Report on field quality in the main LHC dipole collared coils and cold masses: November-December 2004

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This report gives data relative to field quality measured in collared coils and cold masses during the period November 1– December 31 2004, warm-to-cold correlations, comparison to beam dynamics targets, and status of the holding points. Updated graphs can be found in the field quality observatory http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs.html.

EDMS n. 546198

The dashboard

- Available measurements:
  - 660 collared coils and 591 cold masses at room temperature,
  - 127 dipoles plus 14 half dipoles (one aperture only) for a total of 134 equivalent dipoles at 1.9 K[1].
- In these two months we had:
  - 73 new collared coils (23 from Firm1, 19 from Firm2 and 31 from Firm3) measured at room temperature,
  - 6 complete dipoles measured at 1.9 K[1].

What's new

- **Half of the dipole** collared coils have been manufactured.
- **Production rate** is at 37 collared coils per month, notwithstanding the Christmas holidays. The rate is 2.6, 2.2 and 3.6 collared coils per week in Firm1, Firm2 and Firm3, respectively.
- **Length of feedback loop:** The minimal delay between collared coil magnetic measurements and magnetic measurements at 1.9 K is 50 days (obtained for magnet 1136). The last magnet measured at 1.9 K is the 488th, and since then another 172 collared coils have been produced.
- **Trends in transfer function:** The spread of the integrated transfer function between Firms is very low in the production of the last two months (within ±5 units).
- **Random component:** We give for the first time a tentative estimate of the random component for the first four sectors of the machine (see pg. 5).
- **Trends in b3:** The situation is improving: the spread between Firm2 and Firm1-3 is now around 2.5 units. The systematic b3 (average of all Firms) is in the optimal range.
- **Trends in b5:** The situation is improving in all Firms. A negative trend is bringing average b5 within the target range.
- **Trends in a4:** Systematic a_4 in Firm2 is oscillating between 0 and 1 units. A test magnet where the collared coil has been installed capsized in the cold mass, thus leading to a negative a4, has been manufactured. This solution could be used to further reduce systematic a4.
- **Assembly faults:** No assembly faults detected in these two months.

[1] These numbers refers to complete measurements of either magnets or single apertures available in AT-MTM Oracle database. From this report on, we include in our analysis also complete measurements of single apertures, thanks to the code implemented by P. Hagen. On the other hand, we still do not include measurements where either the transfer function or the multipoles are missing.

CONTENTS

The new format of the report

We remind the reader the most important features of the report.

- The first section deals with the number of measured magnets in the last two months and the assembly data (X-section type and shim size).
- In the second section we have the summary of the measured field quality of all collared coils versus beam dynamics targets. This gives a quick overview of the best guess for the status of field quality versus beam dynamics.
- The third section is devoted to trends in field quality.
    - The trend plots show multipole moving averages for each manufacturer versus the magnet progressive number[2]. Each marker is the average of 5 measurements:
        - the collared coil characterized by the progressive number in the horizontal axis
        - the two collared coils previously produced <u>by the same Firm</u>
        - the two collared coils produced afterwards <u>by the same Firm</u>
    - We always give plots for the collared coil measurements, except the case of bending strength where also cold masses measurements are adding important information. When comparing these cold masses to collared coils, one has to take into account that usually the last 60 collared coils have not yet become cold masses, and therefore a different pattern has to be expected in the end of the plot (see Figs. 9-10, and 11-12).
    - We give the reduction to nominal shims only for b3. Now shims are nearly always nominal.
    - Correlations are not presented in the standard plot ‘warm-vs-cold’, but rather as a trend plot of the offset between warm and cold vs the magnet progressive number. In this way we can visualize trends in correlations and the type of sampling that is being carried out at 1.9 K.
    - From this report on, all plots give integral values (i.e. including contribution of coil heads). This gives in some cases an offset in the y scale with respect to plots of the previous reports, corresponding to the head contribution.
- The final Section is devoted to field quality used to detect a faulty assembly procedure.

[2] We recall the definition of magnet progressive number, used as abscissa axis in most of our trend plots: it is a number running from 1 to 1232 which is associated to each magnet, according to the date of the first magnetic measurement at room temperature.

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 73 new collared coils have been measured (collared coils 588th to 660th).
  - 23 of Firm1 (1080,1153, 1178, 1181, 1183-1201).
  - 19 of Firm2 (2133-2151)
  - 31 of Firm3 (3283-3311,3313-4)

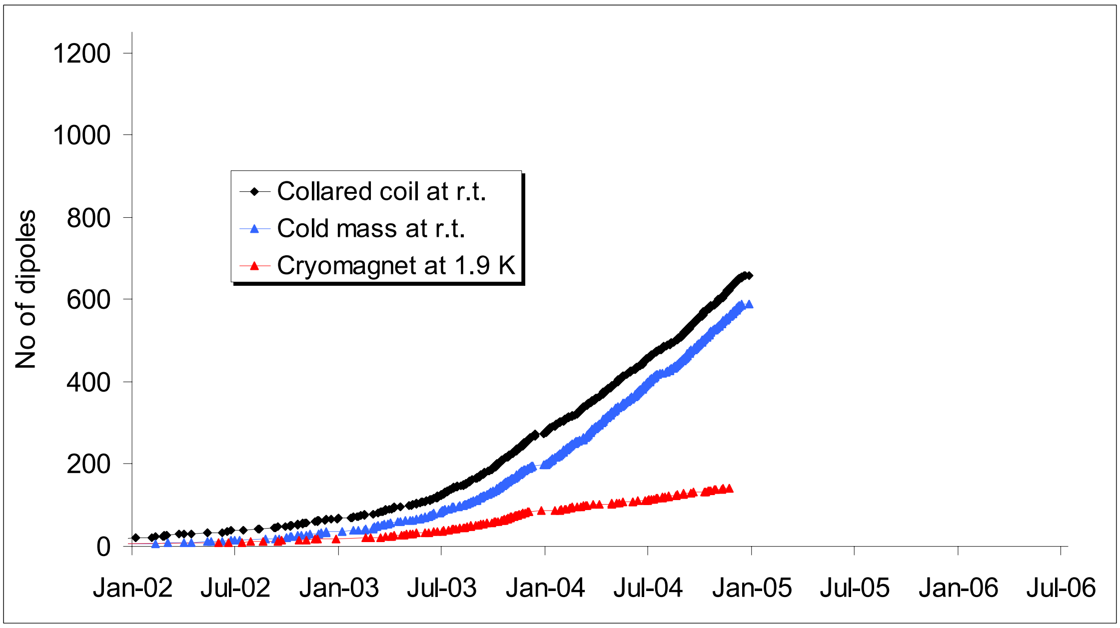

Fig. 1: Number of magnets measured at CERN at 1.9 K and at the manufacturers at room temperature at different stages of assembly procedure

- Cross-section: collared coils have X-section 3.
- Shims are nominal in all Firms (see Fig. 2).

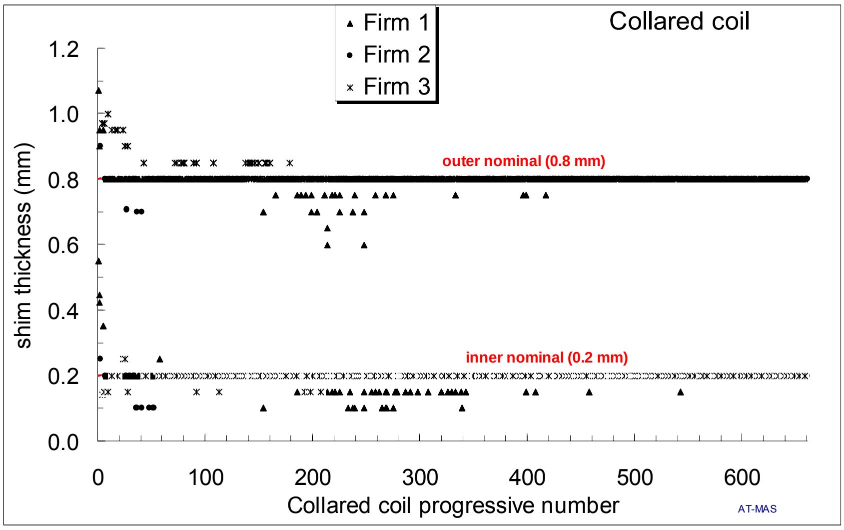

Fig. 2: Thickness of the polar shims used in the collared coils

PART II: MEASUREMENTS VERSUS BEAM DYNAMICS TARGETS

2.1 Summary of systematic components

- Best estimates of skew and even normal systematic components are given in Fig. 3. All the multipoles are within specifications. Details on trends are given in Part III.

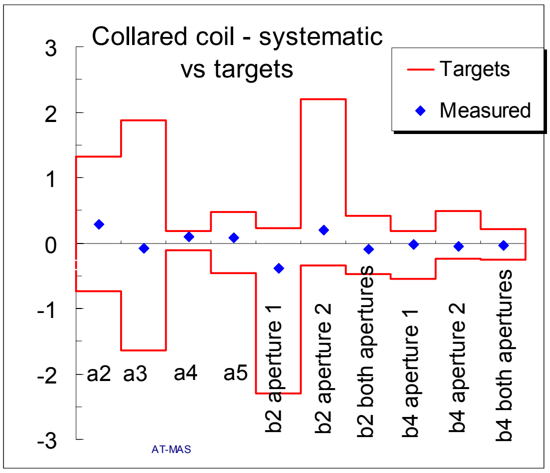

Fig. 3: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line).

