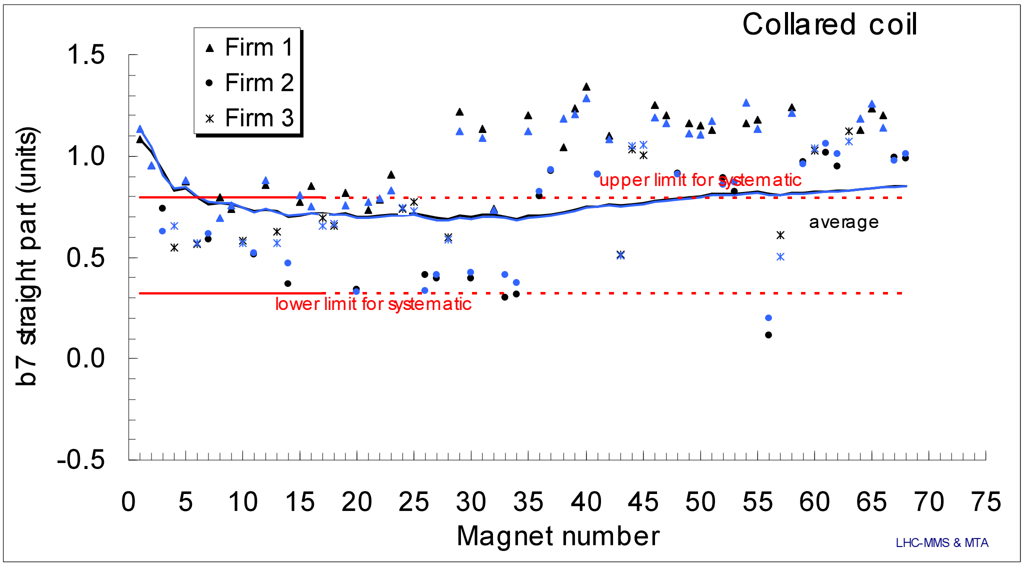


Fig. 24: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles.

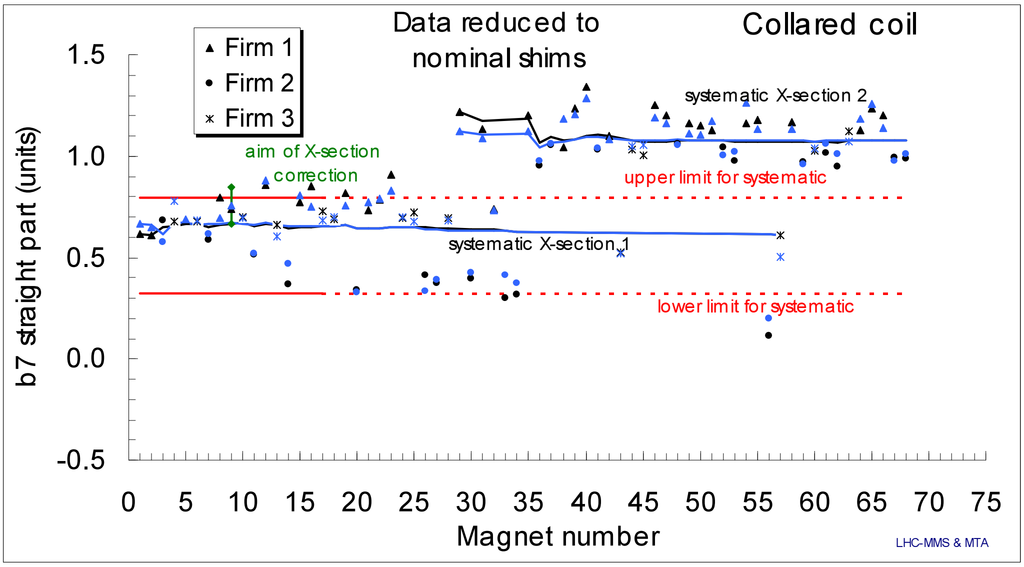


Fig. 25: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 17 cryodipoles. Data are reduced to nominal shims and separated 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 some statistics for the new cross-section: all the multipoles are within specifications. Features observed in the previous report (large randoms out of tolerances in a_2 and b_2 for some firms) disappeared.

