Report on field quality in the main LHC dipole collared coils: September-October 2003

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This report gives data relative to field quality measured in collared coils during the period September 1– October 31 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. **428156**

The dashboard

- Available measurements: 218 collared coils, 154 cold masses (one octant), 59 cryodipoles.
- In these two months, 55 collared coils: 15 from Firm1, 11 from Firm2 and 29 from Firm3.

What's new

- **Production rate** has ramped up to 27 collared coils per month. Firm3 has reached 3.5 collared coils per week, and has produced as much as Firm1 and Firm2 together. Firm1 and Firm2 are at 1.7 and 1.2 collared coils per week respectively.
- **Length of feedback loop:** The delay between collared coil magnetic measurements and cold test is stable at 12 months (in average), and at 2.5 months (minimal, obtained for 3038).
- **Cold tests:** Results of this year show that it will not be possible to measure the magnetic field of all dipoles at 1.9 K at CERN. A discussion about the size and the strategy of the sampling has been started. More information can be found in the web site of the Field Quality Working Group: http://fqwg.web.cern.ch/fqwg/031111/031111.html
- **Switch to cross-section 3:** the addition of 0.125 mm insulation (X-section 3) in the coil mid-plane is now the baseline. All manufacturers are producing X-section 3. The total number of magnets with X-section 1 and 2 is 35 and 139 respectively, i.e. the second octant will contain 20 magnets with X-section 2 and 134 with X-section 3.
- **Trends in odd multipoles:** we have more than 40 collared coils with cross-section 3. Systematic b_3 and b_5 are within the target range in optimal positions. Systematic b_7 is 0.22 units larger that the upper limit, corresponding to a value of 0.28 units at injection.
- **Trends in skews:** the trends observed in the previous report are confirmed: a large systematic a_3 in Firm3 and a large systematic a_4 in Firm2 (0.9 and 0.45 units respectively, in the last two months). Even though systematic values are comfortably within targets, these trends should be followed carefully. No effect of cross-section 3 on a_2 and a_4 as expected.
- **Coil size:** Firm1 is producing outer layers with large azimuthal coil size, which is forcing to use non-nominal shims up to 0.2 mm less with respect to nominal. This has a non-negligible effect on main field and normal sextupole. The other manufacturer use nominal shims (Firm2) or shims within 0.05 mm from nominal (Firm3). Details in Section 1 and in the report by I. Vanenkov (see also http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/obs_coil.html
- **Trends in integrated main field:** collared coil data after calibration of magnetic length show that the systematic difference in integrated main field between Firm3 and Firm1-2 is of 10 units, and it is then reduced by the addition of iron laminations. We refer to results of Section 3. For the moment no necessity of correction is needed.
- **Closed case, assembly fault:** collared coil 2032 showed large spikes (more than 8 sigma) in a few high order multipoles (mainly b_6 and a_8) along the axis. These variations can be obtained from simulations by inner radial movements of 0.5 to 1.5 mm of the inner layer close to the pole. The collared coil has been opened on November 18th, finding out what expected from simulations. This shift is due to a non-correct gluing of the cables of the inner layer, and affects several positions along the magnet axis. Such a collared coil, if had become a cryomagnet, would very probably have had a bad quench performance in the straight part. More information in Section 10, pg. 16 and in http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/2032.html

1. Measured magnets and assembly data

- 55 new collared coils have been measured (collared coils 164th to 218th)
  - 15 of Firm1 (1043, 1056, 1058, 1060-4, 1066-71 and 1074)
  - 11 of Firm2 (2045,2049,2050,2052-8 and 2061)
  - 29 of Firm3 (3031-3, 3040 and 3069-93).
- 6 more measurements have been performed: 3068 has been re-measured since it has been decollared, 3075 has been measured twice to check the new measuring system, 2053 and 3071 have been measured two times due to faulty measurements, 1067 have been measured three times due to faulty measurements.

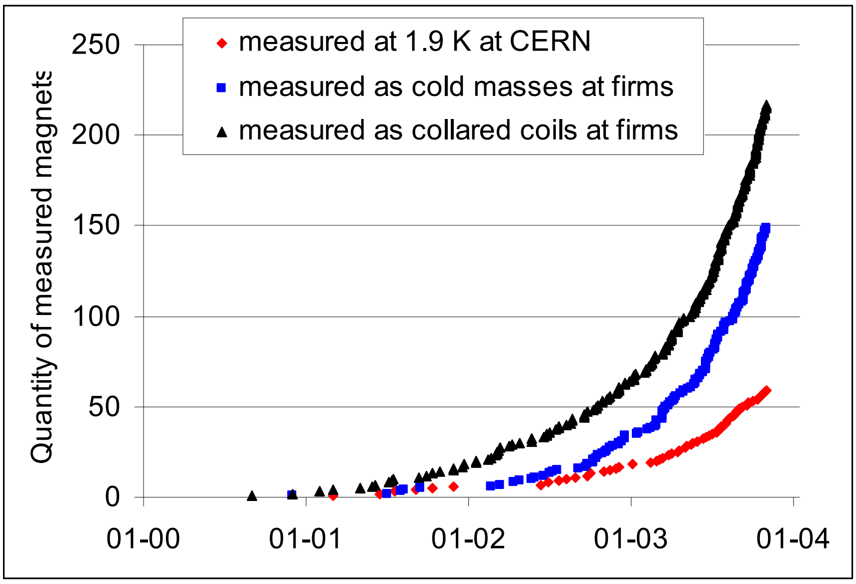

Fig. 1: Number of magnets measured at CERN at 1.9 K and at the manufacturers at room temperature at different stages of assembly procedure

- Cross-section: 17 magnets have X-section 2, and the remaining 38 magnets have X-section 3, i.e. 0.125 mm additional mid-plane insulation (see list in Appendix). Total number of magnets with cross-section 2 is 139. We will have 20 magnets with cross-section 2 in the second octant.
- Shims are nominal in Firm2. In Firm3, we have 5 cases of non-nominal shims within 0.05 mm. On the other hand, in Firm1 we have 8 cases of non-nominal shims, within 0.05 mm on the inner layer but with non-nominalities up to 0.2 mm for the outer layer. This affects main field and normal sextupole.

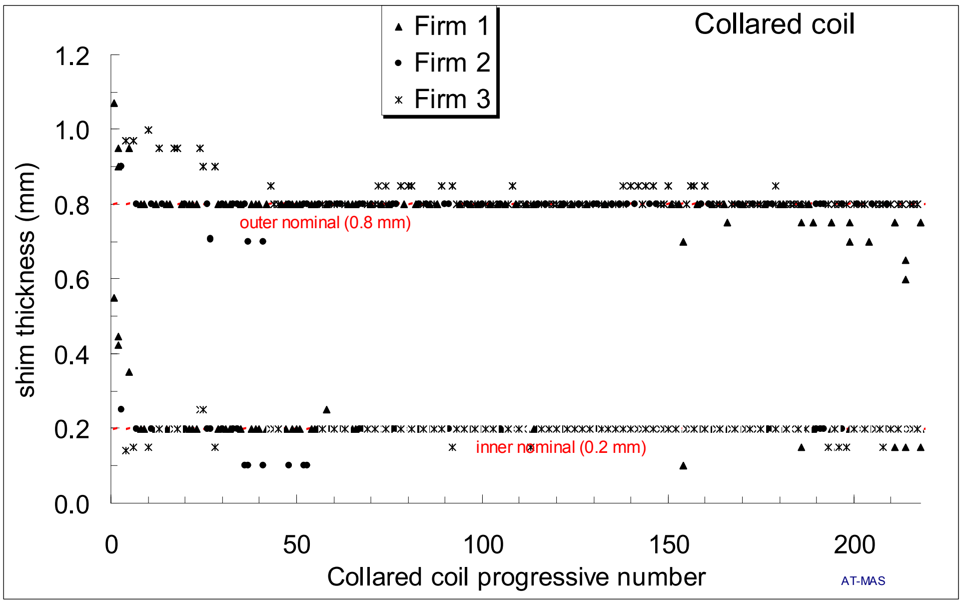

Fig. 2: Thickness of the polar shims used in the collared coils

2. Estimated coil waviness

- Coil waviness estimated from the variation of the multipoles along the axis is below 30 microns. Only exceptions are one aperture of 1063 and one of 1076, with slightly higher values. The general situation of this parameter is very good in all firms.