- Best estimates for systematic odd normal multipoles are shown in Fig. 4. 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 towards optimal ranges: b_3 is within target and b_5 is larger than the upper target of 0.22 units.
- In the right part of Fig. 4, data are separated according to the three cross-sections (34 collared coils have cross-section 1, 147 have cross-section 2, 478 have cross-section 3, plus one hybrid 1-2). With cross-section 3, b_3 in the collared coil is 1.3 units below the upper limit (i.e., 1.9 units at high field), and also b_5 is within targets, at the edge of the upper limit (i.e., 1.18 units at injection). Finally, b_7 in the collared coil is 0.27 units larger than the limits (i.e. 0.33 units at injection).

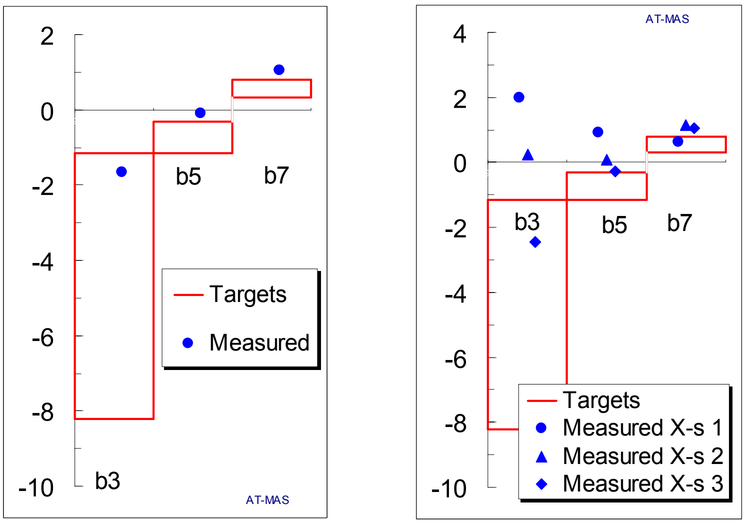

Fig. 4: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). Raw data (left) and data separated according to different cross-sections (right).

2.2 Summary of random components

- We evaluate the standard deviation of the bending strength and multipoles for each Firm and for all magnets (see Fig. 5). We analyse only magnets with cross-section 3 (478 collared coils). Standard deviation of multipoles in collared coil are divided by 1.18 to give the best estimate of the random due to geometric in the cold mass, and compared to the target for the beam dynamics (**whose budget includes the random components induced at 1.9 K**). All values are well within targets, with the exception of the main field in straight part B; please note that the relevant constraint for beam dynamics is only on the bending strength BdL, which is within targets.

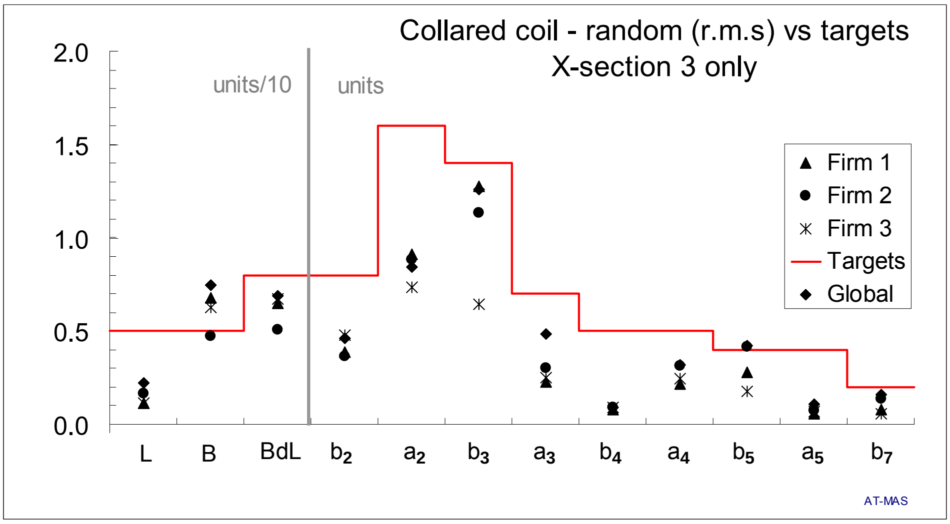

Fig. 5: Random component in the measured collared coils and rescaled to cold mass values, cross-section 3 only compared to targets for random at 1.9 K.

- In Fig. 6 we give an estimate of the actual spread due to the geometric component in the sectors 7-8, 8-1, and two more sectors denoted by Latin numbers: III and IV. Sector 7-8 contains R type magnets with inner cable 01B (cross-section 1 and 2). Sector 8-1 contains L type magnets with inner cable 01B and high b3 (mainly cross-section 3). Then we give an estimate by putting the remaining magnets according the baseline rules: sector III contains magnets of type L with inner cable B (136 magnets available), and low b3, sector IV of type L with cable E (57 magnets available). The other sectors would have a number of magnets which is lower than 30 and therefore are not statistically significant.
  - o The spread of integrated main field and b3 is below targets with the exception of sector 7-8, which contains the beginning of the production (non-nominal shims, mixing of cross-section 1 and cross-section 2).
  - o The spread of b5 is above target for sector 7-8, 8-1 and sector III.

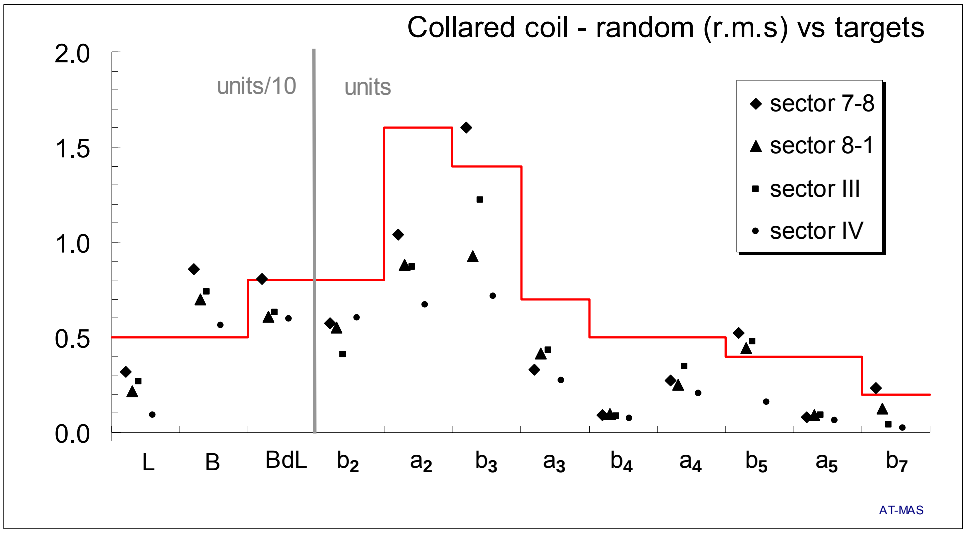

Fig. 5: Random component in the measured collared coils (rescaled to cold mass), for six sectors, compared to targets for random at 1.9 K.

PART III: TRENDS IN FIELD QUALITY

3.1 Trends in bending strength

3.1.1 Trends in magnetic length

- Magnetic length of the collared coils is extremely stable in all Firms since magnet progressive number 100 (see Fig. 7). Magnetic length in Firm1 is 5 units higher than in Firm2 and Firm3.

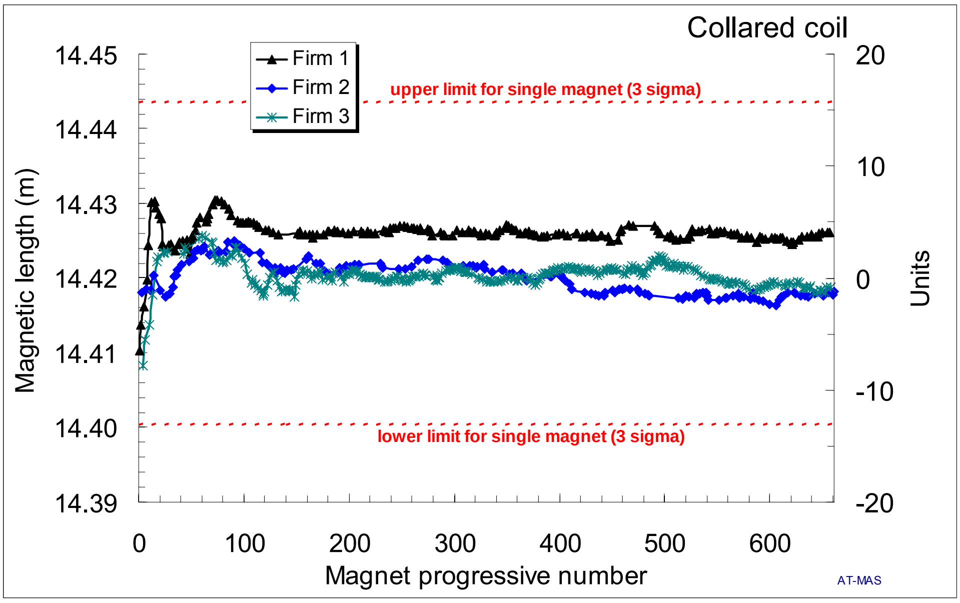

Fig. 7: Magnetic length of the measured collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm).

