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

E. Todesco, AT-MAS-MA

This report gives data relative to field quality measured in collared coils and cold masses during the period May 1– June 30 2004, 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. 487005

The dashboard

- Available measurements: 448 collared coils, 389 cold masses, 95 cryodipoles[1].
- In these two months, 62 collared coils: 15 from Firm1, 14 from Firm2 and 33 from Firm3.

What's new

- **Production rate** is at 31 collared coils per month. The production in Firm1 is slowing down with respect to the previous months (16 collared coil produced in May and June, against 24 in March and April). Firm3 is now at 3.8 collared coils per week, Firm1 at 1.7 collared coils per week and Firm2 at 1.6 collared coils per week.
- **Length of feedback loop:** The minimal delay between collared coil magnetic measurements and cold tests is 2.5 months.
- **Trends in b3:** we observe a decrease of b3 of 2.5 units in Firm2 and an increase of 2 units in Firm3. The systematic is stable, but this trend could affect the random component (see Figs. 13 and 14 at pg. 11).
- **Trends in b5:** Systematic b5 is increasing and is now at the limit of the target (see Figs. 15 at pg. 12).
- **Trends in a4:** the situation for the systematic a_4 in Firm2 is worsening (see Fig. 25, pg. 15). We have a systematic component of about 0.5 units in the more recent production.
- **Additional cross-section 2 magnets:** 10 additional cross-section 2 magnet are being built by Firm1 to complete the sector of type R, and 7 collared coils have been already manufactured. One observes that allowed multipoles are higher than what previously built (+1 unit of b3, +0.5 units of b5, +0.1 units of b7). This is an additional proof of positive trends in allowed multipoles along the production.
- **Assembly faults:** we had additional cases of bad quality of the assembly detected by magnetic measurements.
  - In Firm1 two more cases of movement of block6 were traced back to a not correct gluing of the block6 to the inner layer. The curing procedure has been optimized and a careful visual inspection of the coil before assembly is being done. We had no more cases since June.
  - In Firm2 we had a series of magnets whose magnetic measurements showed movements of block6. Three of them were de-collared, showing the expected displacement in one case only, and a correct gluing. This series of magnets was released, and quench performances of two of them have been good. Also in this case, it seems that the origin of the problem has disappeared since field anomalies are not present in the last collared coils.

  More information can be found in the crisis page http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/crisis.html
- **Format of the report:** we also give trend plots of the offsets between measurements at room temperature and at 1.9 K for the most important cases (see pg. 16-18).

[1] These numbers refer to complete measurements available in Oracle database; at 1.9 K one has to add 21 incomplete measurements (one aperture missing, or transfer function missing) and 7 to be analysed and loaded [data available on 20th July 2004 from MTM web site http://mtauser.home.cern.ch/mtauser/MTM-AS/ASLogbook.html].

CONTENTS

PART I: MEASURED MAGNETS AND ASSEMBLY DATA……………………………………………………...pg. 3

PART II: MEASUREMENTS VERSUS BEAM DYNAMICS TARGETS……………………………………pg. 4
2.1 Summary of systematics components……………………………………………………………pg. 4
2.2 Summary of random components………………………………………………………………...pg. 5

PART III: TRENDS IN FIELD QUALITY…………………………………………………...………………pg. 6
3.1 Trends in bending strength……………………………………………………..…………………pg. 6
3.2 Trends in normal odd multipoles…………………………………………..…………………...pg. 9
3.3 Trends in normal even multipoles……………………………………………………………….pg. 11
3.4 Trends in skew multipoles………………………………………………..……………………..pg. 14
3.5 Trends in systematic differences between firms…………………..…………………………….pg. 15
3.6 Trends in correlations to measurements at 1.9 K.…….………………..………………………….pg. 16

PART IV: QUALITY CONTROL………………………..………………………………...………………pg. 18
4.1 Holding point results……………………………………………………………..…………………..pg. 18
4.2 Coil waviness……………………………………..…………….……………………………..pg. 19

The new format of the report

We changed the format of the report and of most of his plots to better adapt it to this phase of the production. This report and the following ones are organized as follows

- 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). Its structure is unchanged with respect to the previous reports.
- The summary of the measured field quality of all collared coils versus beam dynamics targets has been shifted to the second Section. This gives a quick overview of the status of field quality versus beam dynamics computed over all the collared coils.
- The largest section has been devoted to trends in field quality.
    - The previous plots, that were showing measured field quality versus magnet progressive number[2], have been replaced by graphs with moving averages (one per firm). 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 by the same firm
        - the two collared coils produced afterwards by the same firm

      With this smoothing of the data, we lose the detail of the individual magnet, but we gain a better visualization of trends in the production.
    - We dropped the separation between apertures (except for the case of b2 and b4) since data of the previous reports show that the difference is negligible
    - We added plots for the bending strength in cold masses, since these measurements are giving important additional information on this critical parameter. When comparing these plots to collared coils, one has to take into account that usually the last 70 collared coils have not yet become cold masses, and therefore a different pattern has to be expected in the end of the plot.
    - We dropped the plot with the reduction to nominal shims for main field, b5 and b7 since in this phase of the production (shims nominal within 0.1 mm) the impact on non-nominal shims is relevant only for b3.
    - Cold mass data are shown only for the bending strength, since for the multipoles they are adding little information to what is already measured in collared coils.
- The final Section is devoted to field quality used to detect a faulty assembly procedure. We added a summary plot of the faulty assemblies found with magnetic measurements, and the cases occurred during the two months are briefly discussed. The plot of coil waviness, previously in Section 1, is also given.
- A list of magnets and special topics (when present) are given in the Appendix.

[2] We recall the definition of magnet progressive number, used as horizontal 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 collaring.

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 62 new collared coils have been measured (collared coils 387th to 448th).
    - 15 of Firm1 (1128-33,1135-40, 1142,1143,1146).
    - 14 of Firm2 (2084-91, 2101, 2104-08)
    - 33 of Firm3 (3146, 3154, 3164, 3182, 3184-87, 3189-99, 3201-3. 3205-14, 3216)

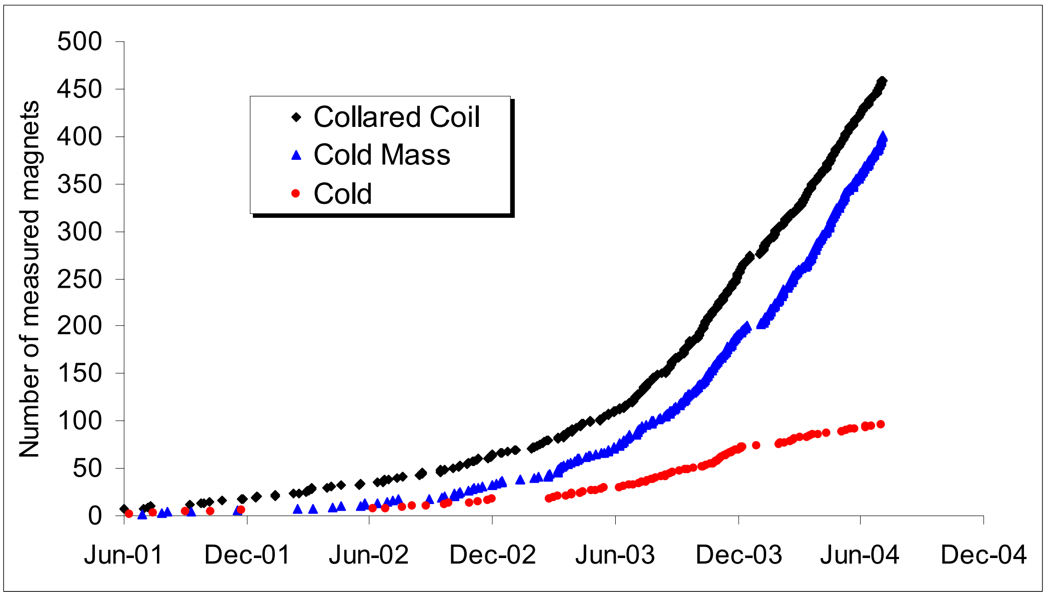


Fig. 1: Number of magnets measured at CERN at 1.9 K and at the manufacturers at room temperature at different stages of assembly procedure

- Cross-section: collared coils have X-section 3, with the exception of 1133, 1135-40, 1142 that belong to the additional X-section 2 magnets ordered to Firm1 to complete the first octant of type R. Magnets 1133 to 1142 will have cross-section 2 (i.e., no additional mid-plane insulation).
- Shims are nominal in Firm2 and in Firm3, and within 0.05 mm in Firm1. The coil size crisis of Firm1 that we had between collared coil progressive number 180 and 350 (see Fig. 2) is now over.

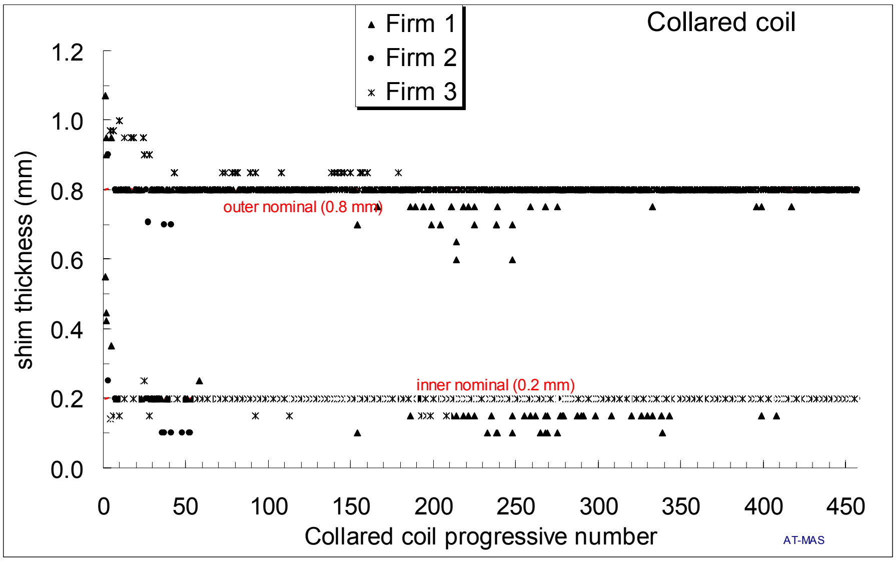


Fig. 2: Thickness of the polar shims used in the collared coils

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.