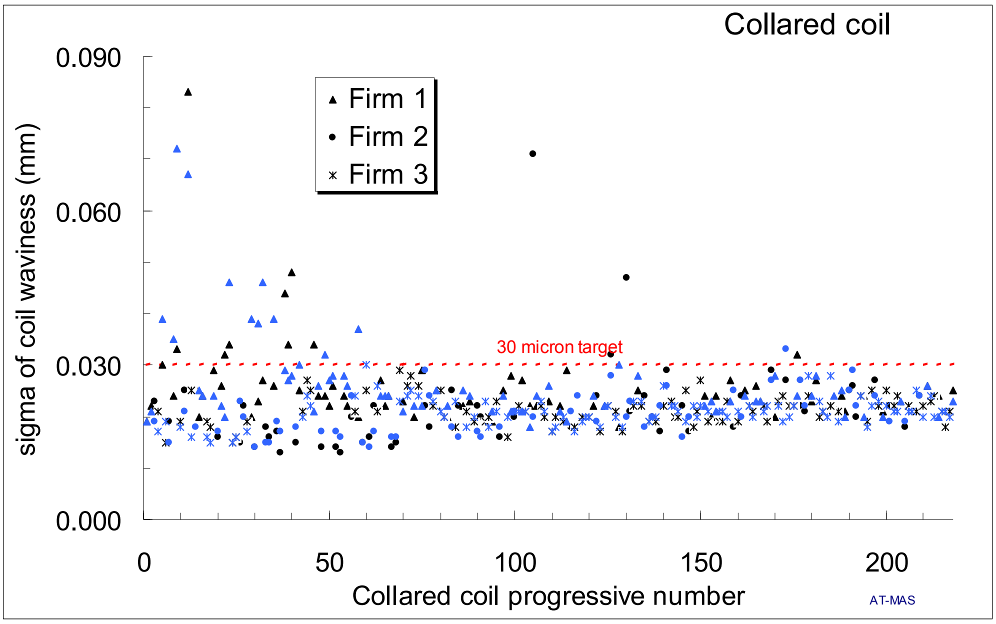

Fig. 3: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

3. Magnetic length and transfer function

- Magnetic lengths of collared coils 164th to 218th are well within targets (see Fig. 4). The spread in magnetic length is very low (3 units). We have one case (3040, i.e. 187th in Fig. 4) of a large difference between apertures (8 units). We present data after the calibration of the second generation measuring system that shifts Firm3 values down of 5 and 7 mm with respect to values in Firm2 and Firm1 respectively.

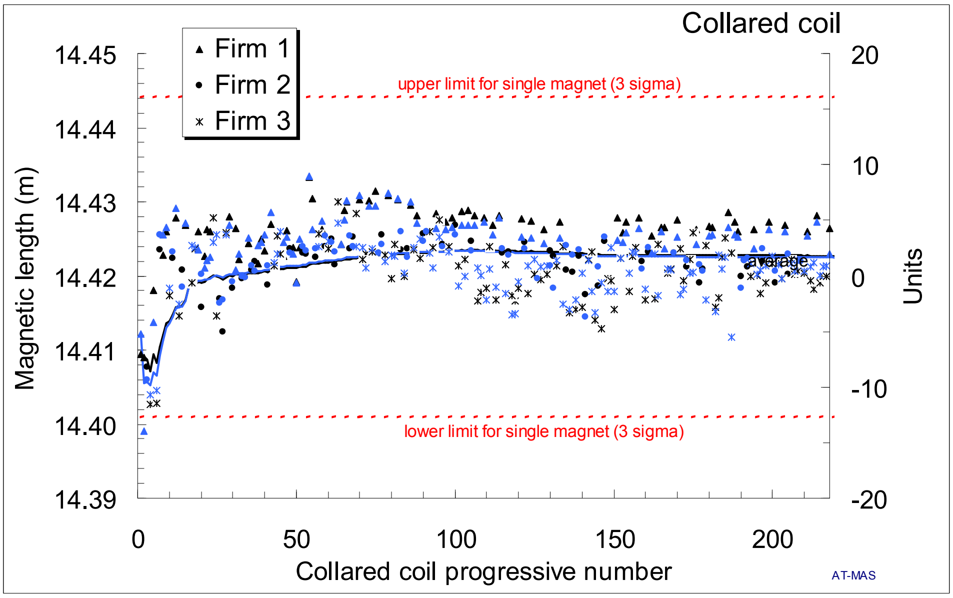

Fig. 4: Magnetic length of the measured collared coils (black dots: aperture 1, blue dots: aperture 2)

- A few collared coils from Firm1 (1067, 1069, 1070 and 1071, i.e. 199th, 204th, 211th and 214th in Figs. 5 and 6) show very low main field, which is only partly due to non-nominal shims. They all feature X-section 3. The procedure of correction of magnetic length to compensate low main field has been asked.
- In general, the introduction of cross-section 3 has shifted down the main field by 4 units, which results from a decrease of 6 units in Firm1 and Firm3 and no shift in Firm2.
- In cross-section 3, data reduced to nominal shims, we observe a difference of 14 units between Firm3 and Firm1, and Firm2 is placed in between.

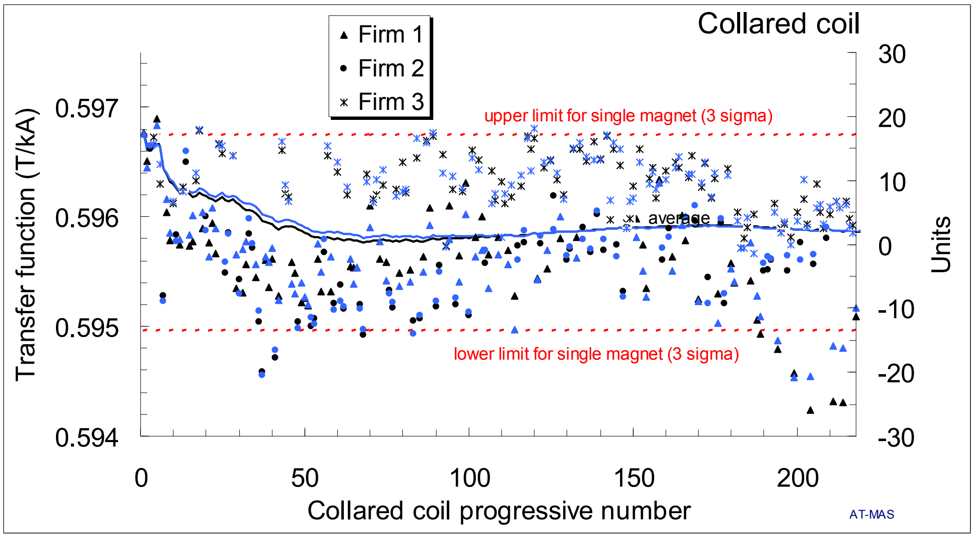

Fig. 5: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines).

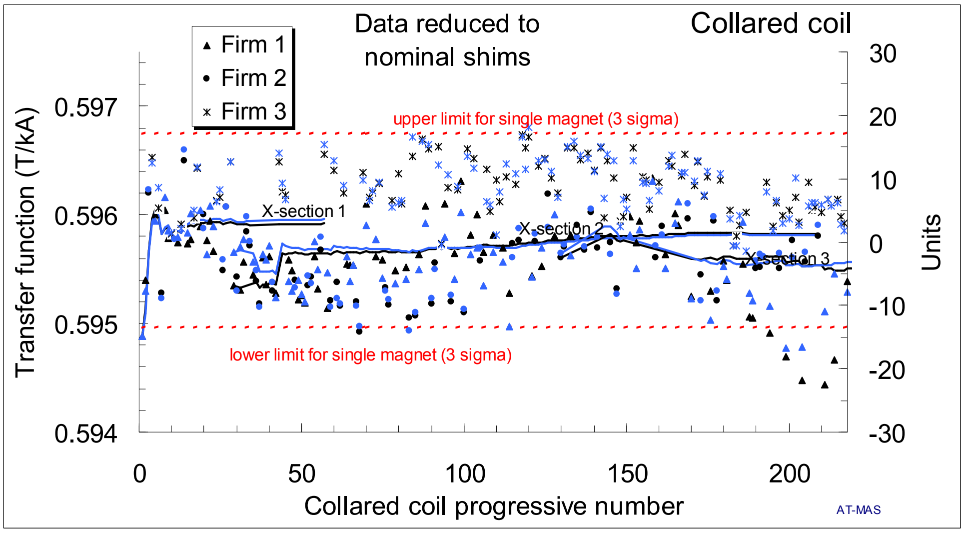

Fig. 6: Main field in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

- The spread of the integrated transfer function in all collared coils is 7 units (one sigma), i.e. within the target. The main difference with respect to values in the previous report (10 units) is due to calibration of magnetic length.
- Spread within the same firm is 5 units in Firm2 and Firm3, and 7 in Firm1.
- In cross-section 3, we have a difference of 10 units between Firm3 and Firm1 average, Firm2 being in between.
- Cold mass data show that the systematic difference between firms is reduced by the iron yoke (see also http://fqwg.web.cern.ch/fqwg/031111/031111.html). This is in agreement with measurements at 1.9 K. The spread between firms in integrated main field is within specifications. We therefore implement no corrective action, with the exception of acting on isolated magnets showing anomalous main field due to non-nominal shims.