- Magnetic length of **cold masses** is also extremely stable in all Firms since magnet progressive number 100 (see Fig. 8). When iron laminations are added, magnetic length in Firm3 is getting smaller than in Firm1 and 2. The net result is that there are around 8 units of difference between Firm1 and Firm3. Firm2 is in between, and is converging to values of Firm3 in the more recent production.

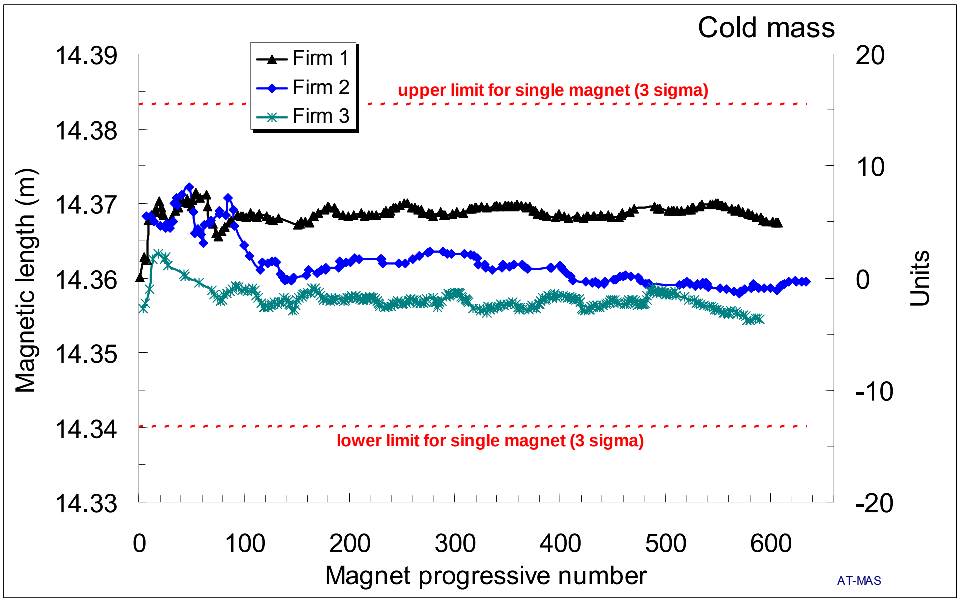

Fig. 8: Magnetic length of the measured **cold masses**, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm).

3.1.2 Trends in transfer function

- Transfer function in collared coils 588th to 660th is rather stable in all Firms. All Firms are within ±5 units (see Fig. 9).

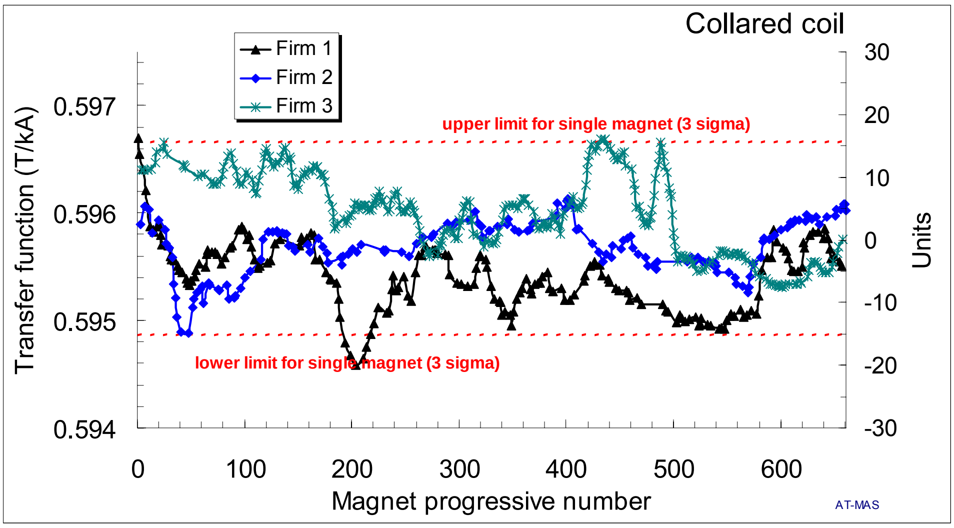

Fig. 9: Transfer function of the measured collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm).

- The systematic difference in the transfer function between Firms observed in collared coils is confirmed, but reduced of around 20% (i.e., the iron yoke contribution), in **cold mass** data (see Fig. 10).

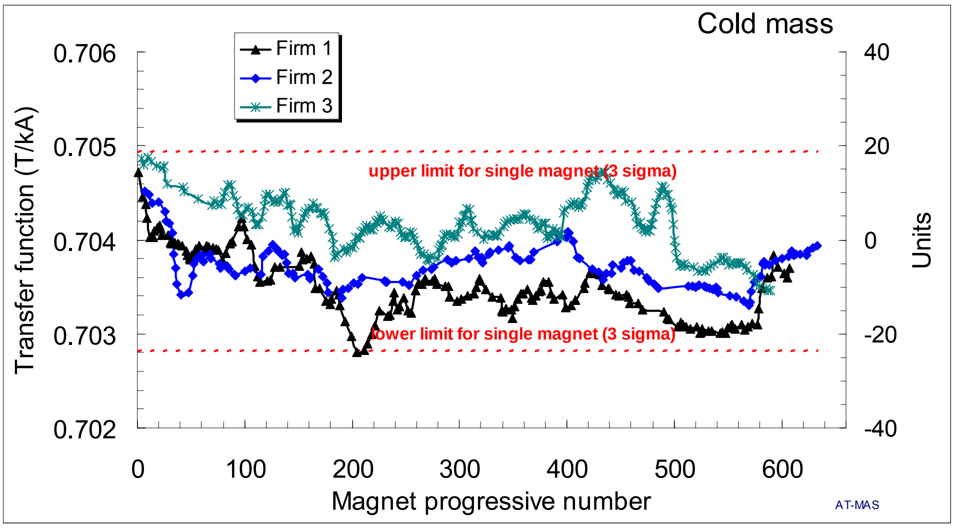

Fig. 10: Transfer function of the measured **cold masses**, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm).

3.1.3 Trends in integrated transfer function

- The integrated transfer function shows a spread between Firms of at most ±5 units in recent production (see Fig. 11).

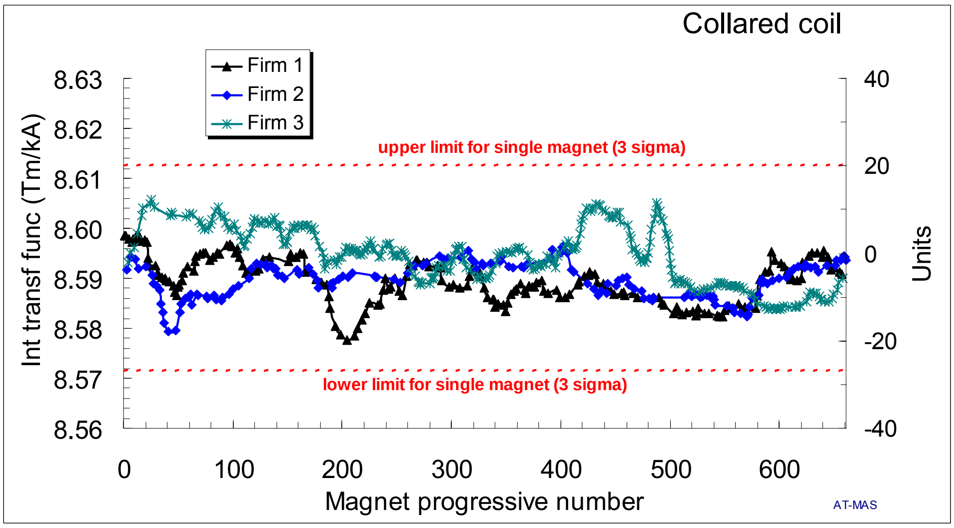

Fig. 11: Integrated transfer function of the measured collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm).

- In the **cold masses** data the spread of the integrated transfer function between Firms is reduced by 20% (see Fig. 12).