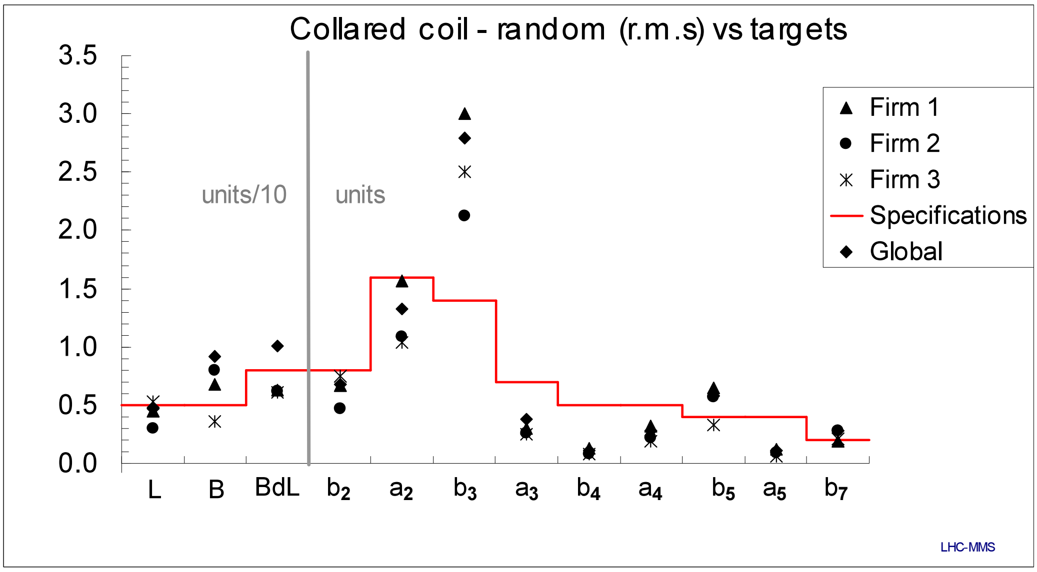


Fig. 26: Random component in the measured collared coils

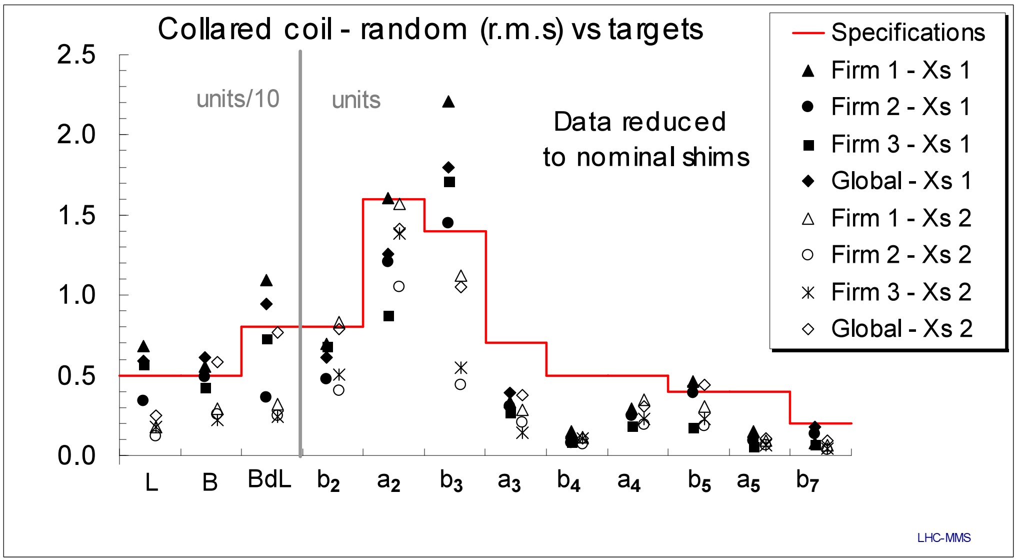


Fig. 27: Random component in the measured collared coils. Data reduced to nominal shims and split according to different cross-sections.