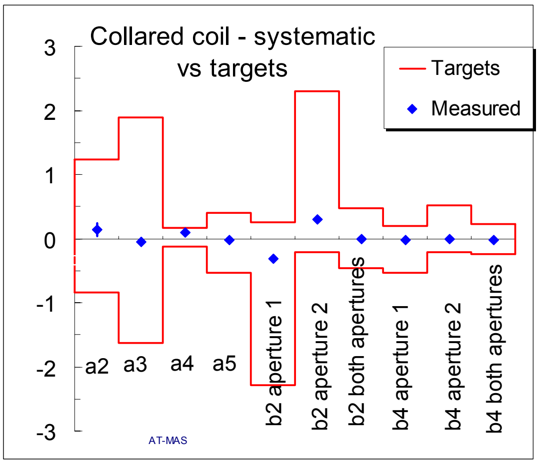
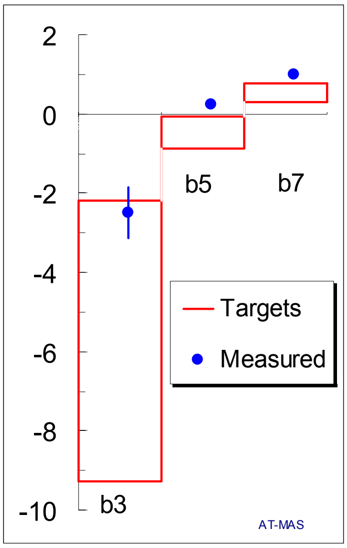


Fig. 3: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematic components.

- 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 now within target and b_5 is larger than the upper target of 0.31 units.
- In the right part of Fig. 4, data are reduced to nominal shims and separated according to the three cross-sections (34 collared coils have cross-section 1, 146 have cross-section 2, 267 have cross-section 3, plus one hybrid 1-2). With cross-section 3, b_3 in the collared coil is within targets, 1.6 units below the upper limit (i.e., 1.7 units at high field), and also b_5 is within targets, at the edge of the upper limit (i.e., 1.1 units at injection). Finally, b_7 in the collared coil is 0.25 units larger than the limits (i.e. 0.31 units at injection). A positive drift is being observed for b_5, see also Section 3.2



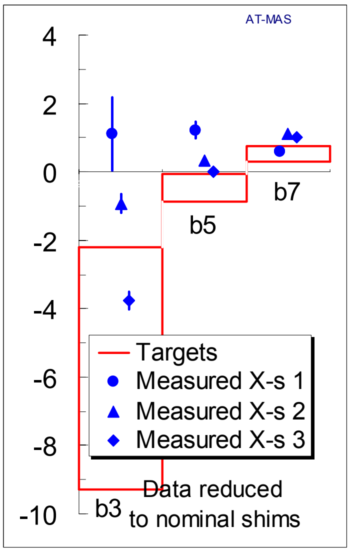


Fig. 4: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections (right).

2.2 Summary of random components

- We evaluate the standard deviation of the bending strength and multipoles for all Firms and separated according to different Firms. We analyse only magnets with cross-section 3 (267 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 also the random components induced at 1.9 K**). All values are well within targets, with the exception of main field in straight part B; please note that relevant constraint for beam dynamics is only on the bending strength BdL, which is within targets.

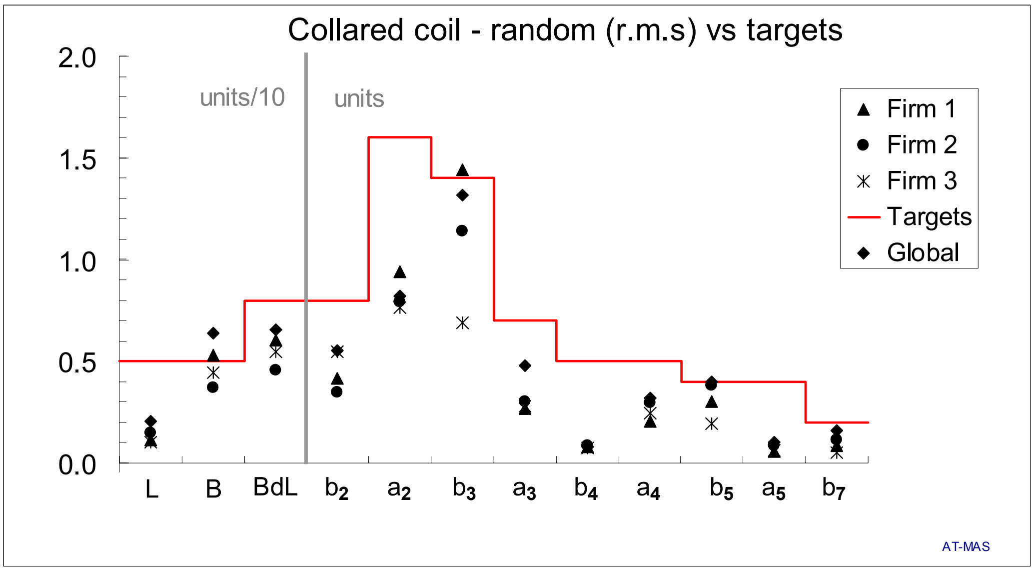


Fig. 5: Random component in the measured collared coils and rescaled to cold mass values, cross-section 3 only compared to targets for random at 1.9 K.

- We give an estimate of the actual spread due to the geometric component in the sectors of type R and L. The sector with R polarity has 150 manufactured cold masses (31 cross-section 1 and 119 cross-section 2) and the sector with L polarity has 254 manufactured cold masses (25 cross-section 2 and the others of cross section 3).
- The spread of the sector R is out of target for b3 and b5. This is mainly due to the use on non-nominal shims and to the mix of X-section 1 and X-section 2.
- In the type L sectors all values are within targets. The situation for b3, which is on the edge (i.e. the geometric is eating all the budget for the random at 1.9 K), should gradually improve for the next octants where magnets of cross-section 2 will not be present any more.

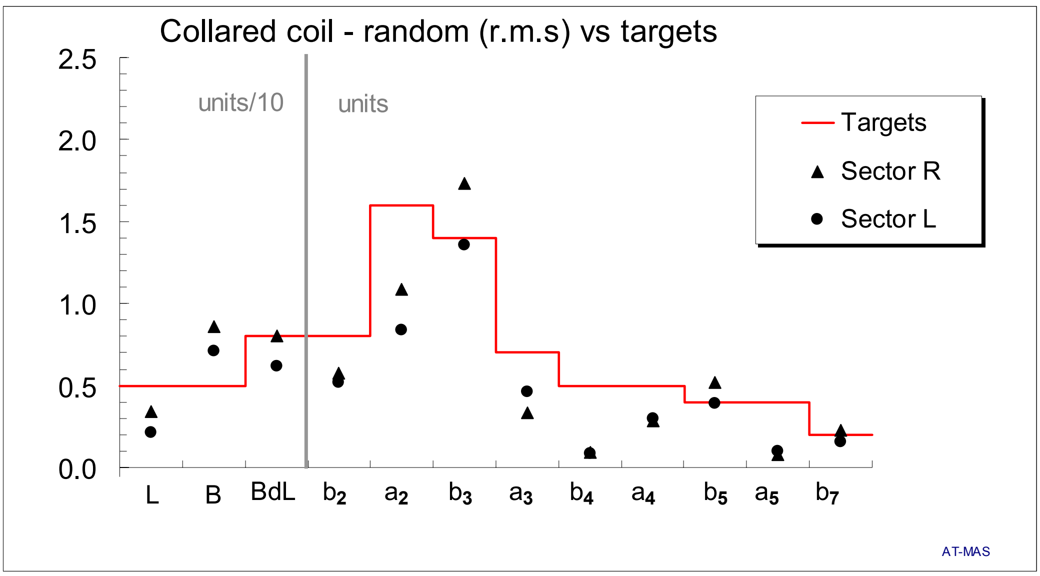


Fig. 5: Random component in the measured collared coils (rescaled to cold mass), for the first and second arc, compared to targets for random at 1.9 K.

PART III: TRENDS IN FIELD QUALITY

3.1 Trends in bending strength

3.1.1 Trends in magnetic length

- Magnetic length of the recent production of collared coils is extremely stable in all Firms (see Fig. 7). Magnetic length in Firm 1 is 3-4 units higher than in Firm2 and Firm3.

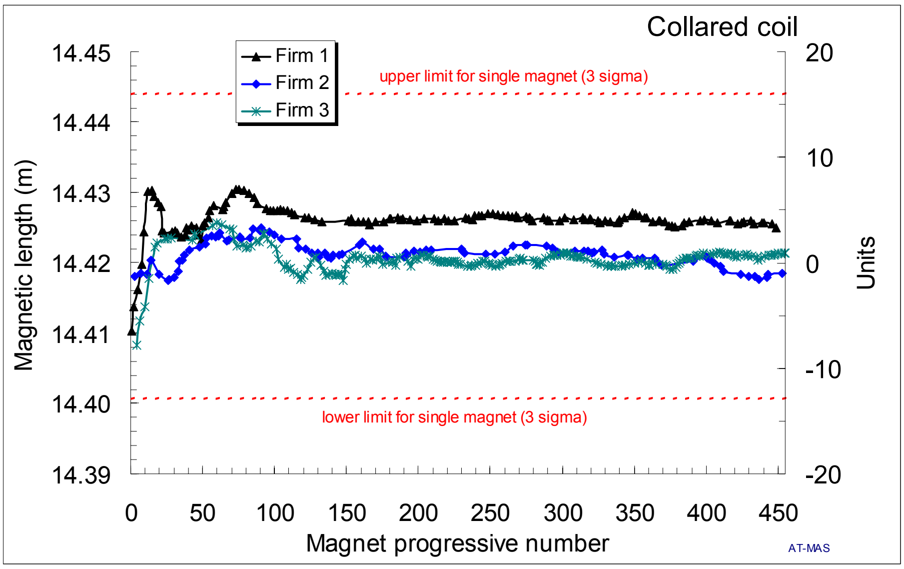


Fig. 7: Magnetic length of the measured collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm).

- 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, and Firm2 is in between.