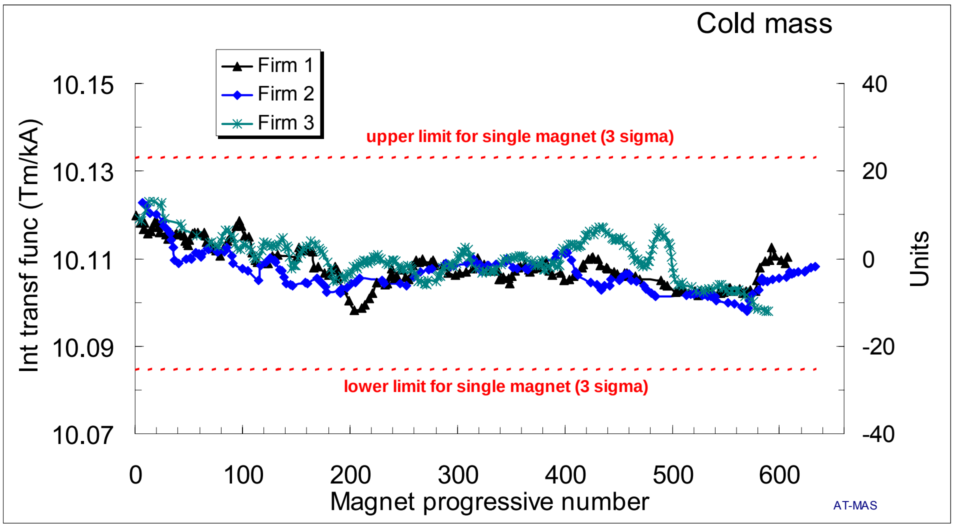

Fig. 12: Integrated transfer function of the measured **cold masses**, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm).

3.2 Trends in odd normal multipoles

- The negative trend of average b3 in Firm2 (magnets 350th to 550th in Fig. 13) has been disappeared. Average b3 in Firm2 is now around –3.5 units, and 2 units higher in Firm1 and Firm3. In the last weeks, average b3 has decreased in Firm1-3 and now agrees with values from Firm2.
- We remind the reader that the peak in Firm1 collared coils around magnet progressive number 430 is due to the additional cross-section 2 magnets.

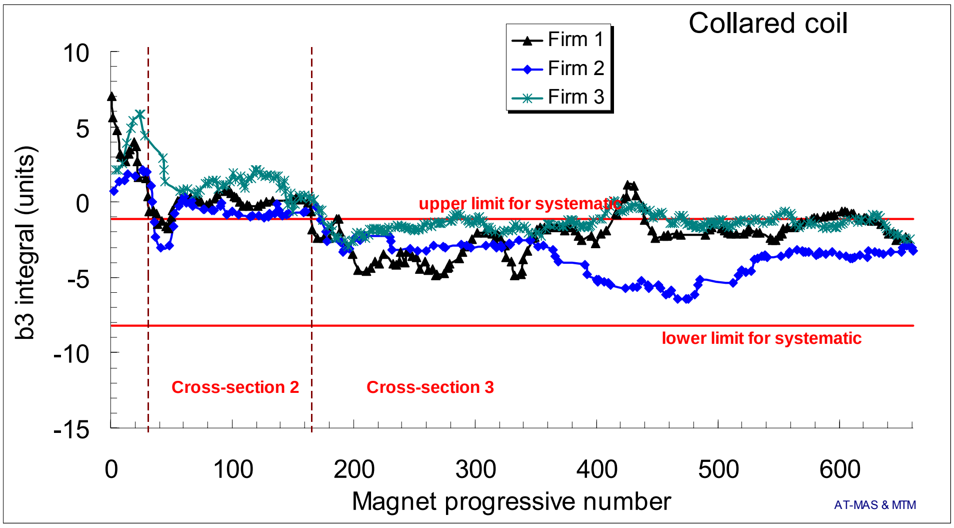

Fig. 13: Average b3 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

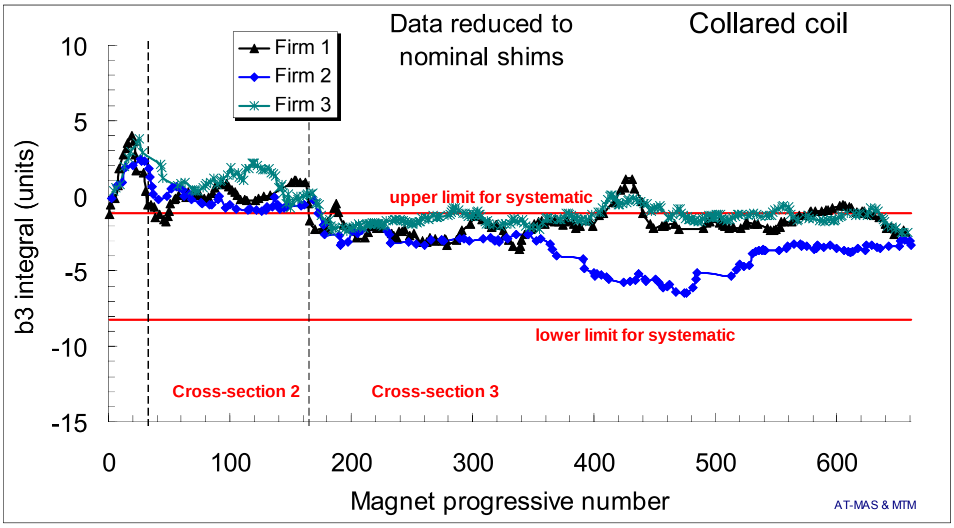

Fig. 14: Average b3 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles. Data reduced to nominal shims[3].

[3] This plot is very similar to the plot of Fig. 13 since shims are nominal for most of the production

- The positive trend of b5 in Firm2 observed between 380th and 520th has disappeared. Measured b5 in Firm2 is decreasing, reaching the lower limit (see Fig. 15).
- Average b5 in Firm3 is also slightly decreasing, but still within targets.
- Average b5 in Firm1 is around 0.3 units, i.e. around 1 unit higher than in Firm2 and Firm3.
- Systematic b5 in the recent production of these two months has decreased and is around 0.4 units, i.e. within target but on the upper side.

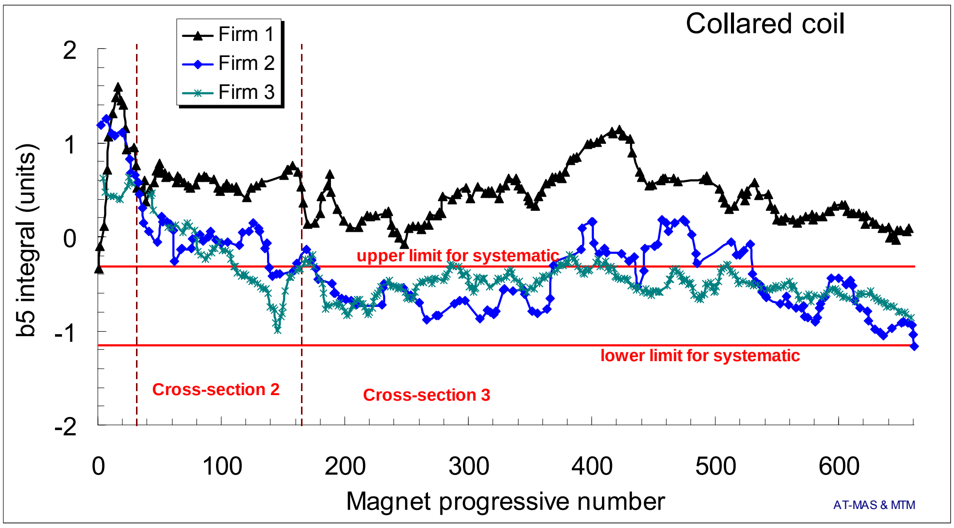

Fig. 15: Average b5 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

- Normal 14th pole b7 slightly decreased (0.1 units) in Firm1 and Firm3, and is stable in Firm2.

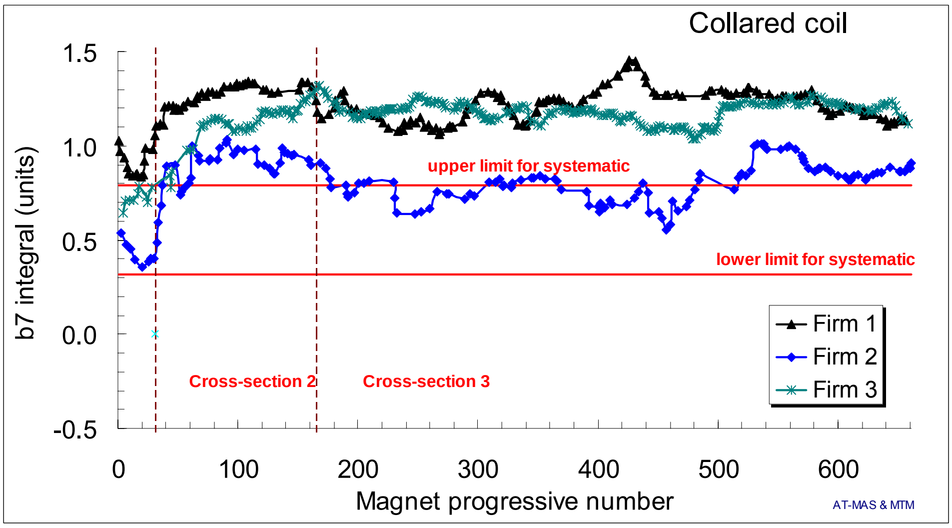

Fig. 16: Average b7 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

3.3 Trends in even normal 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 the two-in-one symmetry).

3.3.1 Trends in normal quadrupole

- The systematic per aperture is in the upper (lower for aperture 2) part of the target range (see Figs. 17 and 18).