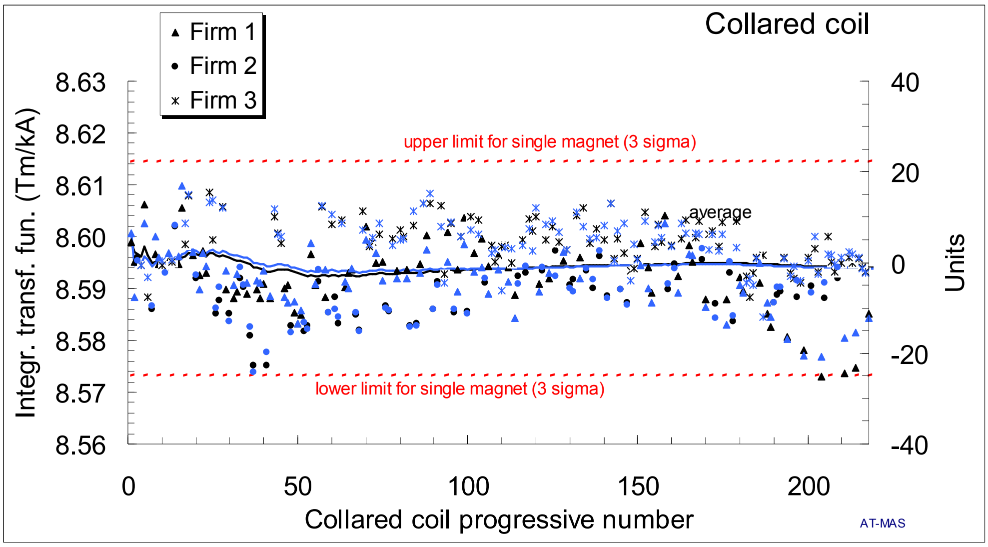

Fig. 7: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and average over all collared coils (solid lines)

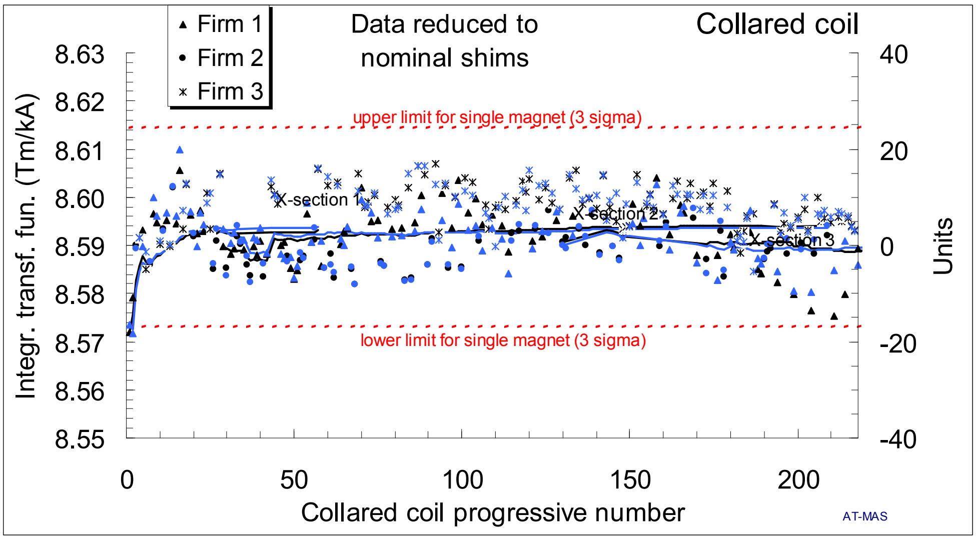

Fig. 8: Integrated transfer function (black dots: aperture 1, blue dots: aperture 2) and best estimate of systematic (solid lines). Data are reduced to nominal shims and separated according to different cross-sections.

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.

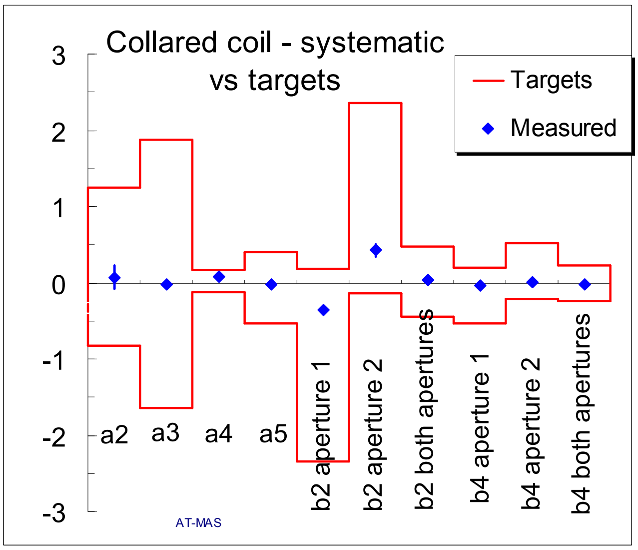

Fig. 9: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics.

- Best estimates for systematic odd normal multipoles are shown in Fig. 10. In the left part, raw data are plotted. This gives the actual situation for global values relative to all manufactured collared coils, which are slowly moving toward optimal ranges: b_3 and b_5 are larger than the upper specifications of 0.6 and 0.36 units respectively.
- In the right part of Fig. 10, data are reduced to nominal shims and separated according to the two cross-sections (35 collared coils have cross-section 1, 139 have cross-section 2, 44 have cross-section 3). With the cross-section 3, b_3 is within targets, 1.8 units below the upper limit (i.e., 1.5 units at high field), and also b_5 is within targets, 0.2 units below the upper limit (i.e., 0.95 units at injection). Finally, b_7 is 0.22 units larger than the targets (i.e. 0.28 units at injection).

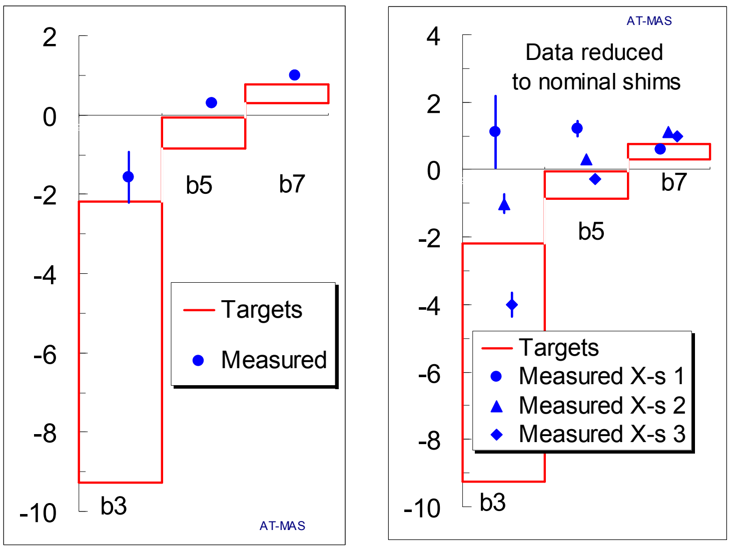

Fig. 10: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections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

5. Summary of systematic differences between firms

We observe a relevant systematic difference between firms only for the main field:

- Main field: Firm3 is higher than Firm1 of around 14 units, Firm1 being in between (see Fig. 5).