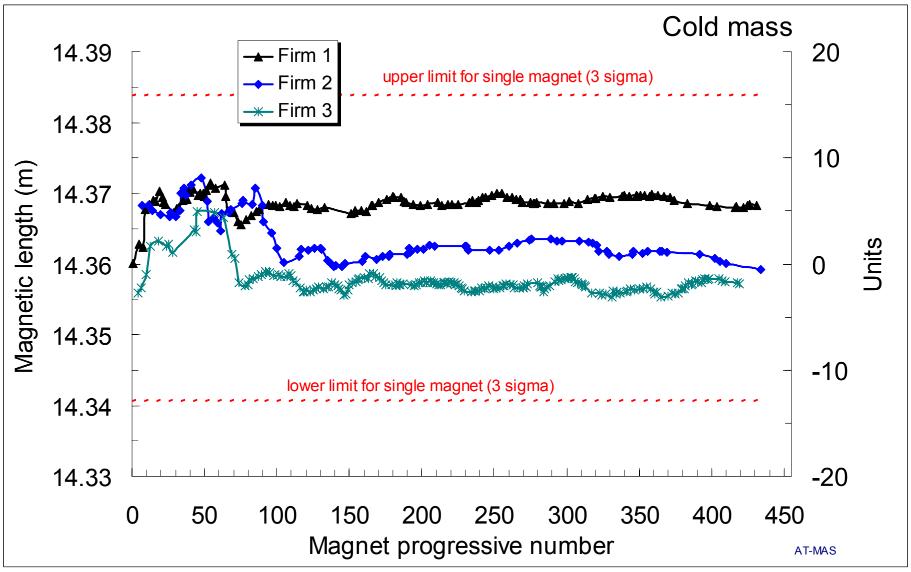


Fig. 8: Magnetic length of the measured **cold masses**, separated per Firm (each dot is average of 5 consecutive magnets of the same firm).

3.1.2 Trends in transfer function

- Transfer function in collared coils 387th to 448th is increasing at Firm3, and is rather stable in Firm1 and Firm2 (see Fig. 9). Firm3 transfer function in the last collared coils is around 15 units larger than in Firm2 and 25 units larger than in Firm1.

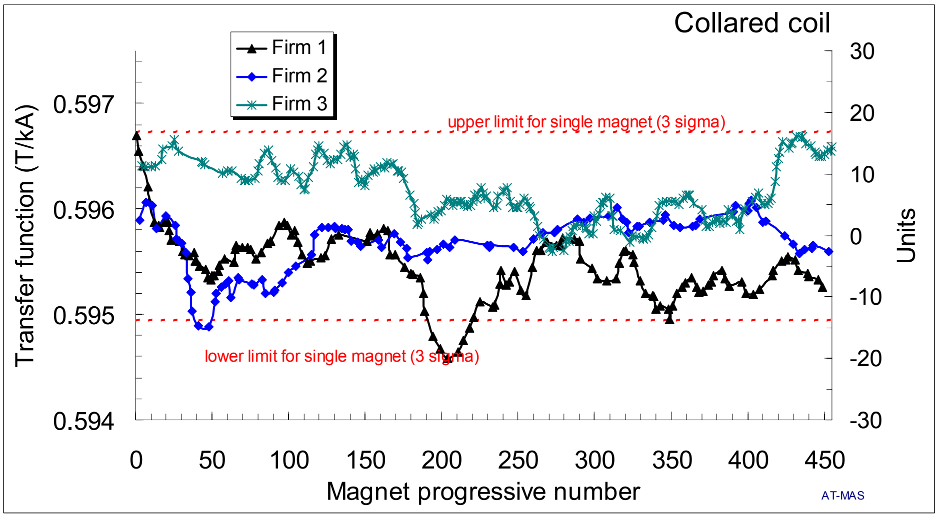


Fig. 9: Transfer function of the measured collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm).

- The systematic difference in the transfer function between firms observed in collared coils is confirmed, but slightly reduced, in **cold mass** data (see Fig. 10).

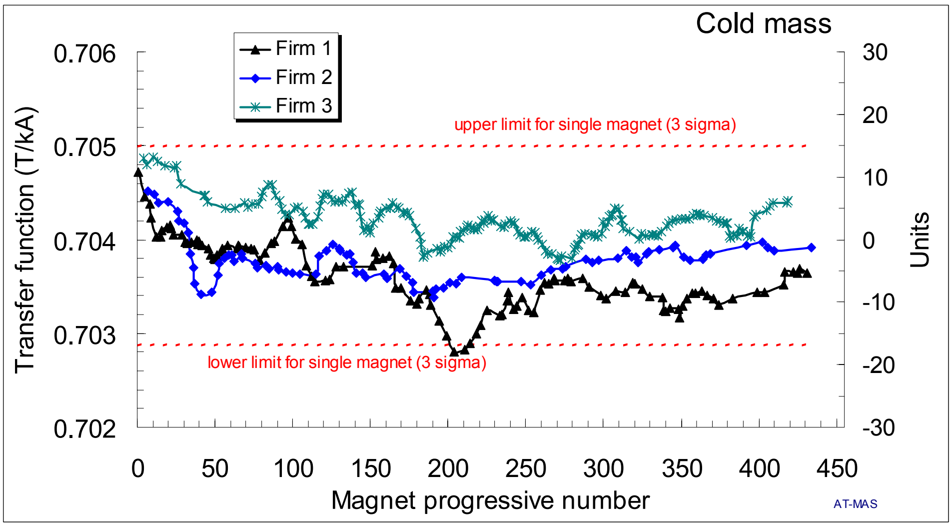


Fig. 10: Transfer function of the measured **cold masses**, separated per Firm (each dot is average of 5 consecutive magnets of the same firm).

3.1.3 Trends in integrated transfer function

- Due to the compensation between the lower transfer function in Firm1, and the longer magnetic length, the integrated transfer function shows a spread between firms of at most 20 units in recent production (see Fig. 11).

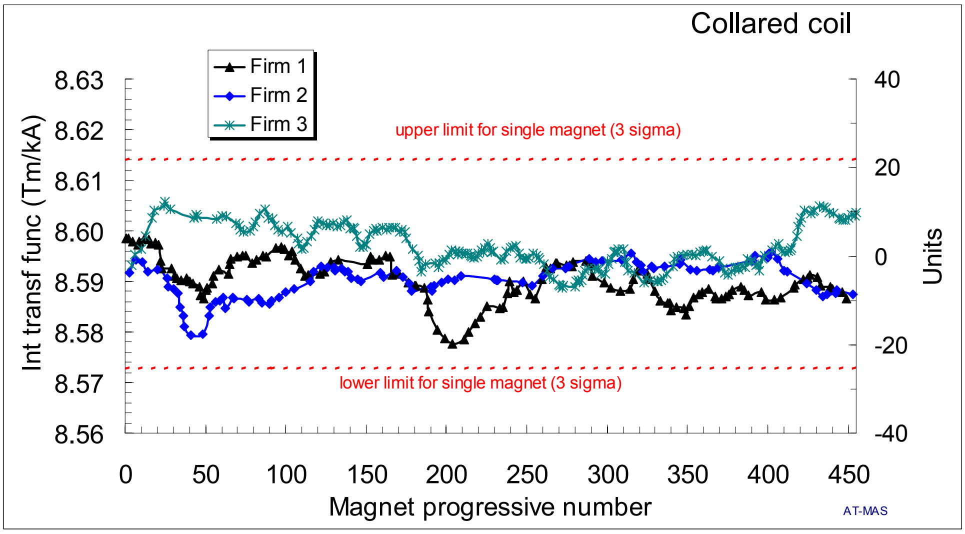


Fig. 11: Integrated transfer function of the measured collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm).

- In the **cold masses** data the spread of the integrated transfer function between firms is further reduced (see Fig. 12). Trends in the more recent production are negligible.

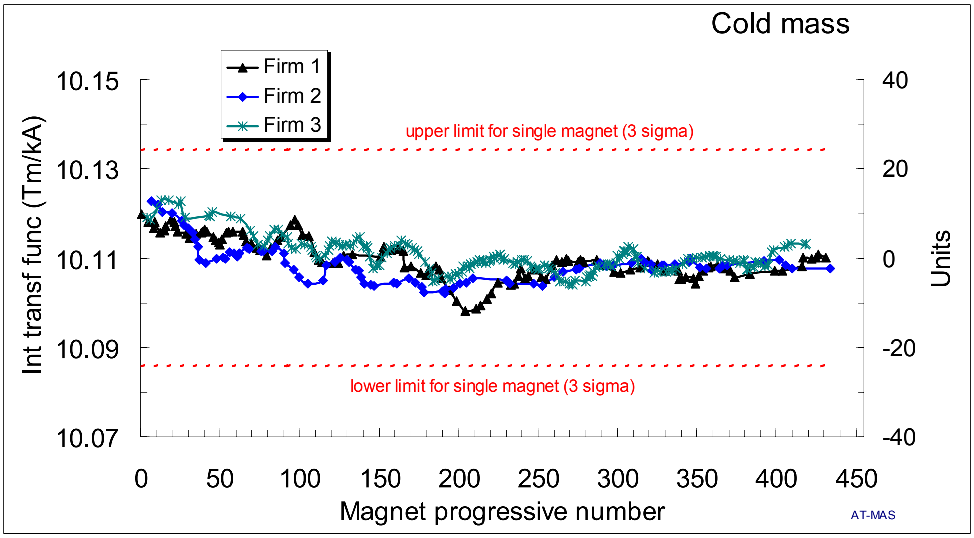


Fig. 12: Integrated transfer function of the measured **cold masses**, separated per Firm (each dot is average of 5 consecutive magnets of the same firm).

3.2 Trends in odd multipoles

- Normal sextupole has increased in Firm3 of about 2.0 units, and is now out of target (see Fig. 13). At the same time in Firm2 the sextupole decreased of about 2.5 units. This is increasing the random component, that in the last 60 manufactured collared coils (20 per Firm) is 1.7 units, against a value of 1.1 units for the previous months (note that these values are rescaled to cold mass). The systematic is not affected by these trends.
- An analysis of the geometric dimension of the copper wedges by B. Bellesia has shown that they cannot be the origin of these trends.
- The peak in b3 of collared coils with magnet progressive number around 425 is due to the production of 10 additional magnets with cross-section 2. The value of systematic b3 in these magnets is 1 unit higher than the previously built Firm1 magnets with cross-section 2.