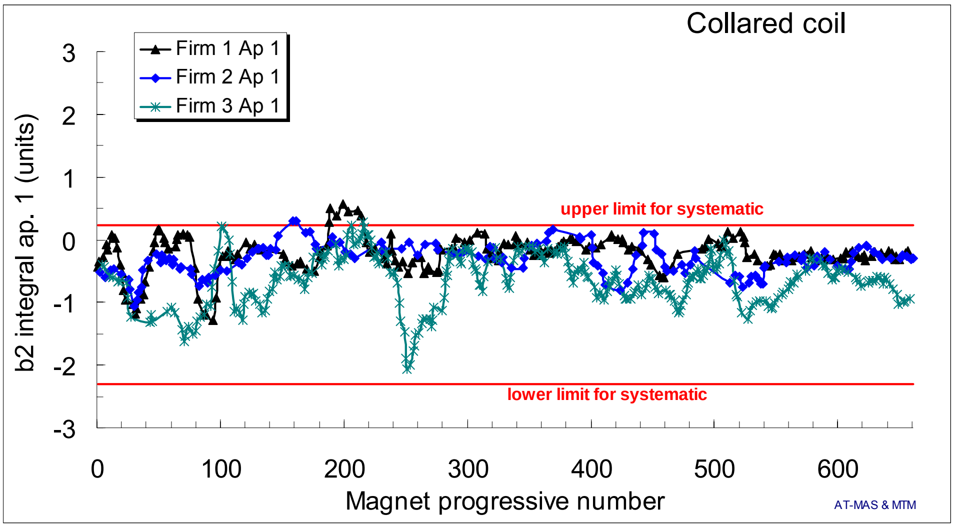

Fig. 17: Average b2 in straight part of the collared coils (aperture 1), separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

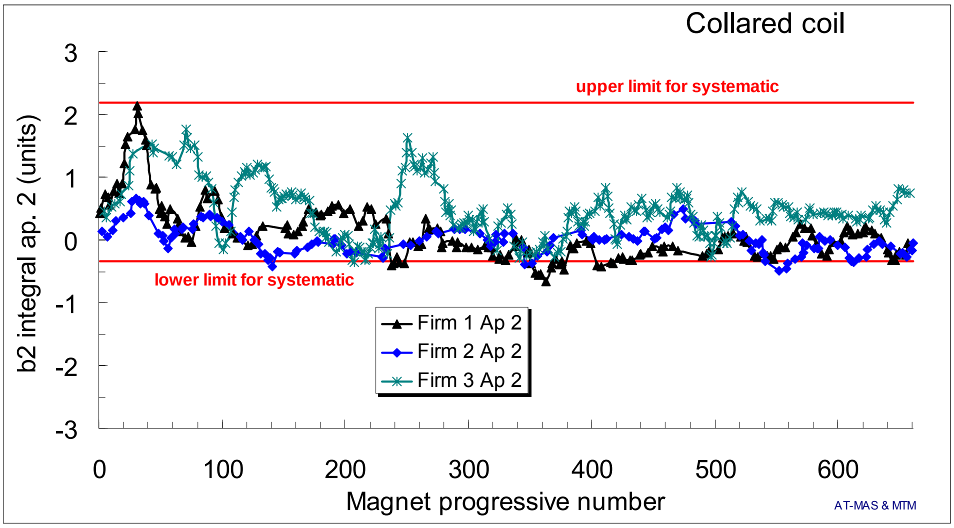

Fig. 18: Average b2 in straight part of the collared coils (aperture 2), separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

- The systematic normal quadrupole per beam is within specifications (see Fig. 19).

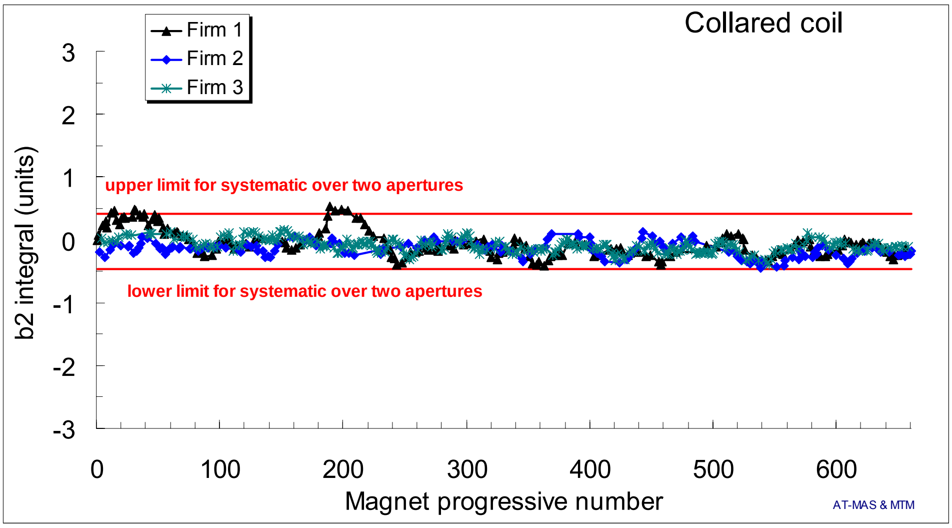

Fig. 19: Average b2 in straight part of the collared coils (average of the apertures), separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

3.3.2 Trends in normal octupole

- The systematic per aperture is within specifications in both apertures (see Figs. 20 and 21).
- The systematic per beam is also within specifications (see Fig. 22).

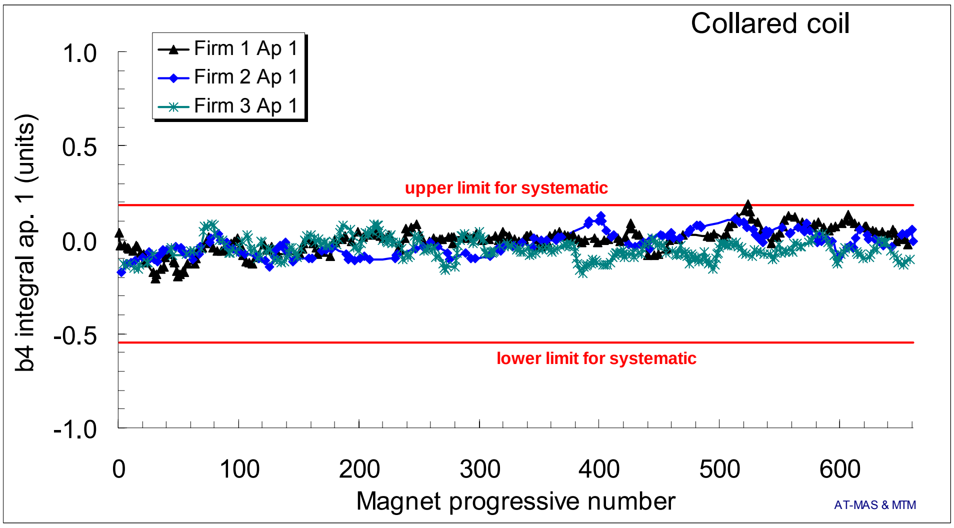

Fig. 20: Average b4 in straight part of the collared coils (aperture 1), separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

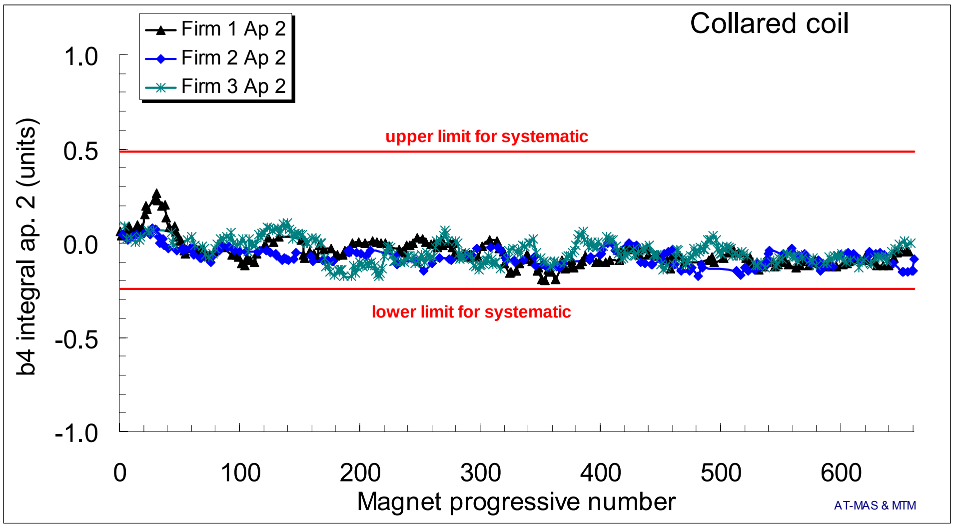

Fig. 21: Average b4 in straight part of the collared coils (aperture 2), separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