In other cases, we observe a small systematic difference between firms (from one to two times the natural sigma within the same manufacturer).

- Normal decapole b_5: Firm1 has a systematic b_5 of 0.8 units larger than Firm2, Firm3 being in between. This difference is two times the natural sigma within the same manufacturer.
- Skew sextupole a_3: Firm3 has a systematic a_3 of 0.5 units, against –0.4 units in Firm2, Firm1 being in between. This difference is two times the natural sigma within the same manufacturer.
- Normal 14th pole: b_7 at Firm1 is 0.25 units higher than Firm2, Firm3 being in between. This difference is between one and two times the natural sigma within the same manufacturer.
- Skew octupole a_4: Firm2 has a systematic a_4 of 0.3 units, against 0.0 units in Firm2 and Firm1. This difference is equal to the natural sigma within the same manufacturer.

No systematic differences between firms are visible in a_2, b_2 b_3 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, whereas beam dynamics limits are tighter for a_2 and a_4.
- Indeed, some trends in a_3 and a_4 should be carefully followed and, if possible, understood. These trends were already observed in the previous report (July-August 2003):
  - Collared coils from Firm3 manufactured in the last two months have a systematic a_3 of about 0.9 units (see Fig. 12); this is not worrying for beam dynamics since margins are large, but there is a trend with respect previous months.
  - Collared coils from Firm2 manufactured in the last two months have a systematic a_4 of about 0.45 units (see Fig. 13); also in this case we have a positive trend. This could be worrying since beam dynamics targets are very narrow. Indeed, the systematic is within target.
- The introduction of cross-section 3 produced no effect on a_2 and a_4, as expected.

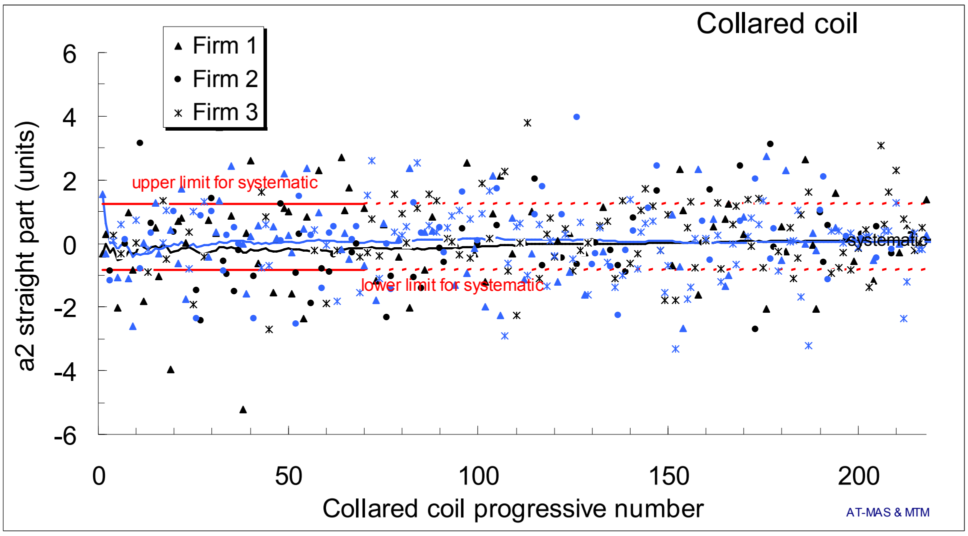

Fig. 11: Average a_2 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 49 cryodipoles.

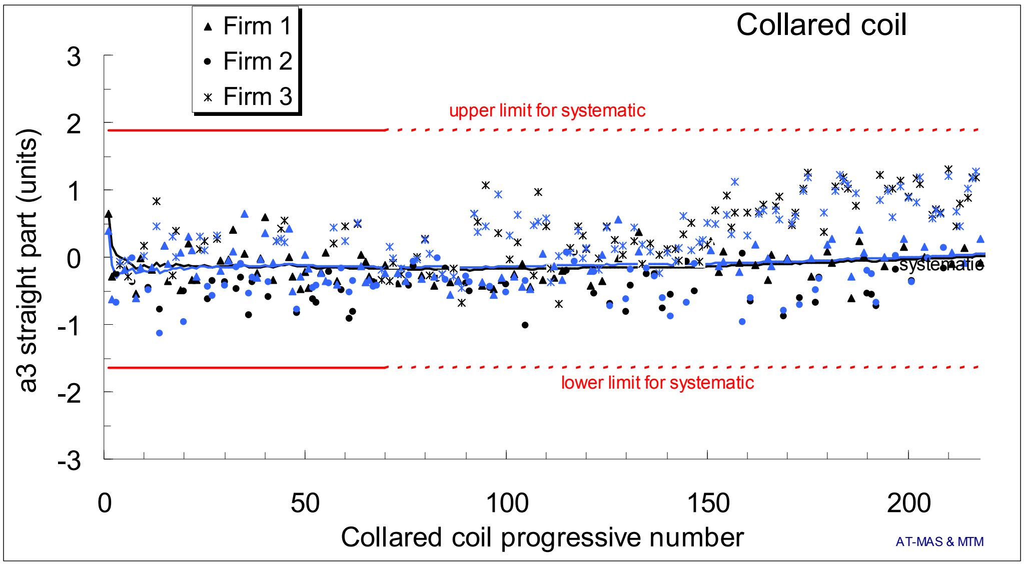

Fig. 12: Average a_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 49 cryodipoles.

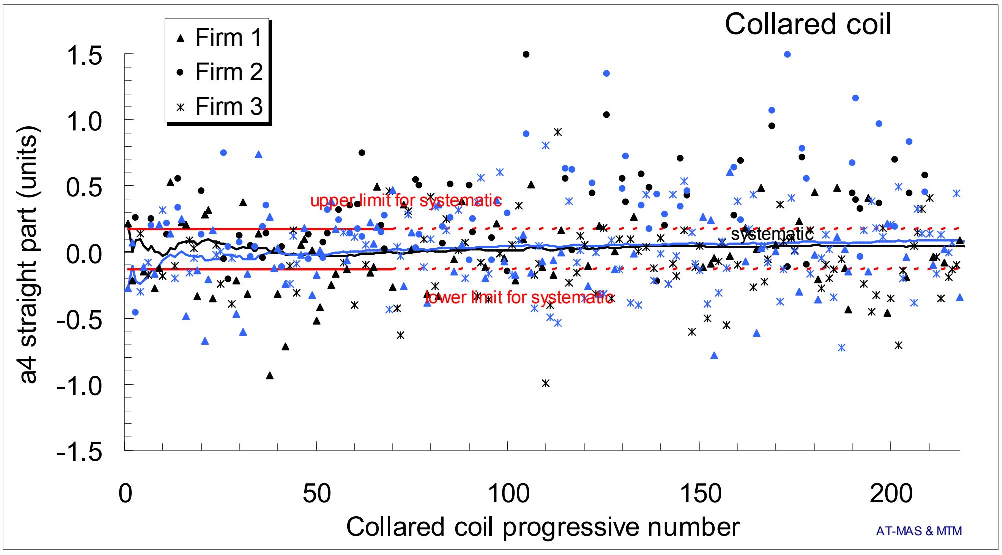

Fig. 13: Average a_4 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

7. Systematic even multipoles

For each multipole being subject to beam dynamics specifications, we present two separated plots for the systematic per aperture, plus 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).