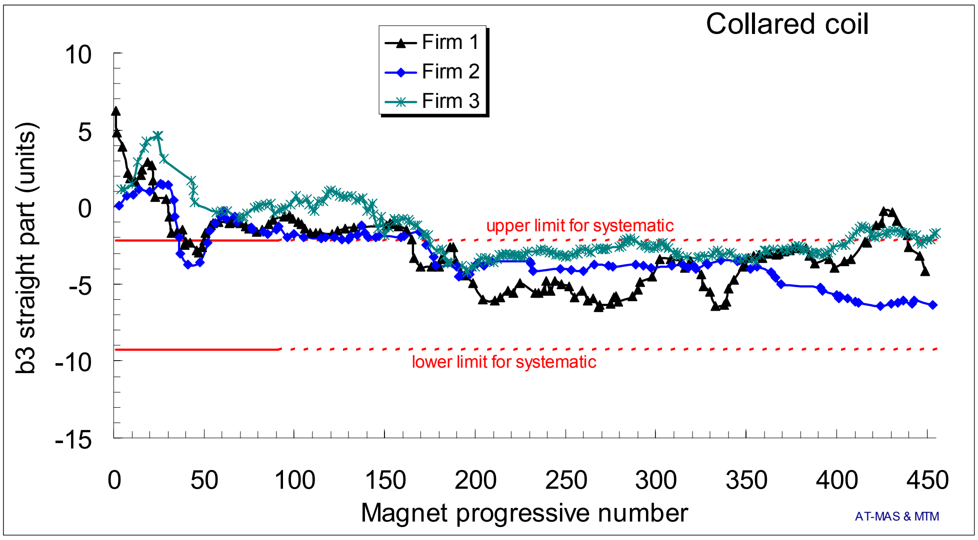


Fig. 13: Average b3 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

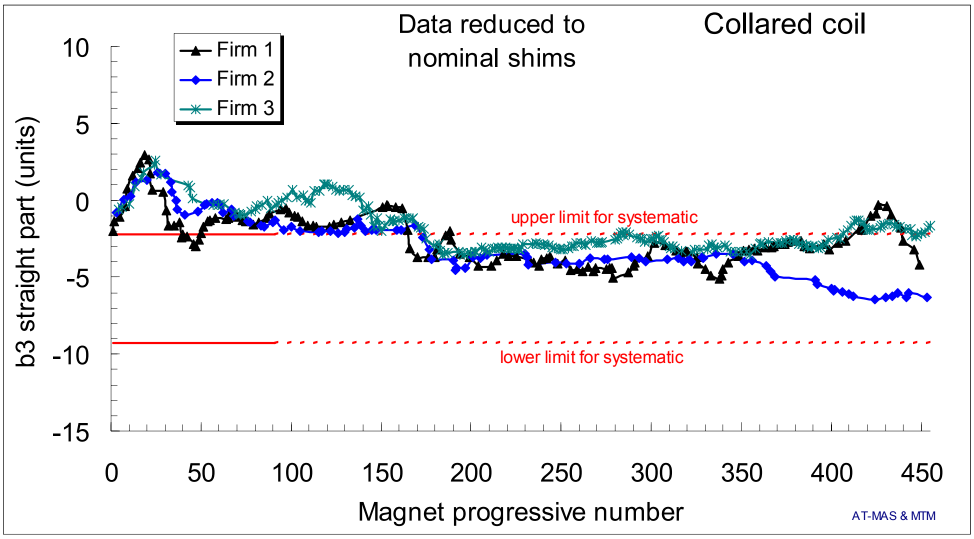


Fig. 14: Average b3 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles. Data reduced to nominal shims

- Firm3 has a normal decapole b5 within targets, whereas in Firm2 a positive trend has brought b5 above target (see Fig. 15).
- In Firm1 we have a peak of b5 due to the presence of magnets with cross-section 2. The value of systematic b5 in these magnets is 0.5 units higher than the previously built Firm1 magnets with cross-section 2.

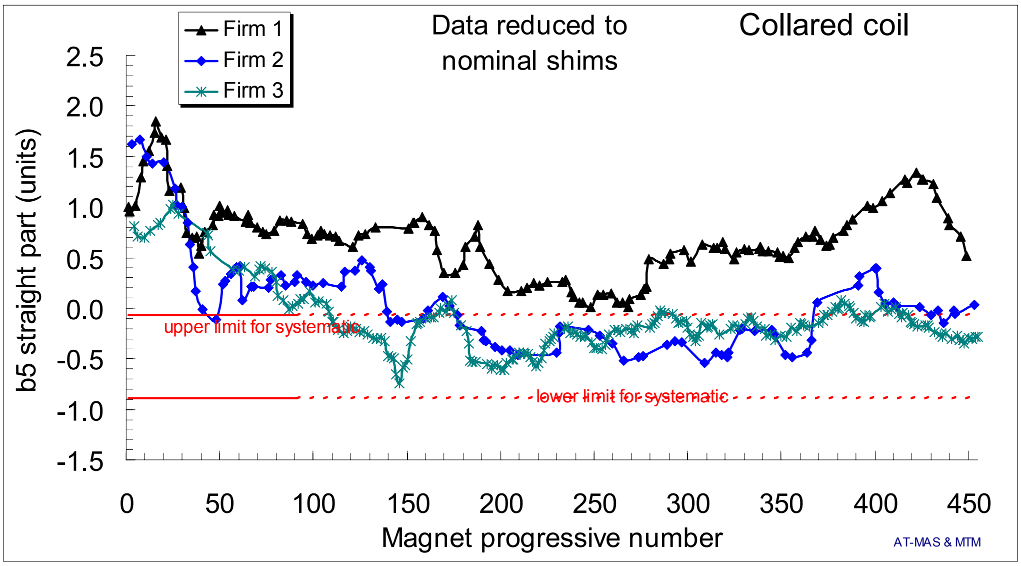


Fig. 15: Average b5 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

- Normal 14th pole b7 is stable in Firm2 and 3 (see Fig. 16).
- Firm2 is the only manufacturer producing magnets with b7 within targets.
- In Firm1 we have a peak of b7 due to the presence of magnets with cross-section 2. The value of systematic b5 in these magnets is 0.15 units higher than the previously built Firm1 magnets with cross-section 2.

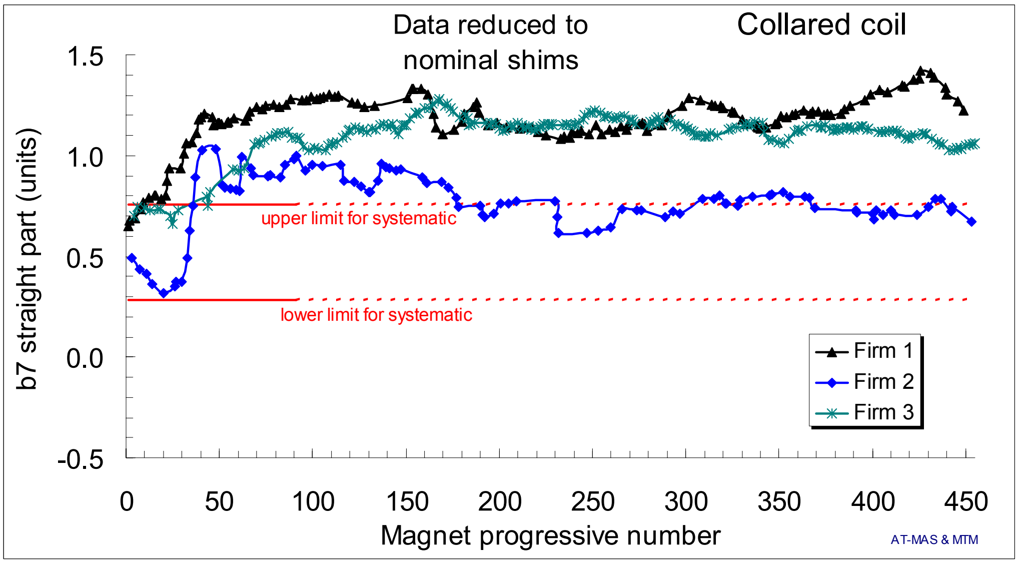


Fig. 16: Average b7 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

3.3 Trends in 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 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).

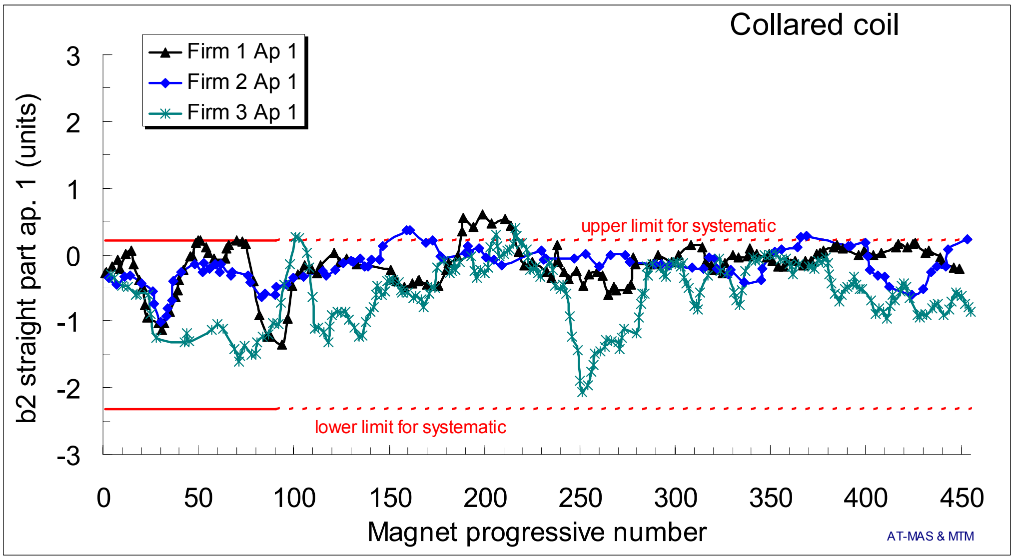


Fig. 17: Average b2 in straight part of the collared coils (Aperture 1), separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

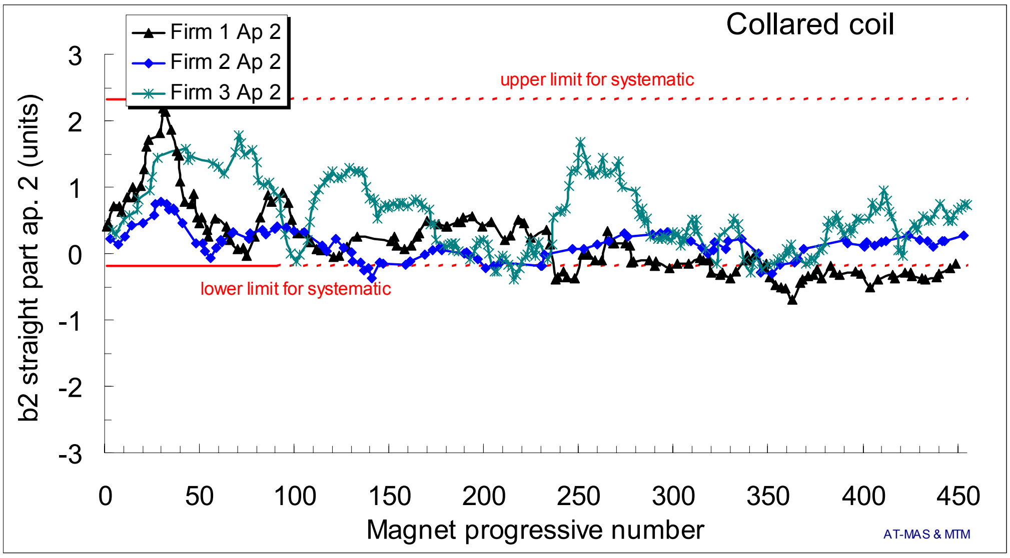


Fig. 18: Average b2 in straight part of the collared coils (Aperture 2), separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