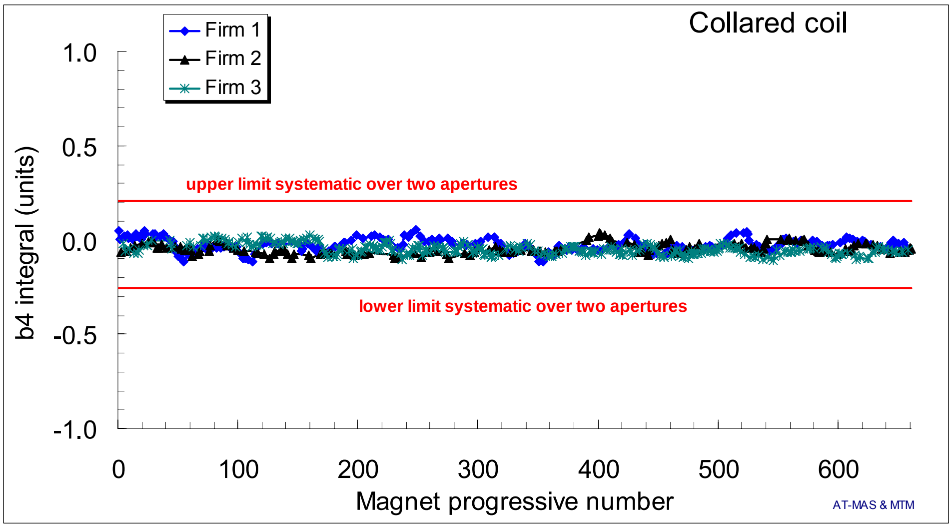

Fig. 22: Average b4 in straight part of the collared coils (average of the apertures), separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

3.4 Trends in skew multipoles

- Skew quadrupole a2 is well within targets, and no trends are observed (see Fig. 23). Firm3 has a systematic component of 0.5 to 1 unit since magnet 200th, whereas Firm2 and Firm1 are well centred around zero.

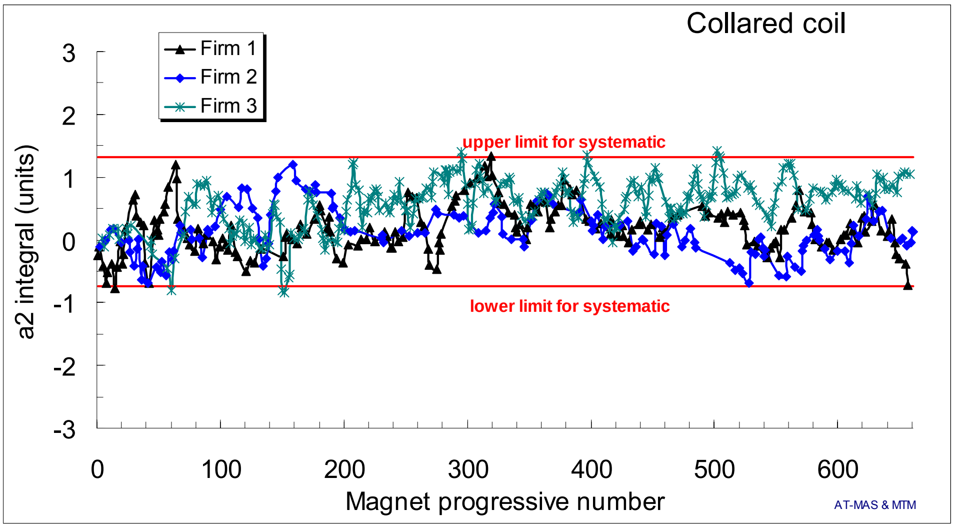

Fig. 23: Average a2 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

- Skew sextupole a3 is well within targets (see Fig. 24). There is a positive systematic component in Firm3 (around 0.5 units), and a slightly negative component (around 0.25 units) in Firm1 and Firm2. Indeed, beam dynamics targets are very loose, and therefore there is no concern on this multipole.

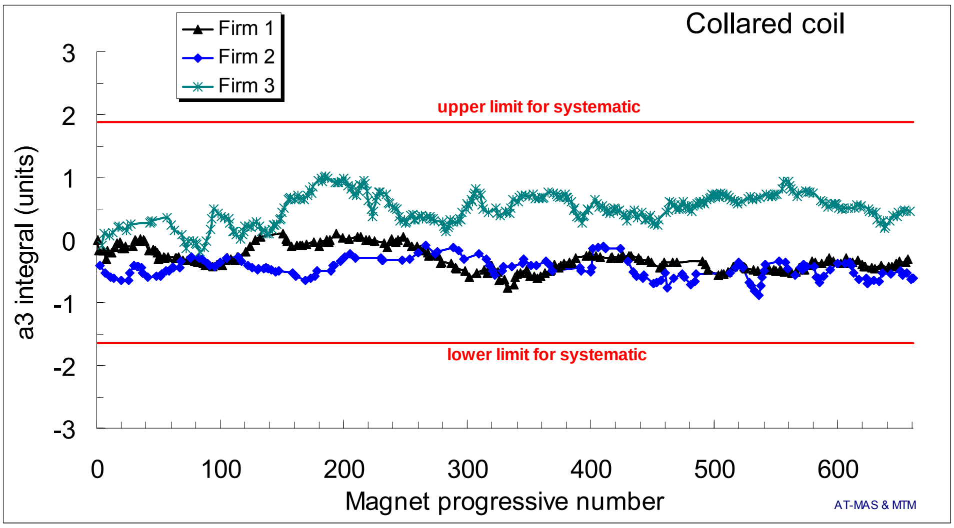

Fig. 24: Average a3 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

- Skew octupole a4 is within the tight beam dynamics targets in Firm1 (see Fig. 25).
- The strong systematic component in Firm2 is oscillating between 0 and 0.7 units.
- The strong systematic a4 in Firm2 is partially compensated by negative values in recent production of Firm3.
- A test magnet (2137) where the collared coil has been installed capsized in the cold mass, thus changing the sign of a4, has been manufactured in Firm2. This is a solution which could be adopted to furtherly reduce the systematic a4.

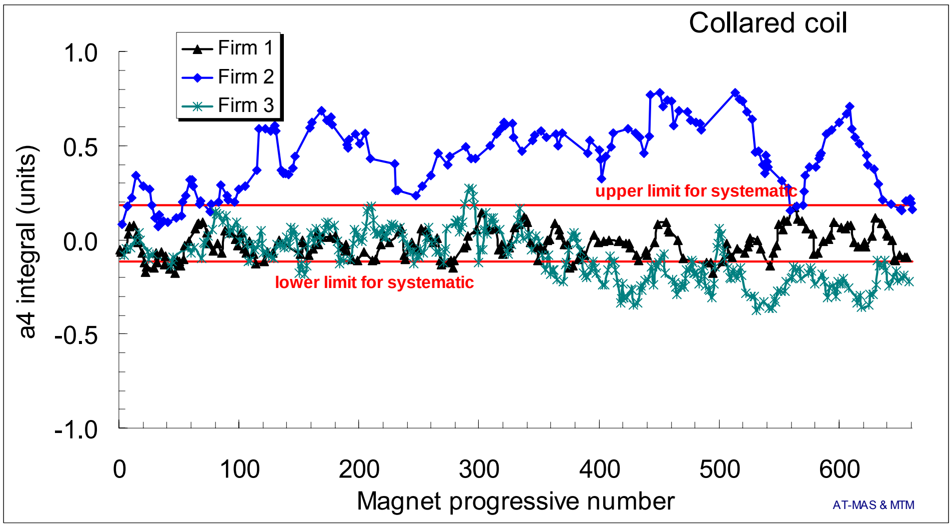

Fig. 25: Average a4 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 134 cryodipoles.

3.5 Trends in systematic differences between Firms

The more relevant signature of Firms is in b_7 and a_3.

- Normal 14th pole: b_7 at Firm2 is 0.4 units lower than Firm3 and Firm1 (see Fig. 16). This difference is three times the natural sigma within the same manufacturer measured in cross-section 3. Firm2 is within targets, whereas both Firm1 and Firm3 are outside.
- Skew sextupole a_3: Firm3 has a systematic a_3 of 0.5 units, against –0.5 units in Firm1-2 (see Fig. 24). This difference is three times the natural sigma within the same manufacturer. All Firms are within targets.

On the more recent collared coils we observe some systematic difference between Firms in b_3:

- Normal sextupole: b_3 at Firm2 is 2 units lower than at Firm1 and Firm3. All Firms are within targets, but Firm2 is placed in the central part of the range, and Firm1 and Firm3 on the upper edge. The difference between Firm1-3 and Firm2 is 2 times the natural sigma within the same manufacturer.

We observe a small systematic difference between Firms (from one to two times the natural sigma within the same manufacturer) in the following cases:

- Normal decapole b_5: Firm1 has a systematic b_5 of 1 unit larger than Firm2-3. This difference is two times the natural sigma within the same manufacturer (see Fig. 15). Firm2-3 are within targets, whereas Firm1 is outside.
- Skew octupole a_4: Firm2 has a systematic a_4 of 0.4 units, against -0.03 and –0.05 units in Firm3 and Firm1, respectively (see Fig. 25). This difference is equal to the natural sigma within the same manufacturer. Firm1 and Firm3 are within targets, whereas Firm2 is outside.