10. Holding point results

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

	Magnet name		Collared coil measure	Data at CERN	Answer to MMS-MD	Answer To manufact.	Result	Comments
57th	HCMB__A001	3000010	06/11/02	12/11/02	13/11/02	14/1/02	OK	
58th	HCMB__A001	1000029	07/11/02	07/11/02	08/11/02	08/11/02	OK-w	Rather strong coil waviness in aperture 2 (37 microns), red alarm on b3 variations along axis
59th	HCMB__A001	2000019	14/11/02	15/11/02	15/11/02	15/11/02	OK	
60th	HCMB__A001	3000014	12/11/02	14/11/02	14/11/02	14/11/02	OK	
61st	HCMB__A001	2000015	03/12/02	03/12/02	04/12/02	04/12/02	OK	
62nd	HCMB__A001	2000020	04/12/02	04/12/02	05/12/02	05/12/02	OK	
63th	HCMB__A001	3000015	02/12/02	06/12/02	06/12/02	09/12/02	OK	
64th	HCMB__A001	1000020	28/11/02	28/11/02	28/11/02	11/12/02	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) - sign correction
65th	HCMB__A001	1000030	05/12/02	10/12/02	10/12/02	11/12/02	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)
66th	HCMB__A001	1000031	17/12/02	19/12/02	19/12/02	22/12/02	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)
67th	HCMB__A001	2000021	19/12/02	20/12/02	20/12/02	22/12/02	OK	
54th	HCMB__A001	1000027	18/12/02	19/12/02	19/12/02	22/12/02	HOLD	2nd measurement after re-collaring for missing shim. Now: Peak of 8 units detected in position 7, aperture 2 of main field, measurement to be repeated
68th	HCMB__A001	2000022	27/12/02	27/12/02	27/12/02	27/12/02	OK-w	Main field lower than expected – in part due to low temperature in the Firm (Xmas holidays)

- 1027 has been recollared after adding the missing shim. The measurements show that the spike in the harmonics of Aperture 1 has disappeared. Nevertheless, we observe an anomalous peak of about 8 units of main field in the other aperture; field harmonics show no pathology. This could be due to a faulty measurement. The measure will be repeated. Information in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/1027.html
- Collared coil 1026 has been measured with the old and woth the new system. A difference of 20 mm in magnetic length and of 2.3 mT/KA in the main field has been found. These data are confirmed by 1027 that has also been measured with both systems. Investigations on the origin of the offset are in progress. All the Firm 1 collared coils measured with the new system are accepted in the hypothesis of this offset between the two systems (see Table I).
- Field quality variation due to a recollaring: (see also http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/2013.html for updated informations)
    - Collared coil 1027 is another case of field quality variation after a recollaring. Differences in multipoles before and after the recollaring have been computed for all positions except the ones affected by the missing shim. Results are shown in Table II, together with the other cases already discussed in the previous reports.
    - All data of Table II refer to no variations of coil lay-out before and after recollaring. When this did not happen (as for 2013, where the shim thickness was changed), we subtract from experimental data the expected effect of the lay-out change.
    - 2002 is the only collared coil where the decollaring was 'soft', i.e. only the collars around the assembly fault have been removed and therefore coil has not been disassembled, and insulation has not been changed; effect on field quality is lower.
    - The other three cases of Table II refer to a complete decollaring with substitution of insulation and quench heaters. Experimental data show a systematic effect on odd

normal multipoles, which is non negligible especially for the b_5 (0.25 to 0.65 units) and to some extent also for the b_7 (-0.04 to –0.28 units).

- This variation is not expected to play an important role in the field quality control of the dipoles, since it is likely that only a small fraction of collared coils will be recollared over all the production.

Table II: Effect of recollaring on field quality, available data on 4 collared coils

Magnet name	Aperture	ΔC_1	Δb_3	Δb_5	Δb_7
2002	1	-2.4	0.39	0.18	-0.04
2002	2	-3.0	0.51	0.14	-0.05
2011	1	1.0	-0.80	0.65	-0.28
2011	2	0.6	-0.67	0.50	-0.23
2013	1	3.4	-0.63	0.54	-0.09
2013	2	4.7	-0.38	0.50	-0.11
1027	1	-0.3	-0.43	0.25	-0.04
1027	2	0.2	-0.46	0.39	-0.05

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, L. Bottura, A. Devred, S. Pauletta, V. Remondino, L. Rossi, S. Sanfilippo, W. Scandale, I. Vanenkov, C. Voellinger, E. Wildner for comments, valuable help and discussions, and C. Laverriere for help with EDMS.

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
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		
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	57th	3010		
18th	3006	38th	1017	58th	1029		
19th	1009	39th	1018	59th	2019		
20th	2004	40th	1019	60th	3014		