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

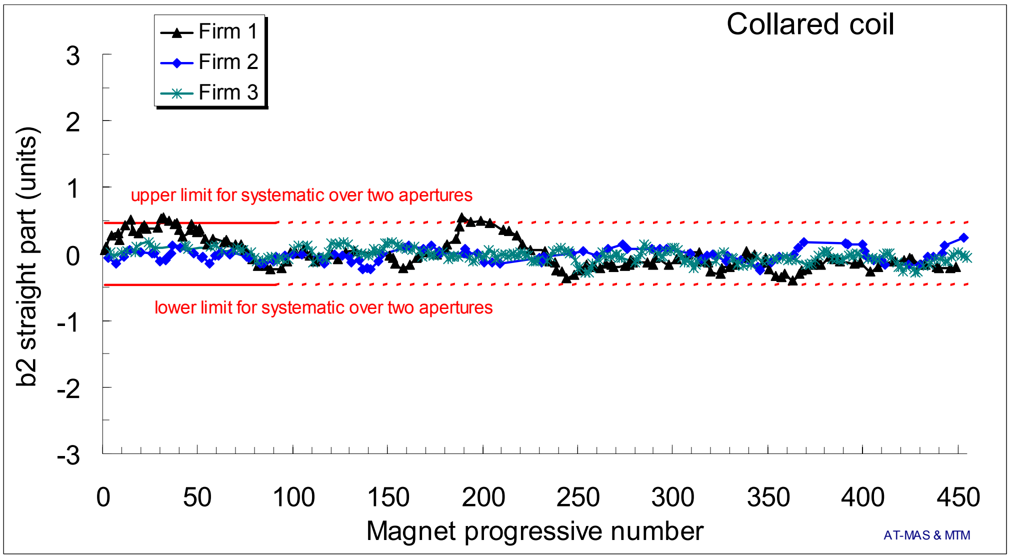


Fig. 19: Average b2 in straight part of the collared coils (both Apertures), separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

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).

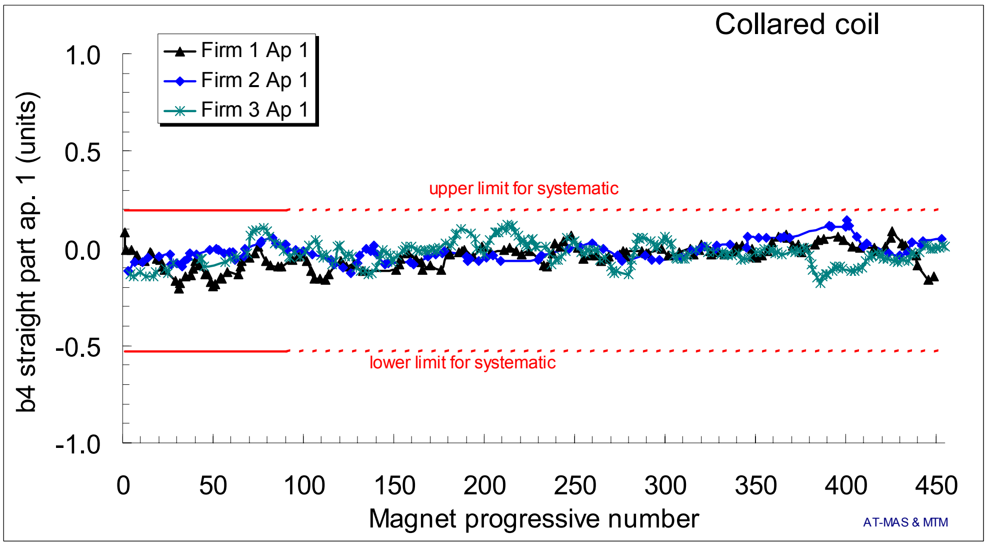


Fig. 20: Average b4 in straight part of the collared coils (Aperture 1), separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

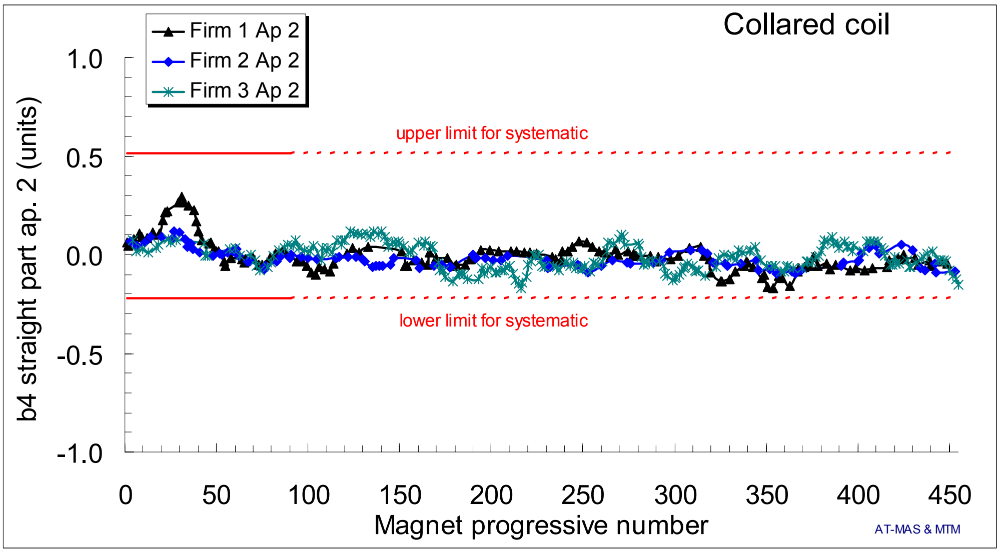


Fig. 21: Average b4 in straight part of the collared coils (Aperture 2), separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

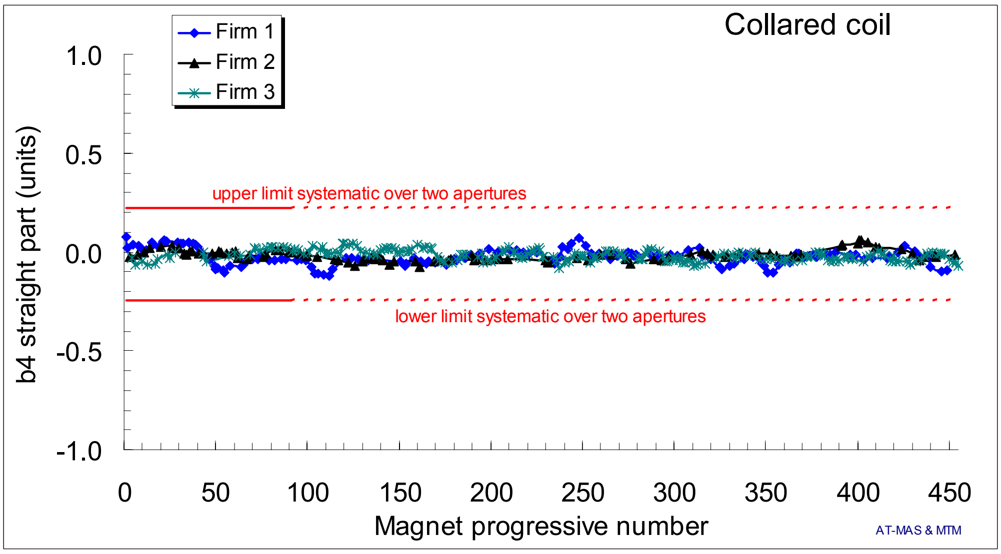


Fig. 22: Average b4 in straight part of the collared coils (both Apertures), separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

3.4 Trends in skew multipoles

- Skew quadrupole a2 is well within targets, and no major trends are observed (see Fig. 23).

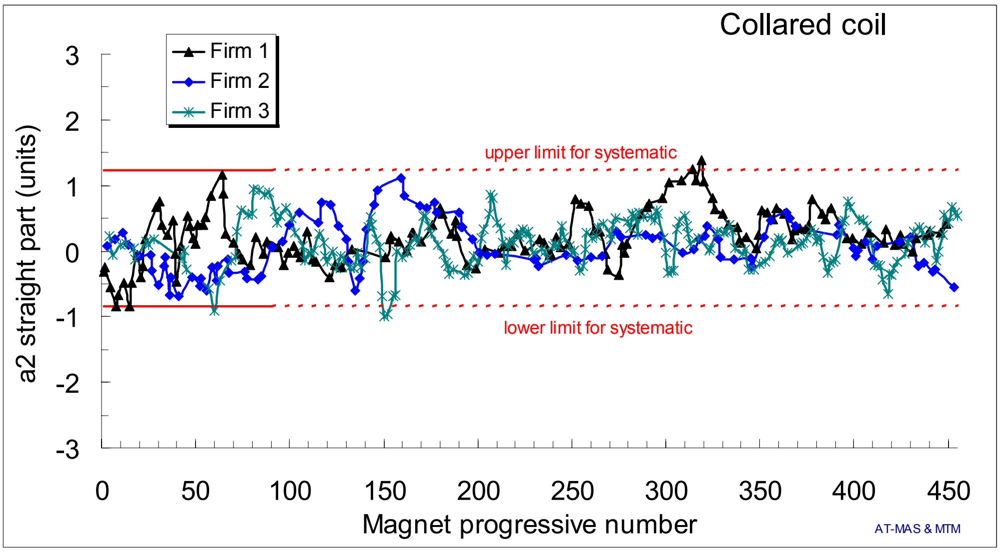


Fig. 23: Average a2 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

- 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.