Systematic differences between Firms are small or negligible in a_2, b_2 and b_4.

3.6 Trends in correlations to measurements at 1.9 K

We give plots of the offsets between the values measured at injection field (or high field) at 1.9 K, without beam screen, and the straight part of the collared coil at room temperature (rescaled by 1.18 for the multipoles). The offsets are given versus the magnet progressive number. This gives a hint on the type of sampling of the production that is being carried out with the measurement at 1.9 K. The last magnet measured at 1.9 K is collared coil 495th, thus implying a delay of 165 collared coils with respect to the last manufactured collared coil (i.e. the 660th), which corresponds to four months of production, and more than an octant.

- Trend plots for the offsets relative to the integrated transfer function are given in Figs. 26 and 27, at injection and at high field, respectively. In both cases no trends are visible after collared coil 100th.

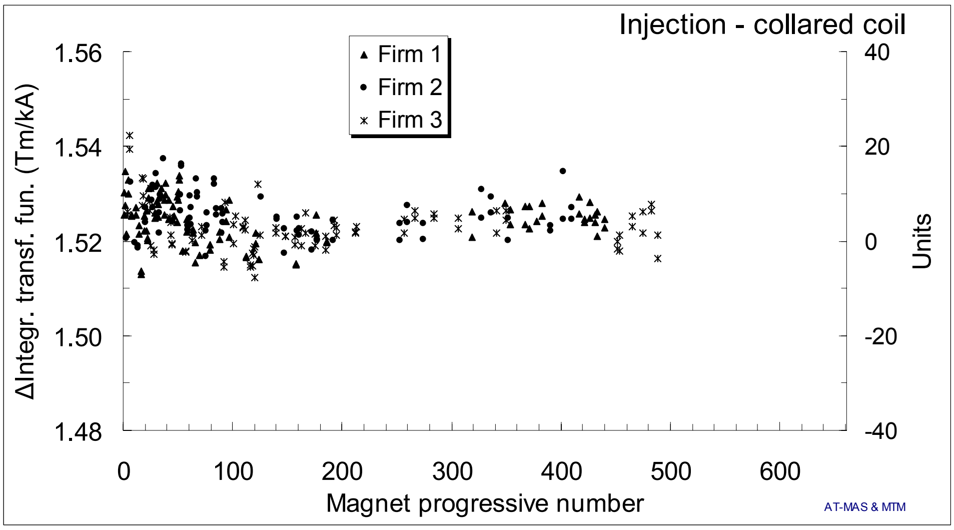

Fig. 26: Difference for the integrated transfer function between measured values at 1.9 K, injection field, and collared coil along the magnet production.

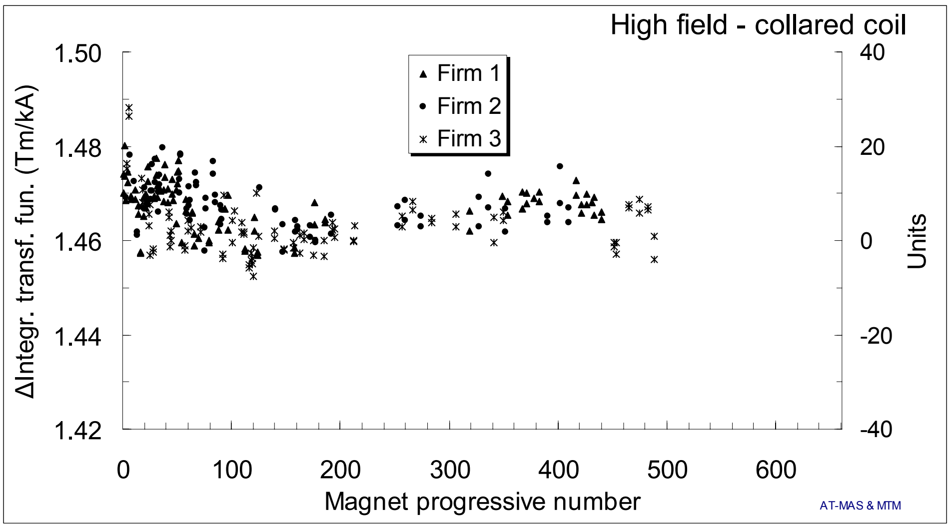

Fig. 27: Difference for the integrated transfer function between measured values at 1.9 K, high field, and collared coil along the magnet production.

- We present data relative to b3-injection and b3-high field in Figs. 28 and 29. Please note the enlarged scale with respect to b3 plots in Figs. 13 and 14. One observes a small reduction (in absolute value) of the b3 offset in the first 100 magnets at injection. In the recent data we have a Firm3 magnet with a smaller value (around –3.5 units) of the offset. At high field (which is the critical quantity for the beam dynamics) the offset is very stable (within 1 unit).

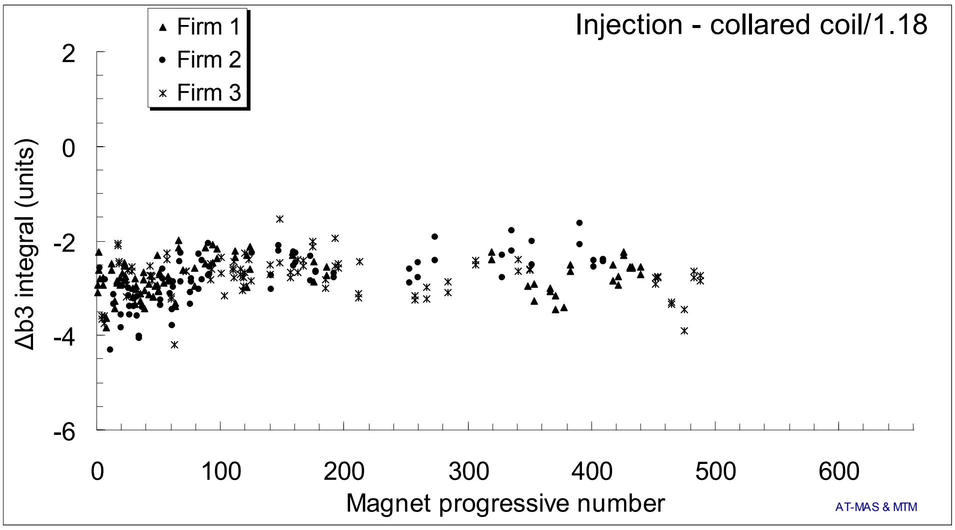

Fig. 28: Difference for the b3 between measured values at 1.9 K, injection field, and collared coil **integral** divided by 1.18, along the magnet production.

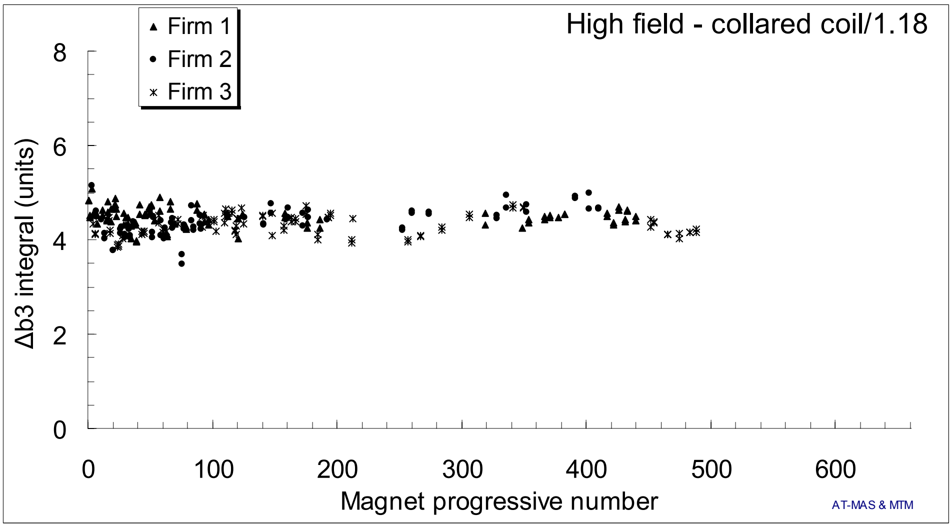

Fig. 29: Difference for the b3 between measured values at 1.9 K, high field, and collared coil **integral** divided by 1.18, along the magnet production.

* Trends for the b5 and b7 offsets between injection and collared coil straight part are given in Fig. 30 and 31. One observes a reduction (in absolute value) of the b7 offset in the first 100 magnets, whereas the b5 offset is stable.