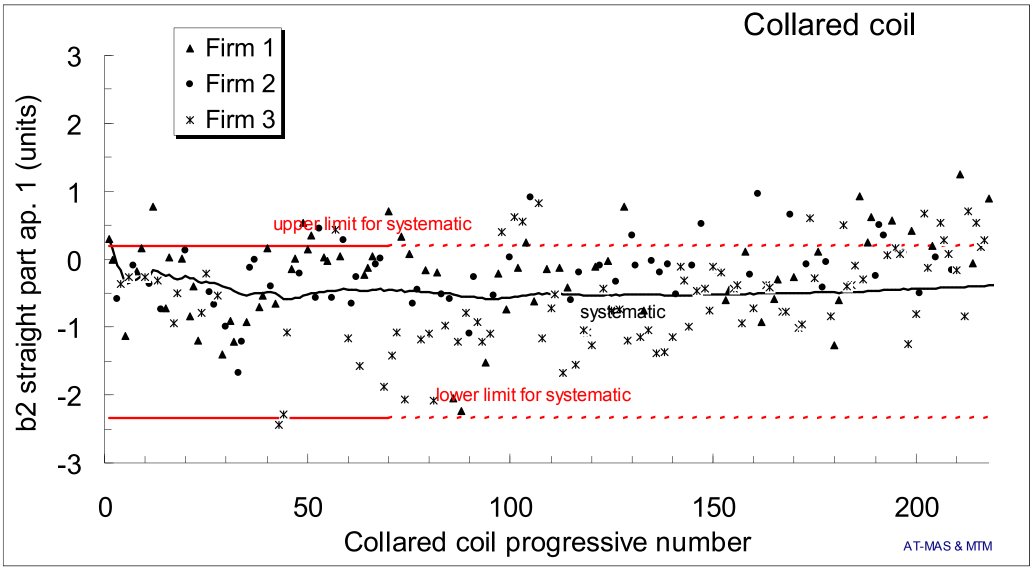

Fig. 14: Average b_2 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

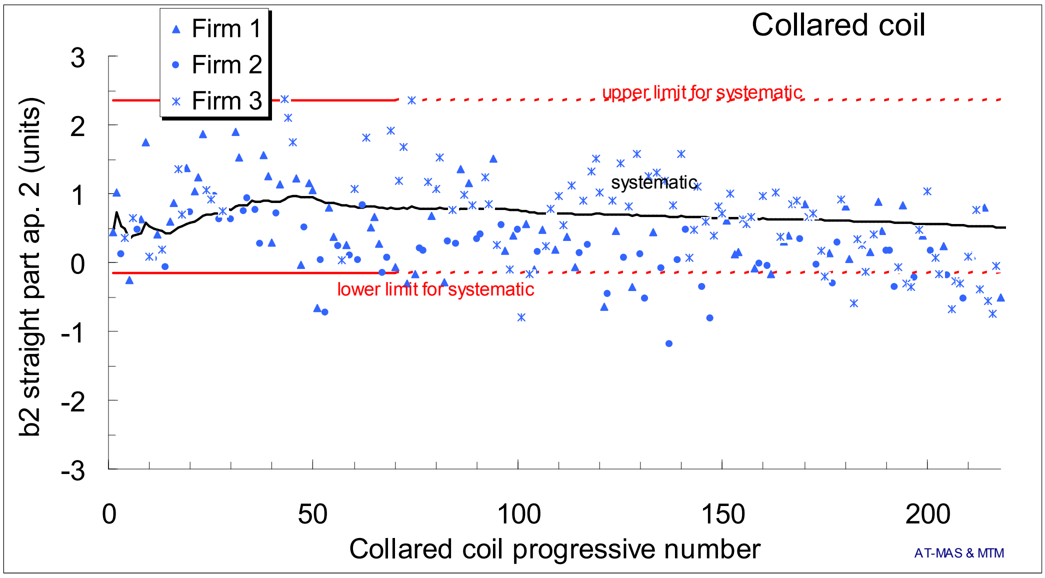

Fig. 15: Average b_2 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (blue line) and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

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

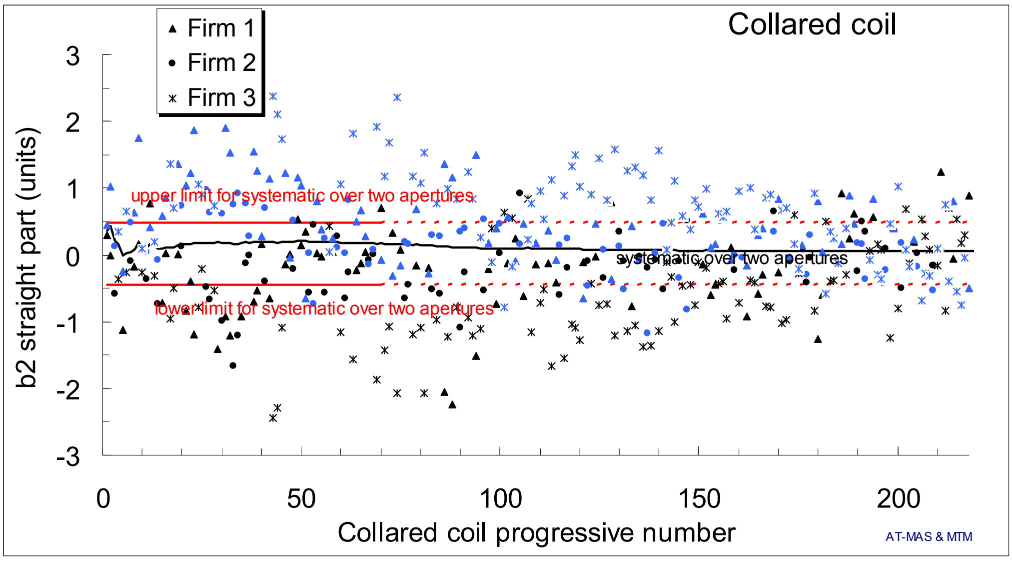

Fig. 16: Average b_2 in the straight part of collared coils ((black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (soild line) and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

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).

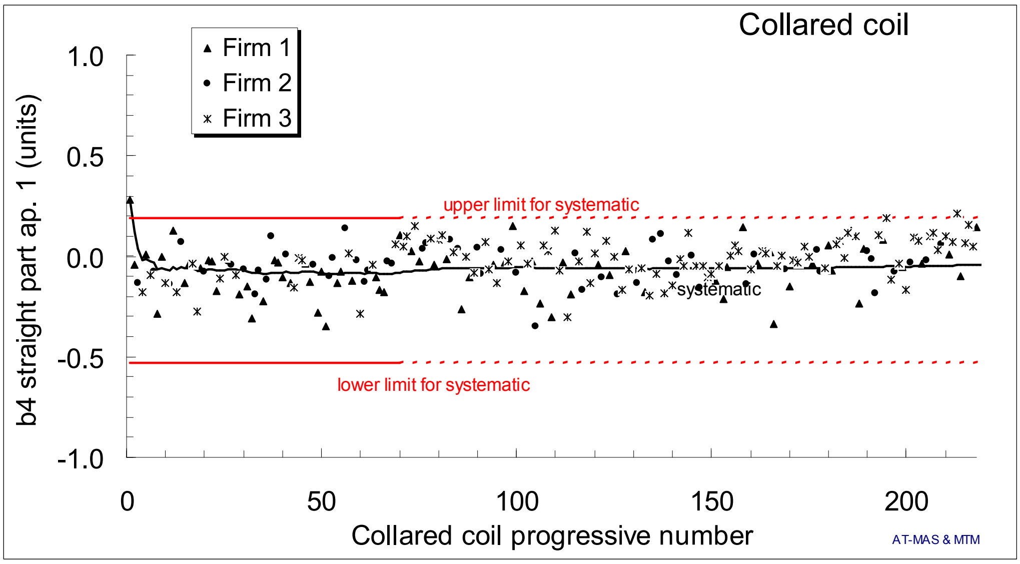

Fig. 17: Average b_4 in the straight part of the aperture 1 collared coils (black dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

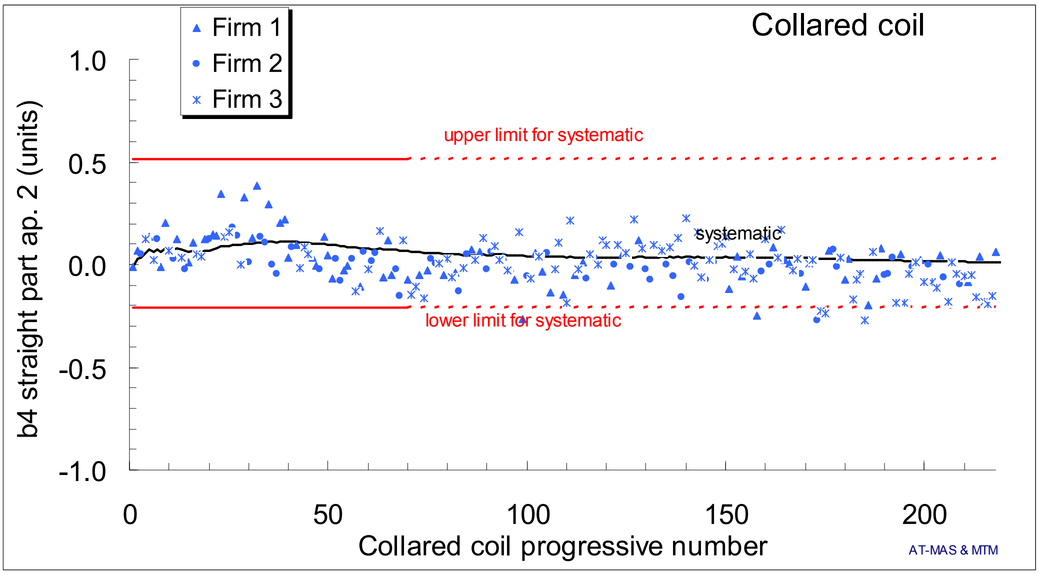

Fig. 18: Average b_4 in the straight part of the aperture 2 collared coils (blue dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