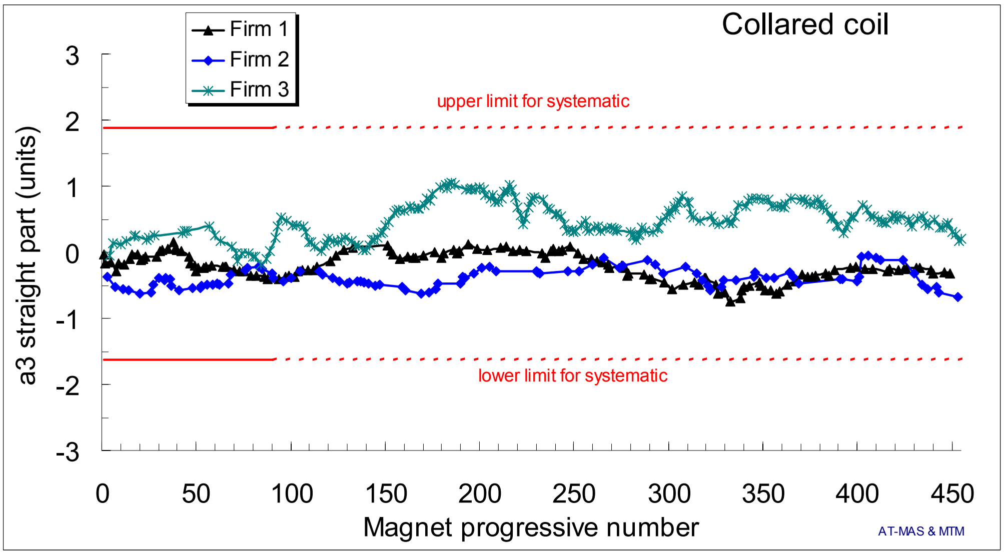


Fig. 24: Average a3 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

- Skew octupole a4 is within the tight beam dynamics targets in Firm1 (see Fig. 25). We continue to observe a strong systematic component in Firm2 (around 0.5 units). Indeed, this is partially compensated by a negative systematic component in Firm3 (around -0.3 units). This parameter should be carefully monitored.

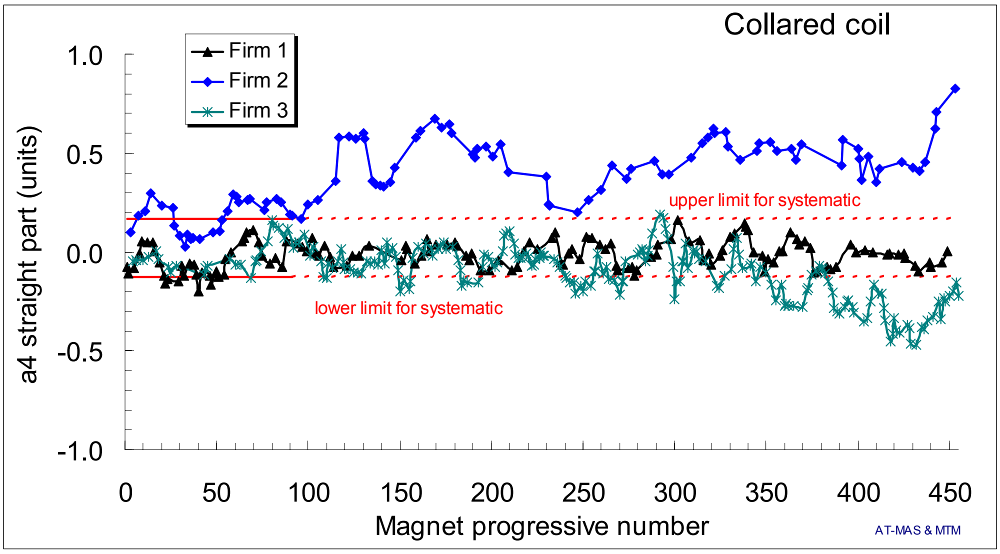


Fig. 25: Average a4 in straight part of the collared coils, separated per Firm (each dot is average of 5 consecutive magnets of the same firm), and beam dynamics targets for the systematic (red lines) based on correlations with 95 cryodipoles.

3.5 Trends in systematic differences between firms

The more relevant signature of Firms is in b_7.

- Normal 14th pole: b_7 at Firm2 is 0.5 units lower than Firm3 and Firm1 (see Fig. 16). This difference is four times the natural sigma within the same manufacturer measured in cross-section 3. Firm2 is within targets, whereas both Firm1 and Firm3 are outside.

On the more recent collared coils we observe a large systematic difference between firms in b_3:

- Normal sextupole: b_3 at Firm2 is 6 units lower than at Firm3. Values measured in Firm1 are in between. Firm3 values are slightly out of the targets. The difference between Firm3 and Firm1 is more than 4 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 0.8 units larger than Firm2-3. This difference is two times the natural sigma within the same manufacturer (see Fig. 15). Firm2 and Firm3 are within targets, whereas Firm1 is outside.
- Skew sextupole a_3: Firm3 has a systematic a_3 of 0.49 units, against –0.41 units in Firm2, Firm1 being at -0.16 units (see Fig. 24). This difference is two-three times the natural sigma within the same manufacturer. All Firms are within targets
- For the transfer function, the situation is rapidly changing. In general, Firm3 is showing values 15 units larger than in Firm1, and Firm3 is in between (see Fig. 9). This difference is around two times the natural sigma within the same manufacturer.
- Skew octupole a_4: Firm2 has a systematic a_4 of 0.37 units, against 0.0 to –0.07 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.

3.5 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), without beam screen, and the straight part of the collared coil rescaled by 1.18. 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 319th, thus implying a delay of 130 collared coils with respect to the last manufactured collared coil (i.e. the 448th), which corresponds to four months of production.

- 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.

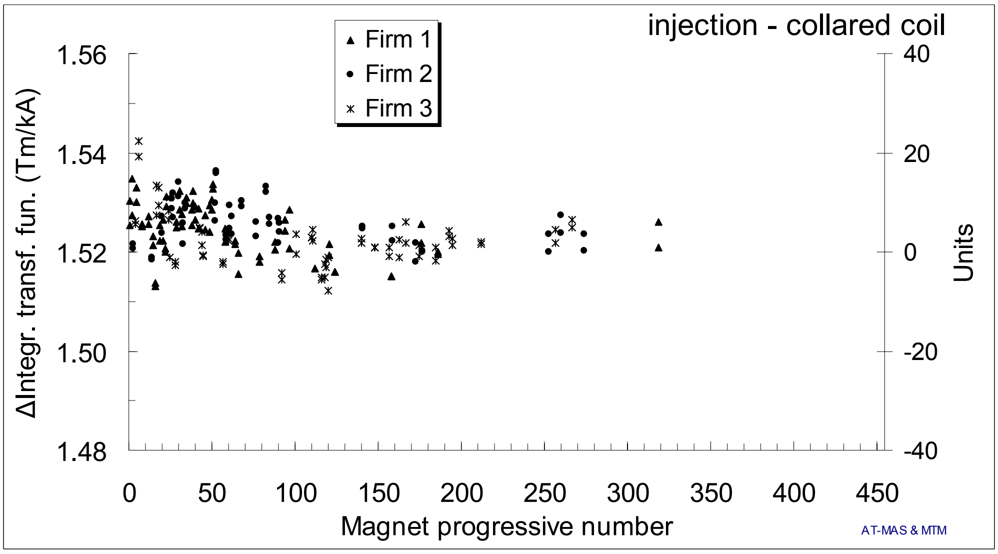


Fig. 26: Difference for the integrated transfer function between measured values at 1.9 K, injection field, and collared coil along the magnet production.

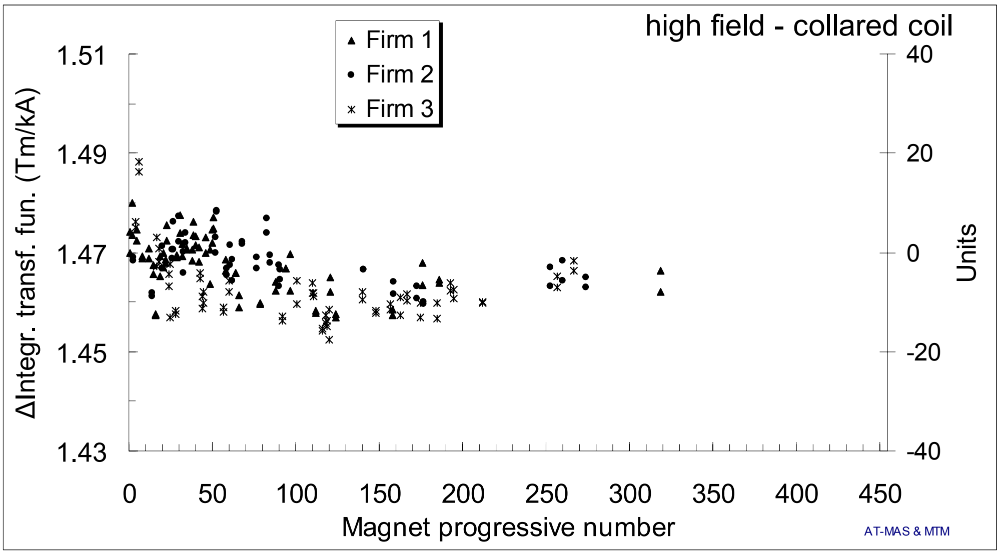


Fig. 27: Difference for the integrated transfer function between measured values at 1.9 K, high field, and collared coil along the magnet production.

- 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 reduction (in absolute value) of the b3 offset in the first 100 magnets at injection, whereas at high field (which is the critical quantity for the beam dynamics) the offset is stable.

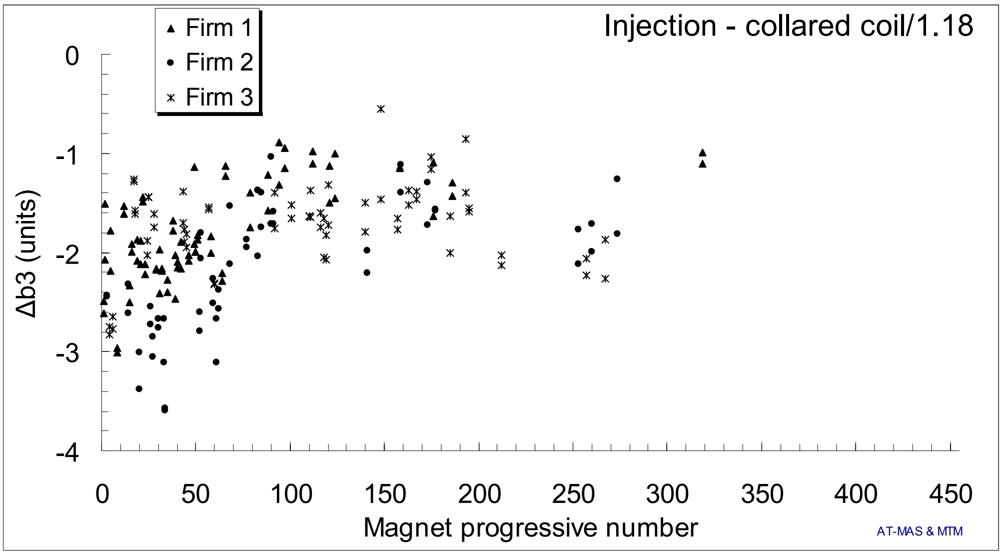


Fig. 28: Difference for the b3 between measured values at 1.9 K, injection field, and collared coil straight part divided by 1.18, along the magnet production.