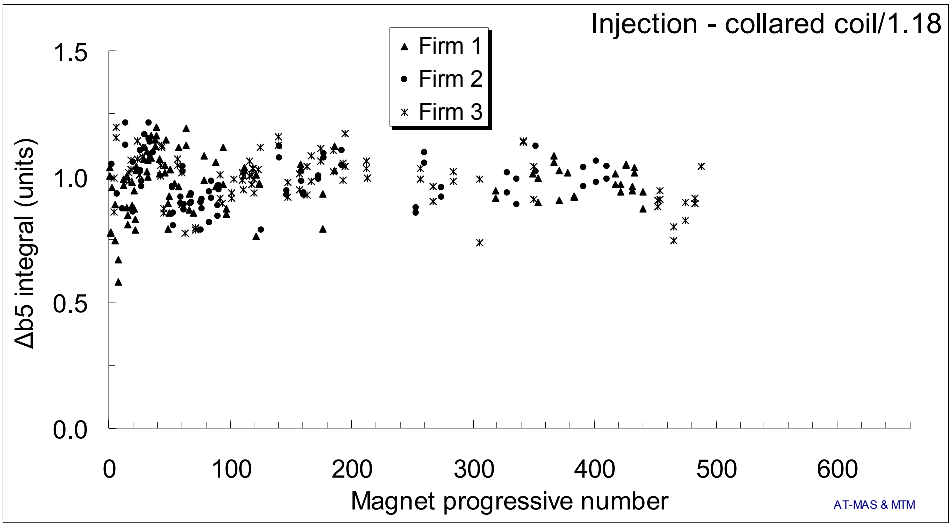

Fig. 30: Difference for the b5 between measured values at 1.9 K, injection field, and collared coil **integral** divided by 1.18, along the magnet production.

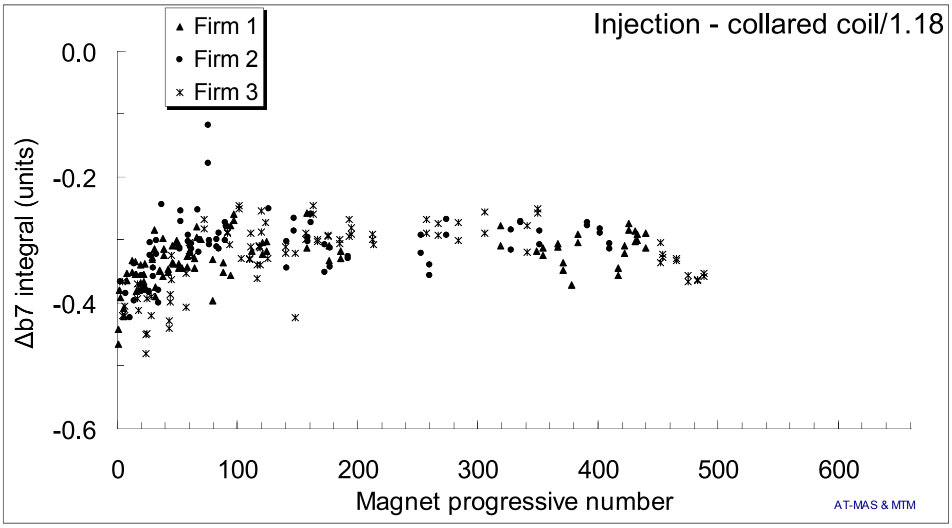

Fig. 31: Difference for the b7 between measured values at 1.9 K, injection field, and collared coil **integral** divided by 1.18, along the magnet production.

PART IV: QUALITY CONTROL

4.1 Holding point results

We had a few cases of field anomalies

- 2134 and 2136 showed peaks along the axis indicating a block6 movement of up to 0.2 mm. They have been released on the basis of the experience acquired on the previous cases.

A summary of the magnets de-collared for anomalies in the magnetic field over all the production is given in Table I. The total number of found defects is 13 over 660 collared coils, i.e. 1.9%. A large fraction of these defects (8 over 13) has been found in collared coil 300^{th} to 400^{th} (see Fig. 32). The situation is improving in the more recent production.

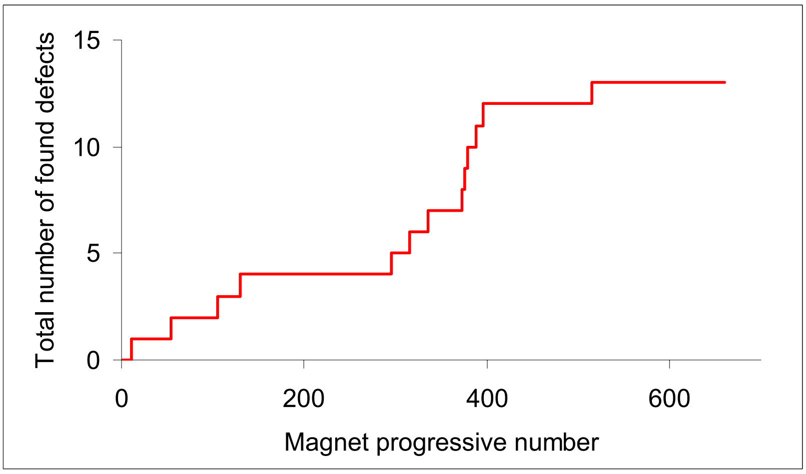

Fig. 32: Total number of defects found with magnetic measurements versus magnet progressive number.

Table I: Summary of magnets decollared on the basis of anomalies in magnetic field.

Magnet	Measured on	Analysis	Opened on	Result
		Bad assembly cases		
Magnet	Measured on	Analysis	Opened on	Result
2002	16-Jul-2001	Spike in main field	17-Jul-2001	Double coil protection sheet
1027	29-Oct-2002	Missing outer shim	01-Nov-2002	Missing outer shim
3135	27-Jan-2004	Inward movement of block5 and 6	17-Feb-2004	Folded outer shim
1108	22-Apr-2004	Missing or additional thickenss on outer pole	12-Jul-2004	No visible defect
3254	06-Sep-2004	Inward movement of block5 and 6	14-Sep-2004	Folded outer shim
		Bad quality of the coil gluing		
Magnet	Measured on	Analysis	Opened on	Result
2032	21-May-2003	Inward movement of block6	18-Nov-2003	Block6 detached from inner layer
2035	14-Jul-2003	Inward movement of block6	27-Apr-2004	Block6 detached from inner layer
1099	20-Feb-2004	Inward movement of block6	16-Mar-2004	Block6 detached from inner layer
3175	20-Apr-2004	Inward movement of block6	11-May-2004	Block6 detached from inner layer
1108	22-Apr-2004	Inward movement of block6	12-Jul-2004	Block6 detached from inner layer
1122	23-Apr-2004	Inward movement of block6	24-May-2004	Block6 detached from inner layer
1128	03-May-2004	Inward movement of block6	05-Jul-2004	Block6 detached from inner layer
1130	10-May-2004	Inward movement of block6	14-Jul-2004	Block6 detached from inner layer
		Other		
Magnet	Measured on	Analysis	Opened on	Result
2065	15-Mar-2004	Inward movement of block6	29-Apr-2004	Good glue, movement observed
2089	18-May-2004	Inward movement of block6	01-Jun-2004	Good glue, no movement observed
2084	10-May-2004	Inward movement of block6	09-Jun-2004	Good glue, small movement observed

4.2 Estimated coil waviness

- Coil waviness estimated from the variation of the multipoles along the axis is in general below 30 microns. The recent part of the production is very stable, showing values of waviness below 25 microns.
- The crisis between collared coils 390th and 480th, due to inward radial movements of block6 in some spots along the magnet axis in Firm2 and Firm1, is over (see Fig. 33).

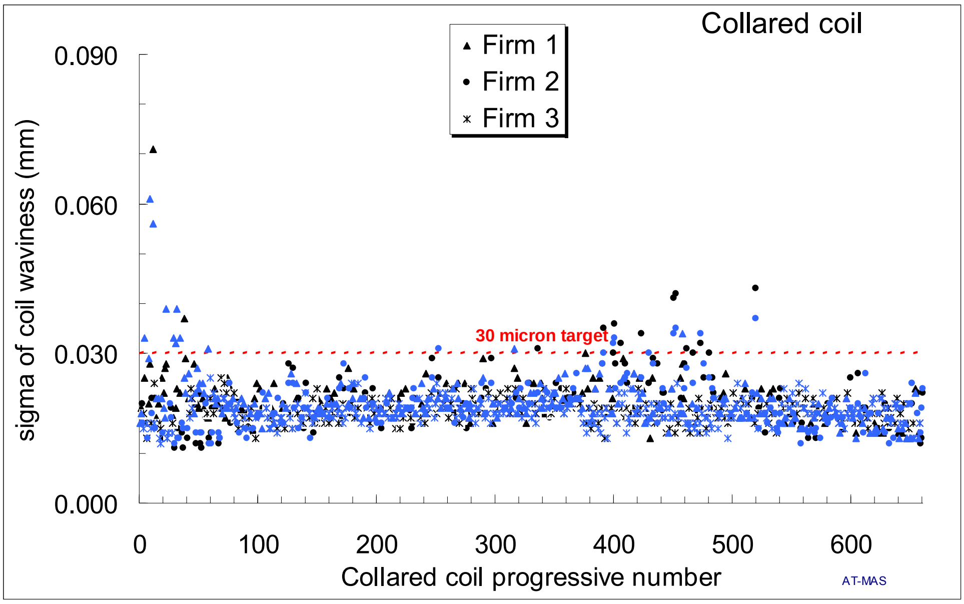

Fig. 33: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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