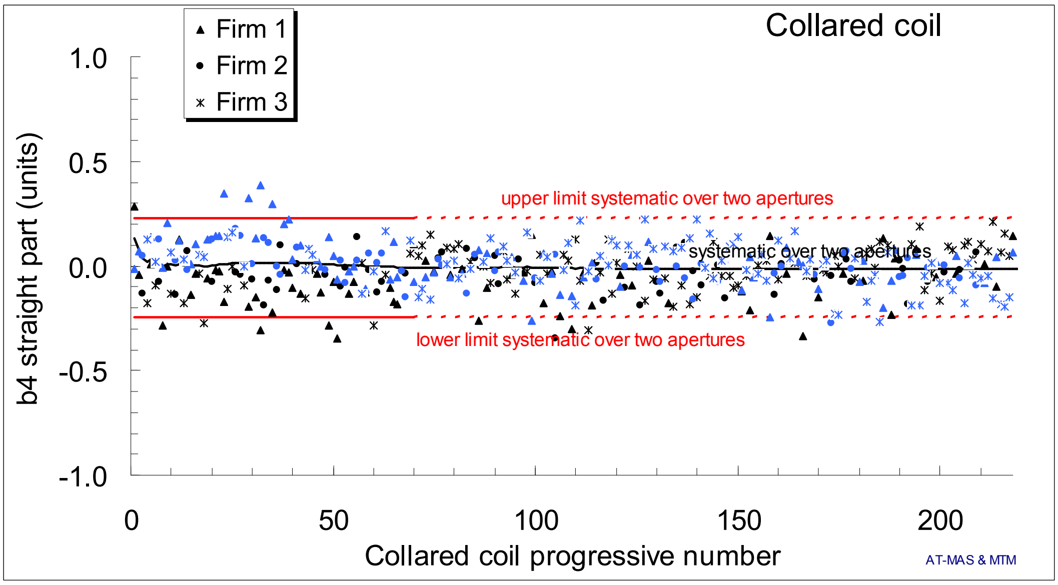

Fig. 19: Average b_4 in the straight part of collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

8. Systematic odd multipoles

8.1 Normal sextupole

- Data not reduced to nominal shims and not separated according to different cross-section show a negative trend due to the introduction of cross-section 2 (at collared coil 30th) and 3 (around collared coil 140th, see Fig. 20).
- The introduction of cross-section 3 has brought b_3 in the upper half of the target range (see Fig. 21). Some collared coils of Firm1 feature a rather low b_3 due to non-nominal shims.
- In cross-section 3, b_3 values show a low spread for Firm2 and Firm3 (0.5 units one sigma), whilst for Firm1 data have a large spread (1.5 units). Shim values and traceability are under verification.
- Average b_3 in cross-section 3 is at -4.6, -3.9 and -3.4 units in Firm1, 2 and 3 respectively, showing little difference between Firms.

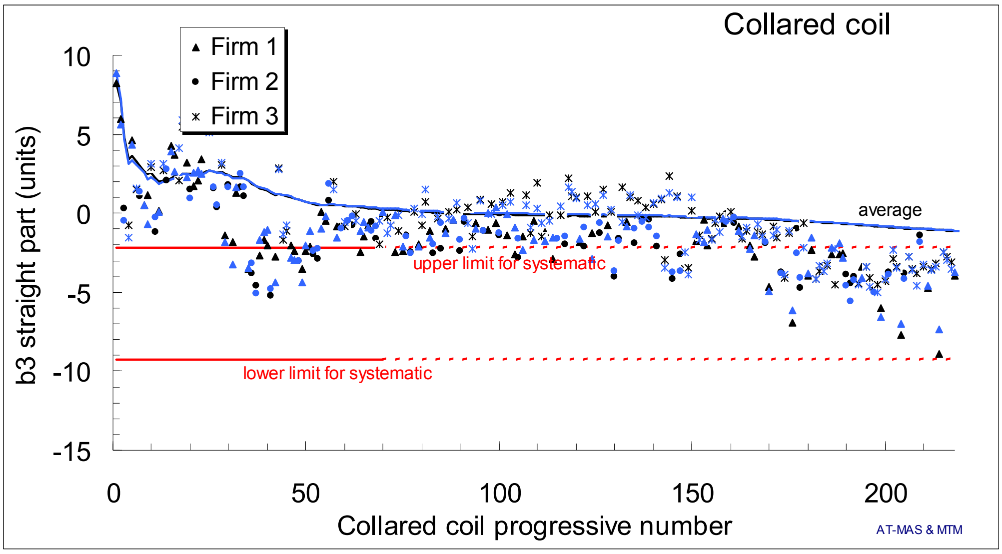

Fig. 20: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

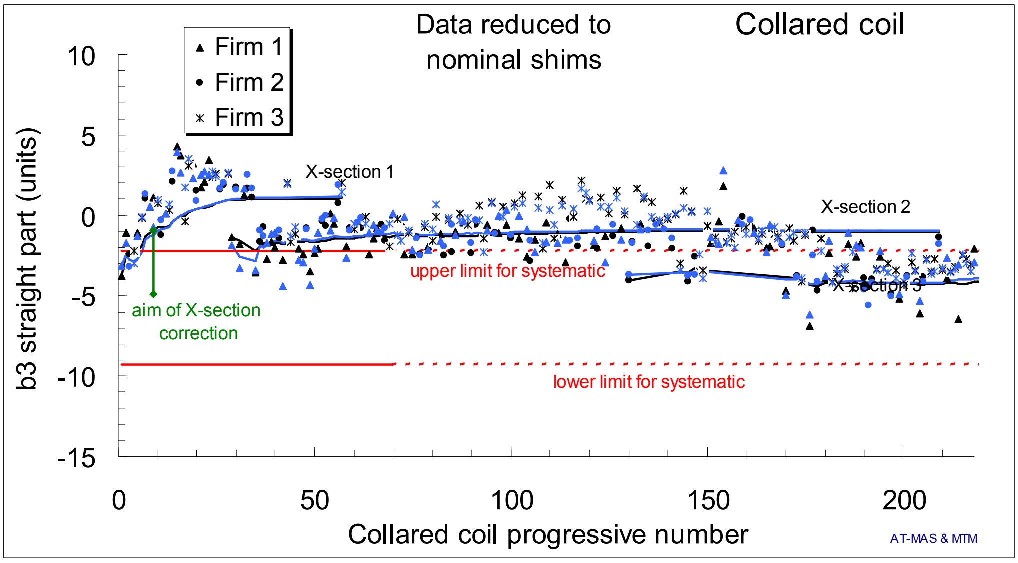

Fig. 21: Average b_3 in the straight part of the collared coils (black dots: aperture 1, blue dots: ap. 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles. Data reduced at nominal shims and separated according to cross-section type.

8.2 Normal decapole

- Data not reduced to nominal shims and not separated according to different cross-section show a negative trend due to introduction of cross-section 2 (see Fig. 22, from 35th to 120th) and then due to the introduction of cross-section 3 (same Figure, after 140th).
- Indeed, when data are separated according to cross-sections and reduced to nominal shims one finds that average b_5 in all cross-sections is stable after a transient due to low statistics (see Fig. 23).
- Cryodipoles with the cross-section 3 should feature 0.95 units of b_5 at injection. This places b_5 safely within the target range, not far from the centre of the range.
- Spread of b_5 for cross-section 3 is very similar in all firms: around 0.25 units.
- Average b_5 for cross-section 3 is at 0.13, -0.39 and –0.55 units in Firm1, 2 and 3 respectively. Therefore, the high value of this multipole in Firm1 it is confirmed: this feature was present also in cross-section 1 and 2.