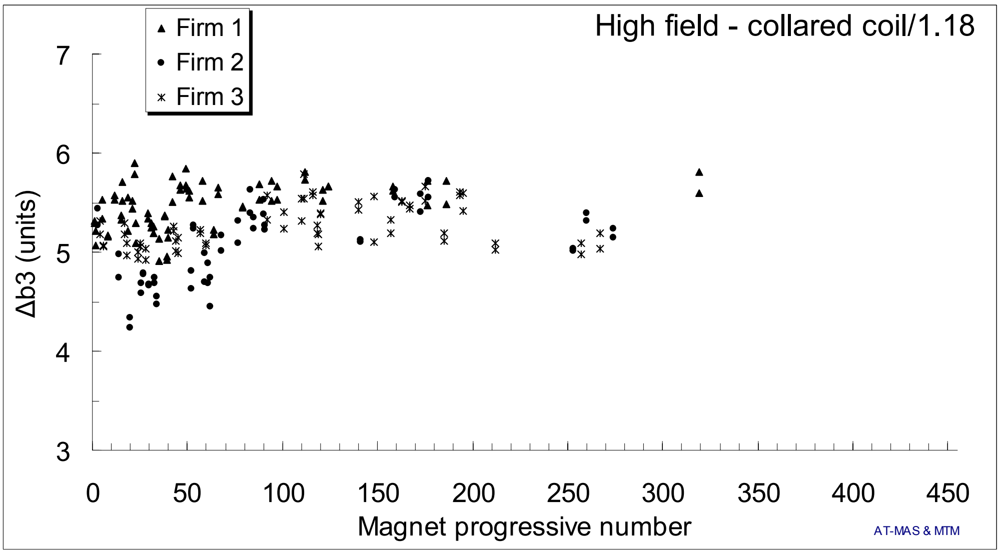


Fig. 29: Difference for the b3 between measured values at 1.9 K, high field, and collared coil straight part divided by 1.18, along the magnet production.

- 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.

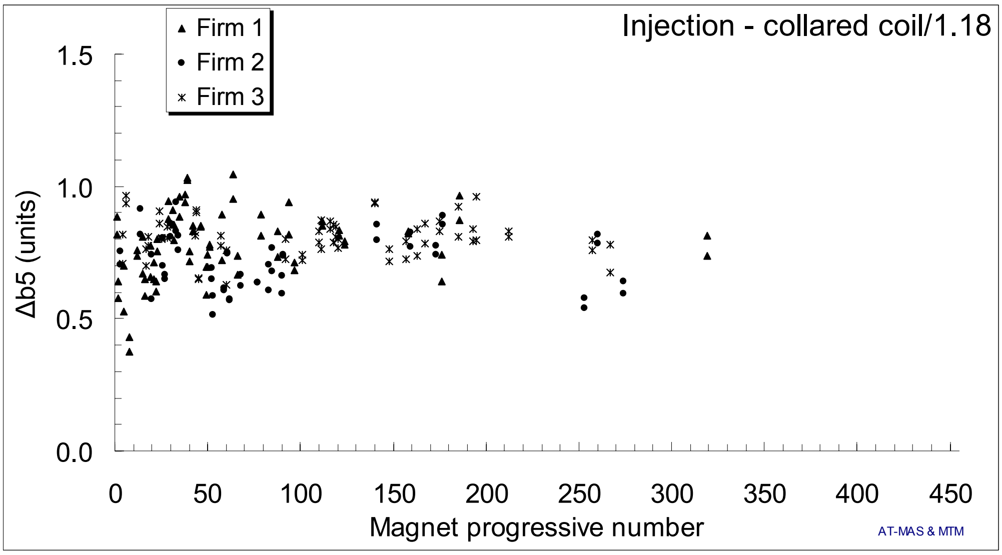


Fig. 30: Difference for the b5 between measured values at 1.9 K, injection field, and collared coil straight part divided by 1.18, along the magnet production.

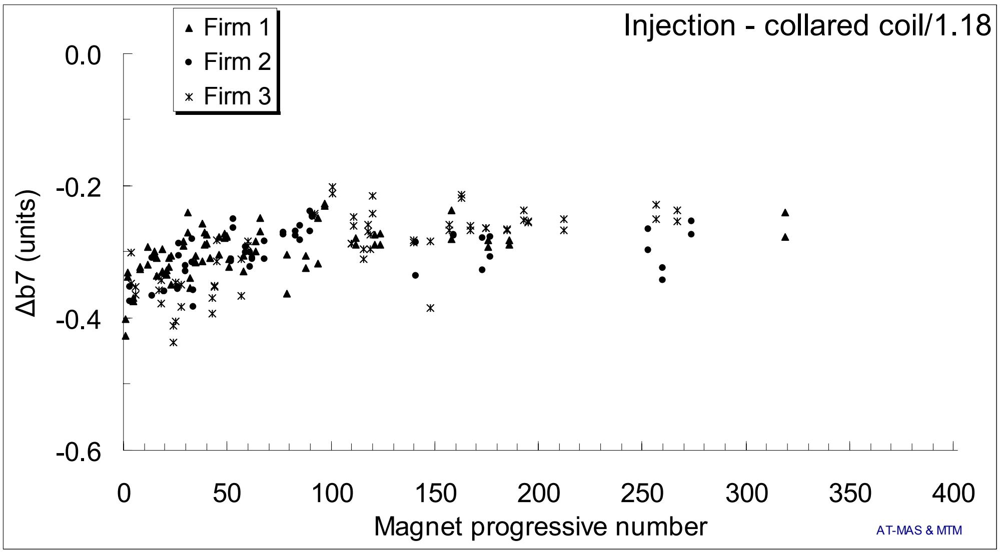


Fig. 31: Difference for the b7 between measured values at 1.9 K, injection field, and collared coil straight part divided by 1.18, along the magnet production.

PART IV: QUALITY CONTROL

4.1 Holding point results

We had the following cases of collared coil held for field anomalies.

- Bad gluing of the inner layer
  - 1108,1122,1128, 1130 showed anomalies in high order multipoles indicating a movement of 0.3 mm to 0.8 mm of block6 in one quadrant, along one or more longitudinal zones (as found for 1099, 2032 and 2035). The de-collaring has shown that the coil was not correctly glued, block6 being detached from the copper wedge. Corrective actions have been taken on the curing cycle and the problem in Firm1 has now disappeared.
  - The same defect was found in collared coil 3175. Contrary to the case of Firm1, this has been an isolated case.

  This kind of defect has been observed in all firms in different phases of the production: in summer 2003 at Firm2 (2 cases), in spring 2004 at Firm1 (5 cases) and at Firm3 (1 case).

- Suspected assembly defect
  - 1108, besides a local movement of block6, was also showing a peak of 10 units in a2 along 0.4 m. Simulations showed that this could be due to a missing or to an additional thickness of 0.4 mm on the pole outer layer. After de-collaring, no visible defect in this region has been found.

- Field anomalies at Firm2: the series 2065-2090
  - 2065, 2075, 2077, 2084-90 were held for field anomalies that could be traced back to movements of block6 from 0.1 to 0.7 mm. Three magnets have been de-collared:
    - 2065, where a displacement of block6 of about 0.5 mm has been found (expected value: 0.8 to 1.0 mm).
    - 2084, where a displacement of block6 of maximum 0.15 mm has been found (expected value of 0.4 to 0.6 mm).
    - 2089, where no displacement of block6 has been found.

    In all cases, the coil was correctly glued. Since, contrary to the previous cases, no coil repair was possible, it has been decided not to decollar the other magnets showing similar defect, and to give high priority to cold test for these magnets. First results on 2065 and 2077 show that the quench behaviour is good.

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 12 over 448 collared coils, i.e. 2.7%. A large fraction of these defects (8 over 12) has been found in collared coil 300th to 400th (see Fig. 32). The situation is improving in the more recent production.

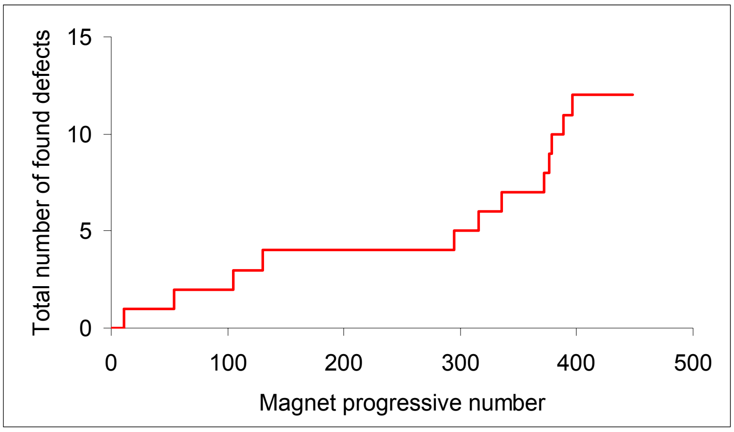


Fig. 32: Total number of defects found with magnetic measurements versus magnet progressive number.

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
		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 below 30 microns. The general situation of this parameter is very good in all firms (see Fig. 33).