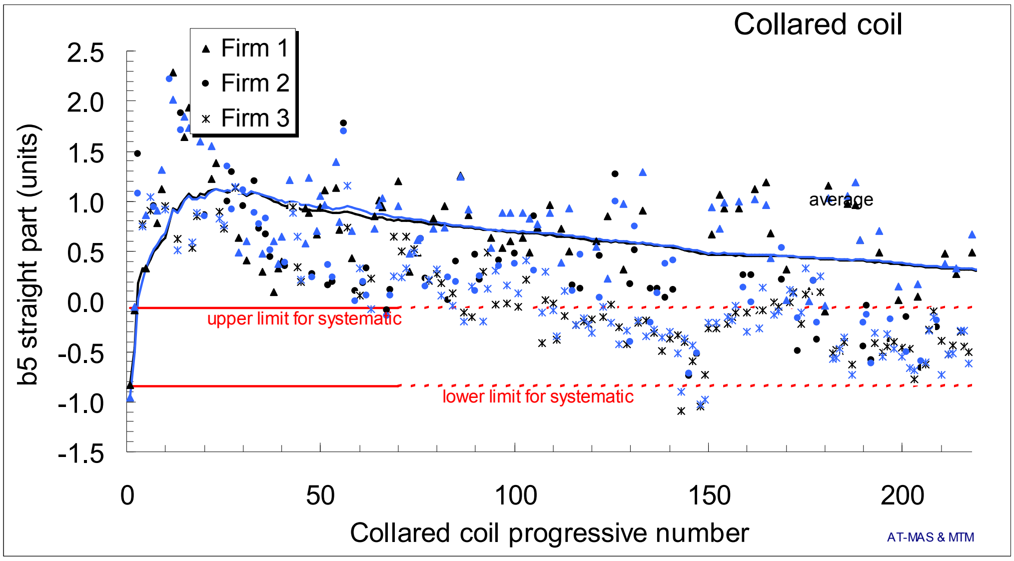

Fig. 22: Average b_5 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

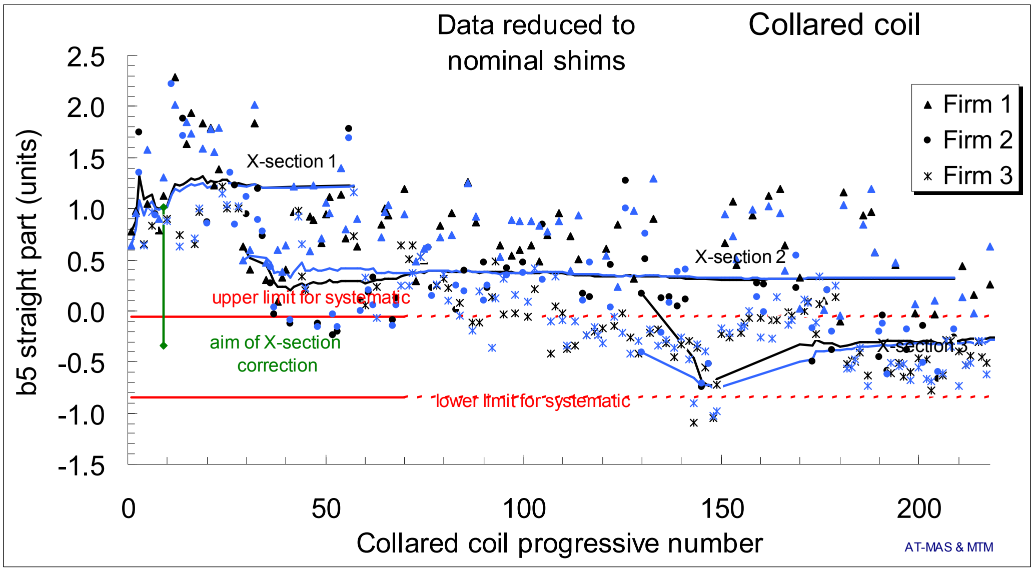

Fig. 23: Average b_5 in the straight part of the collared coil (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

8.3 Normal 14-th pole

- The introduction of cross-section 3 reduced b_7 of 0.21 units in Firm2, of 0.13 units in Firm1, but had no effect in Firm3. For this unexplained feature, the effect of the correction is smaller than expected.
- Firm2 has a very low average b_7 (0.75 units, i.e. 0.35 units less than Firm1 and Firm3), as it observed in cross-section 2: this is one of the few cases where a non-negligible difference between Firms is observed.
- Cryodipoles with the cross-section 3 should feature 0.28 units of b_7 at injection. This would place b_7 above the target, but within the previous target of 0.30 units (see Fig. 31).

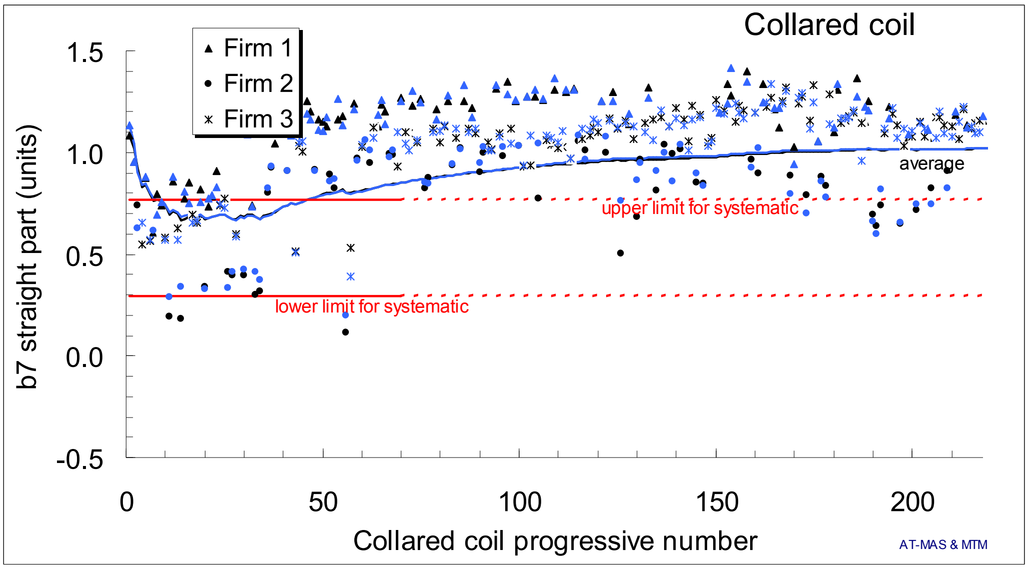

Fig. 24: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles.

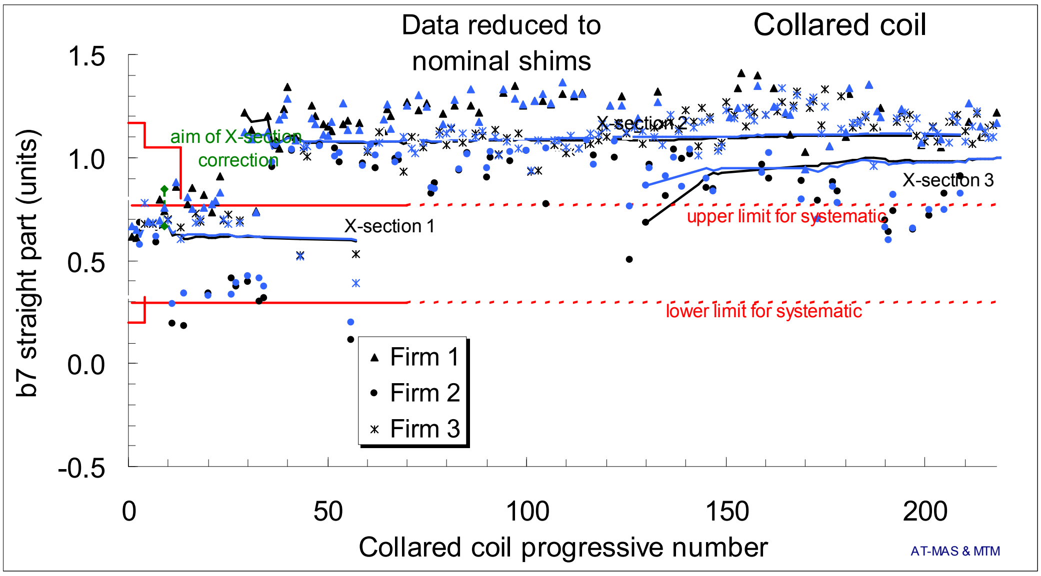

Fig. 25: Average b_7 in the straight part of the collared coils (black dots: aperture 1, blue dots: aperture 2), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red lines) based on correlations with 59 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

9. Random multipoles

We repeat the same considerations made in the previous report, waiting for more statistics on cross-section 3.

- 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 targets for b_3 and b_5. This is mainly due to the change of cross-section that shifted down these multipoles by 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 cross-section 1: this is due to the initial upward trend between collared coil 1st and 20th (see Section 8.1, Fig. 21). This is the only out of tolerance in the cross-section 1.
- For cross-section 2, all the multipoles are within specifications, global integrated main field BdL being slightly above the specification.

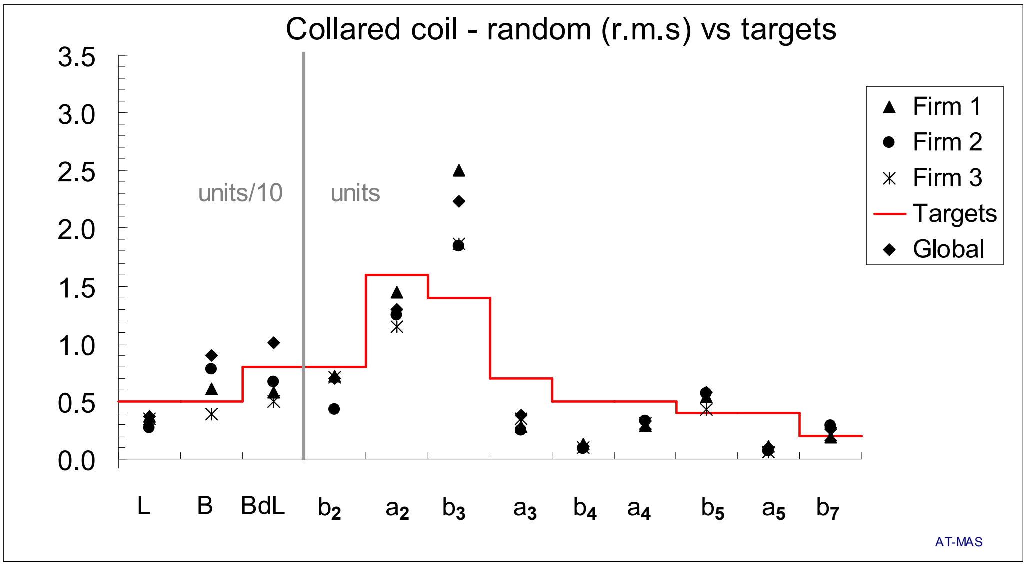

Fig. 26: Random component in the measured collared coils

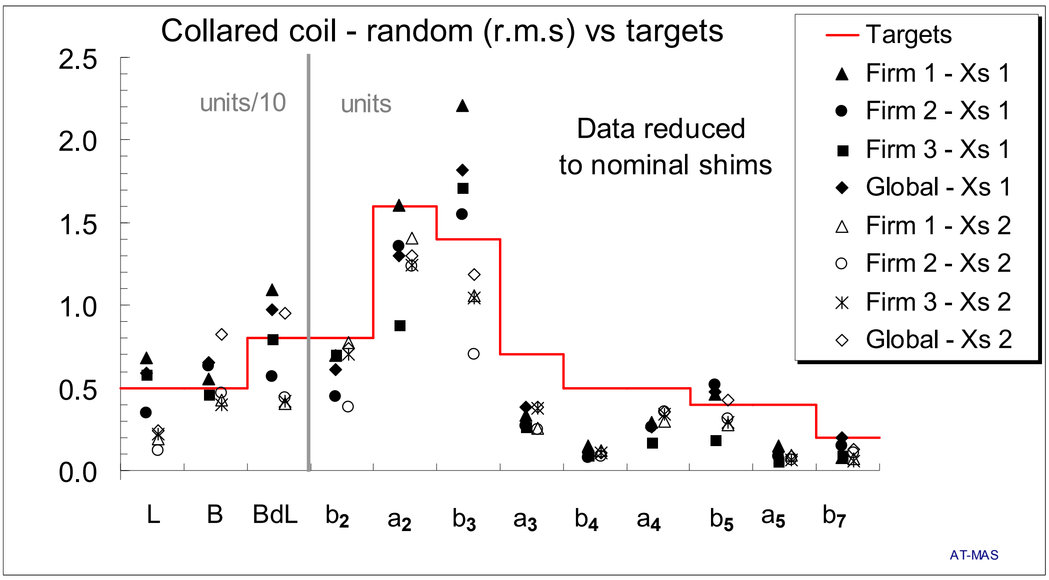

Fig. 27: Random component in the measured collared coils. Data reduced to nominal shims and split according to different cross-sections.

10. Holding point results

- We had three cases (2053 two times, and 1067) of wrong measurements in which the collared coil was held to repeat the procedure. In all cases the problems were solved and a valid measurement is available.
- In Firm1, a warning for the low main field of some collared coils has been given.
- In Firm2 we had a few cases of anomalies in coil heads of allowed multipoles, possibly due to the change of cross-section. Moreover, we had four alarms on field angle (2049, 2053, 2055 and 2057) corresponding to a bad alignment of the collared coil on the measuring table. The problem has been cured. We had two cases of deterioration of coil waviness along the magnet axis (2052 and 2054).
- In Firm3 we had several cases of warning due to anomalies in coil heads of allowed multipoles.
- 2032 has been decollared for showing several anomalies in high order multipoles (a_6 and b_8) along the magnet axis that, even though being rather small in absolute value (0.3 and -0.6 units respectively), where clearly out of our statistic (more than 8 sigma). Simluations pointed out that this coul be due to a inner radial movment of the inner block close to the pole of 0.5 to 1.5 mm in one quadrant. The decollaring and the following disassembly showed that his block was not glued to the rest of the layer and that it was sliding towards the cold bore tube (see Figure 28). More details in the dedicated web page http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/2032.html

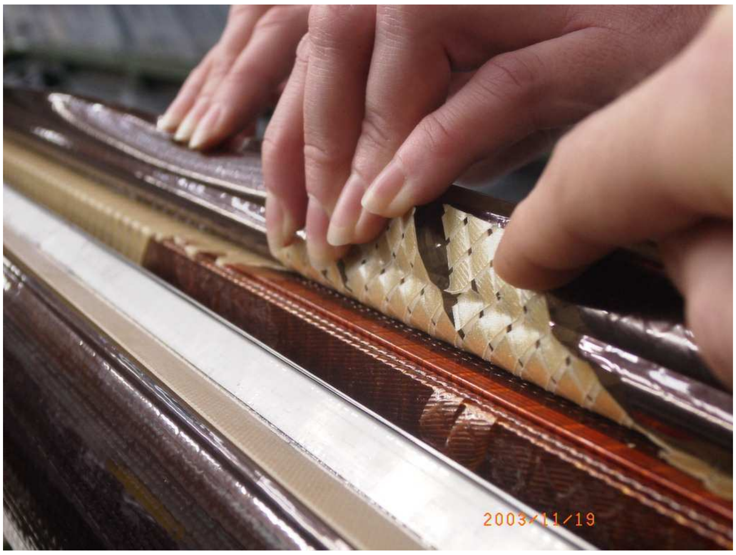

Fig. 28:Bad quality of coil in collared coil 2032, view of the inner layer, with a conductor block not glued to the copper wedge.

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Appendix

From this report on, the link between the progressive number used in figures can be found in the log file that is linked to the field quality observatory. Magnets with cross-section 3 are

- Firm1: 1061, 1063-5, 1067, 1069-71, 1074
- Firm2: 2035, 2040, 2043, 2045, 2049, 2053-5, 2057,2058, 2061
- Firm3: 3031-3, 3040,3056, 3059, 3060, 3075, 3077-93