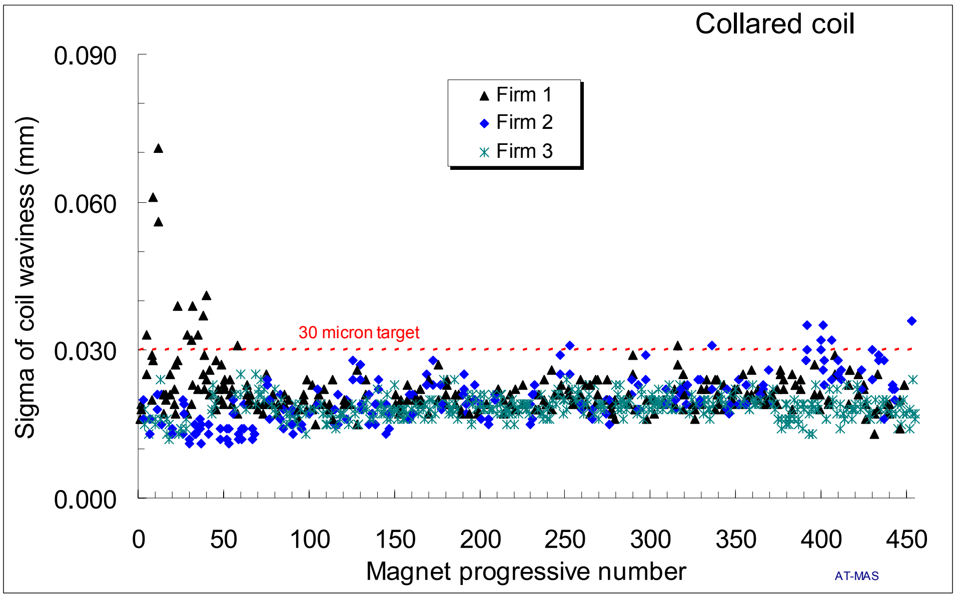


Fig. 33: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

Acknowledgements

We wish to acknowledge all colleagues involved in the measurements at room temperature and at 1.9 K, and all the firm personnel involved in magnetic measurements. We thank P. Hagen, C. Vollinger for data validation and analysis. We finally acknowledge the project engineers for support in the analysis and W. Scandale and C. Vollinger for comments on this manuscript.

Appendix A: collared coil assembly data

Table I: Magnet number, collared coil progressive number used in figures, and cross-section (data available on July 14 2004) for Firm1.

Magnet name	Prog. Number	X-section
1001	1	1
1002	2	1
1003	5	1
1004	8	1
1005	9	1
1006	12	1
1007	15	1
1008	16	1
1009	19	1
1010	21	1
1011	22	1
1012	23	1
1013	29	2
1014	31	2
1015	32	1
1016	35	2
1017	38	2
1018	39	2
1019	40	2
1020	64	2
1021	42	2
1022	47	2
1023	49	2
1024	50	2
1025	51	2
1026	46	2
1027	54	2
1028	55	2
1029	58	2
1030	65	2
1031	66	2
1032	70	2
1033	73	2
1034	75	2
1035	79	2
1036	82	2
1037	86	2
1038	88	2
1039	97	2
1040	102	2
1041	99	2
1042	106	2
1043	186	2
1044	121	2
1045	94	2
1046	104	2
1047	109	2
1048	158	2
1049	112	2
1050	114	2
1051	154	2
1052	124	2
1053	153	2
1054	162	2
1055	133	2
1056	181	2
1057	128	2
1058	165	2
1059	151	2
1060	166	2
1061	170	3
1062	188	2
1063	176	3
1064	180	3
1065	242	3
1066	189	2
1067	211	3
1068	194	2
1069	204	3
1070	199	3

Magnet name	Prog. Number	X-section
1071	214	3
1072	238	3
1073	239	3
1074	218	3
1075	221	3
1076	248	3
1077	225	3
1078	235	3
1079	233	3
1081	244	3
1082	252	3
1083	259	3
1084	255	3
1085	262	3
1086	265	3
1087	268	3
1088	269	3
1089	275	3
1090	277	3
1091	279	3
1092	278	3
1093	287	3
1094	290	3
1095	291	3
1096	298	3
1097	308	3
1098	302	3
1099	316	3
1100	314	3
1101	325	3
1102	357	3
1104	319	3
1105	326	3
1106	343	3
1107	359	3
1108	376	3
1109	338	3
1110	320	3
1111	333	3
1112	339	3
1113	330	3
1114	340	3
1115	349	3
1116	348	3
1117	351	3
1118	363	3
1119	354	3
1120	367	3
1121	371	3
1122	378	3
1123	374	3
1124	368	3
1125	385	3
1126	383	3
1128	388	3
1129	417	3
1130	396	3
1131	399	3
1132	408	3
1133	404	2
1134	458	2
1135	416	2
1136	422	2
1137	425	2
1138	426	2
1139	439	2
1140	433	2

Magnet name	Prog. Number	X-section
1142	431	2
1143	440	3
1144	449	3
1146	446	3
1148	456	3
1150	459	3

Table II: Magnet number, collared coil progressive number used in figures, and cross-section (data available on July 14 2004) for Firm2.

Magnet name	Prog. Number	X-section	Magnet name	Prog. Number	X-section
2001	3	1	2071	315	3
2002	11	1	2072	276	3
2003	7	1	2073	297	3
2004	20	1	2074	321	3
2005	14	1	2075	352	3
2006	30	1	2076	346	3
2007	27	1	2077	328	3
2008	26	1	2078	329	3
2009	34	1	2079	364	3
2010	33	1	2080	366	3
2011	56	1	2081	309	3
2012	37	2	2082	345	3
2013	36	2	2083	369	3
2014	41	2	2084	392	3
2015	61	2	2085	402	3
2016	48	2	2086	400	3
2017	52	2	2087	401	3
2018	53	2	2088	391	3
2019	59	2	2089	406	3
2020	62	2	2090	410	3
2021	67	2	2091	412	3
2022	68	2	2092	453	3
2024	126	2	2093	451	3
2025	77	2	2094	462	3
2026	83	2	2095	460	3
2027	85	2	2101	424	3
2028	90	2	2103	457	3
2029	91	2	2104	442	3
2030	96	2	2105	437	3
2031	100	2	2106	434	3
2032	105	3	2107	443	3
2033	131	2	2108	430	3
2034	117	2	2523	76	2
2035	130	3			
2036	115	2			
2037	122	2			
2038	137	2			
2039	141	2			
2040	145	3			
2041	139	2			
2042	135	2			
2043	147	3			
2044	159	2			
2045	201	3			
2046	253	3			
2047	232	3			
2048	161	2			
2049	190	3			
2050	177	2			
2051	247	3			
2052	169	2			
2053	178	3			
2054	173	3			
2055	191	3			
2056	209	2			
2057	192	3			
2058	197	3			
2059	231	3			
2060	260	3			
2061	205	3			
2062	230	3			
2063	289	3			
2064	266	3			
2065	336	3			
2066	274	3			
2067	322	3			
2068	356	3			
2069	293	3			
2070	318	3			

Table I: Magnet number, collared coil progressive number used in figures, and cross-section (data available on July 14 2004) for Firm3.

Magnet name	Prog. Number	X-section	Magnet name	Prog. Number	X-section	Magnet name	Prog. Number	X-section	Magnet name	Prog. Number	X-section
3001	4	1	3071	179	2	3141	299	3	3211	441	3
3002	6	1	3072	168	2	3142	300	3	3212	444	3
3003	10	1	3073	171	2	3143	301	3	3213	448	3
3005	17	1	3074	172	2	3144	303	3	3214	445	3
3006	18	1	3075	174	3	3145	306	3	3216	447	3
3007	24	1	3076	175	2	3146	421	3	3217	450	3
3008	25	1	3077	200	3	3147	311	3	3218	452	3
3009	28	1	3078	184	3	3148	310	3	3219	454	3
3010	57	1	3079	183	3	3149	317	3	3220	455	3
3011	43	1	3080	182	3	3150	331	3	3221	461	3
3012	44	2	3081	195	3	3151	332	3	3223	463	3
3013	45	2	3082	213	3	3152	360	3	3224	465	3
3014	60	2	3083	185	3	3153	313	3	3504	13	1
3015	63	2	3084	193	3	3154	350	3			
3016	69	2	3085	196	3	3155	324	3			
3017	72	2	3086	198	3	3156	323	3			
3018	71	2	3087	207	3	3157	337	3			
3019	74	2	3088	208	3	3158	342	3			
3020	80	2	3089	210	3	3159	427	3			
3021	78	2	3090	212	3	3160	327	3			
3022	81	2	3091	215	3	3161	334	3			
3023	84	2	3092	216	3	3162	344	3			
3024	87	2	3093	217	3	3163	335	3			
3025	89	2	3094	219	3	3164	341	3			
3026	108	2	3095	220	3	3165	353	3			
3027	92	2	3096	222	3	3166	355	3			
3028	93	2	3097	224	3	3167	358	3			
3029	95	2	3098	223	3	3168	362	3			
3030	98	2	3099	226	3	3169	423	3			
3031	202	3	3100	227	3	3170	365	3			
3032	203	3	3101	228	3	3171	361	3			
3033	206	3	3102	307	3	3172	370	3			
3034	101	2	3103	229	3	3173	373	3			
3035	347	3	3104	234	3	3174	379	3			
3036	103	2	3105	236	3	3175	372	3			
3037	107	2	3106	237	3	3176	380	3			
3038	111	2	3107	240	3	3177	375	3			
3039	113	2	3108	241	3	3178	377	3			
3040	187	3	3109	243	3	3179	382	3			
3041	110	2	3110	245	3	3180	381	3			
3042	116	2	3111	246	3	3181	384	3			
3043	119	2	3112	249	3	3182	389	3			
3044	118	2	3113	250	3	3183	386	3			
3045	120	2	3114	251	3	3184	390	3			
3046	123	2	3115	254	3	3185	387	3			
3047	125	2	3116	256	3	3186	394	3			
3048	127	2	3117	257	3	3187	393	3			
3049	129	2	3118	258	3	3189	395	3			
3050	132	2	3119	261	3	3190	397	3			
3051	134	2	3120	263	3	3191	398	3			
3052	136	2	3121	264	3	3192	405	3			
3053	138	2	3122	267	3	3193	407	3			
3054	140	2	3123	273	3	3194	409	3			
3055	142	2	3124	272	3	3195	411	3			
3056	143	3	3125	270	3	3196	413	3			
3057	144	2	3126	271	3	3197	414	3			
3058	146	2	3127	280	3	3198	415	3			
3059	148	3	3128	281	3	3199	418	3			
3060	149	3	3129	282	3	3201	419	3			
3061	150	2	3130	283	3	3202	420	3			
3062	152	2	3131	284	3	3203	428	3			
3063	155	2	3132	285	3	3205	429	3			
3064	156	2	3133	286	3	3206	435	3			
3065	157	2	3134	288	3	3207	403	3			
3066	160	2	3135	295	3	3208	432	3			
3067	312	3	3136	292	3	3209	436	3			
3068	163	2	3137	296	3	3210	438	3			
3069	164	2	3138	305	3						
3070	167	2	3139	304	3						
			3140	294	3						