Report on field quality in the main LHC dipoles November-December 2005

E. Todesco, AT-MAS-MA

This report gives data relative to field quality measured in collared coils and cold masses during the period November 1– December 31 2005, 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. 693742

The dashboard

- Available measurements:
  - 1030 collared coils and 979 cold masses at room temperature,
  - 176 equivalent dipoles at 1.9 K[1].
- In these two months we had:
  - 49 new collared coils (23 from Firm1, 26 from Firm2) measured at room temperature,
  - 5.5 dipoles measured at 1.9 K[1].

What's new (not much)

- **Firm3** has completed the manufacturing of the collared coils.
- **Production rate** is at 24.5 collared coils per month. The rate is 2.6 and 3.0 collared coils per week in Firm1, Firm2, respectively (this includes Christmas holidays).
- **a4 in Firm2:** the improvement of the systematic value of a4 in Firm2 observed in the previous report is confirmed by the data of these two months. Average a4 in Firm2 in the recent production is around 0.1-0.2 units, compared to previous values of 0.2-0.5 units (see Fig. 24).
- **Trends:** We have no major trends, neither in the warm measurement nor on the warm-cold correlations.

[1] These numbers refers to measurements of either magnets or single apertures available in AT-MTM Oracle database at the time of distribution of the report.

CONTENTS

The 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 (cross-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 mass 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. Shims are nominal since September 2004, except a few cases.
    - 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.
    - All plots give integral values (i.e. including contribution of coil heads).
- 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

- 49 new collared coils have been measured (collared coils 982[nd] to 1030[th]).

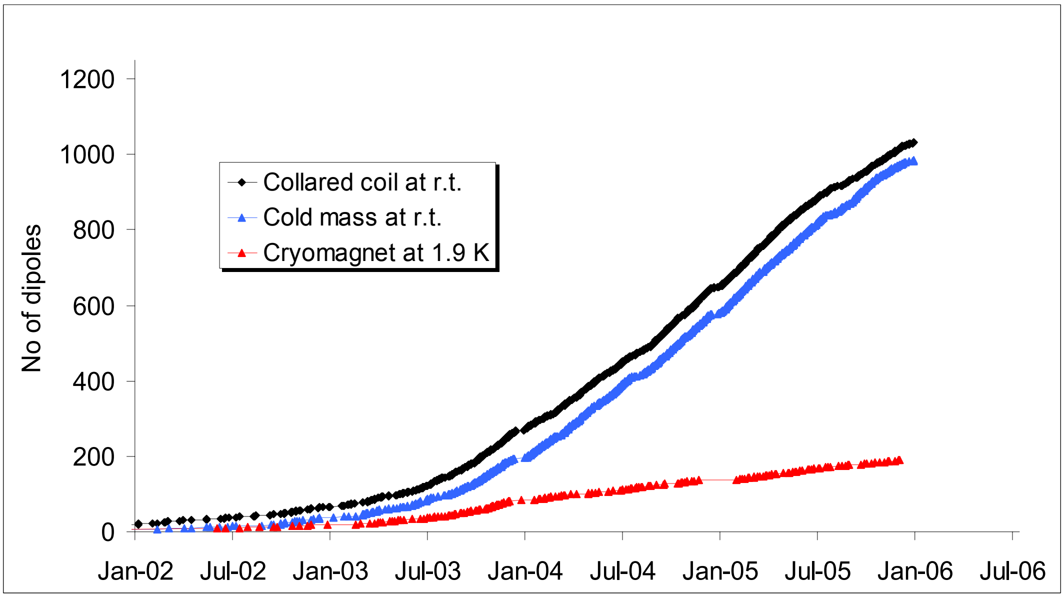

Fig. 1: Number of magnets measured at CERN at 1.9 K and at the manufacturers at room temperature at different stages of assembly procedure.

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

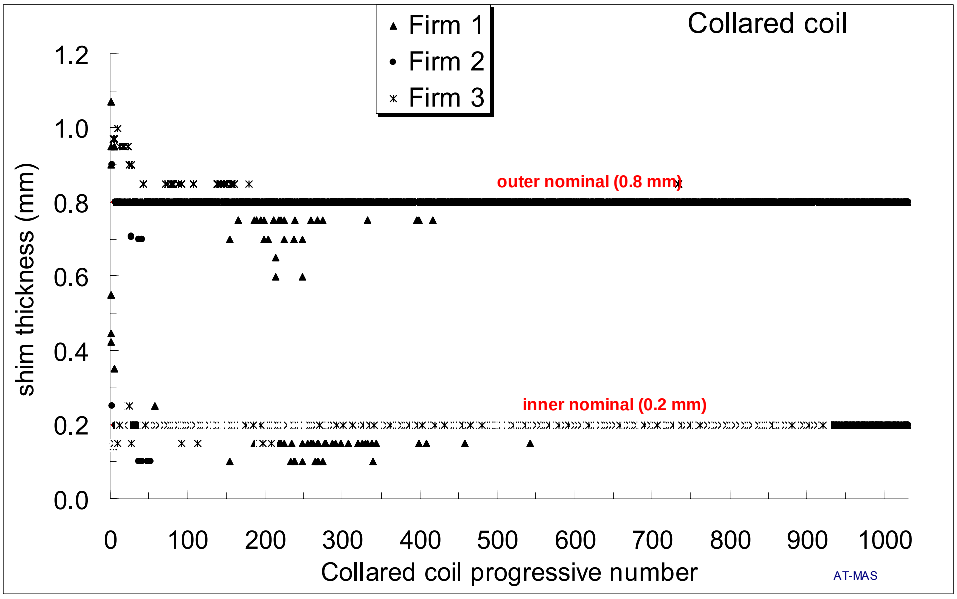

Fig. 2: Thickness of the polar shims used in the collared coils.

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.

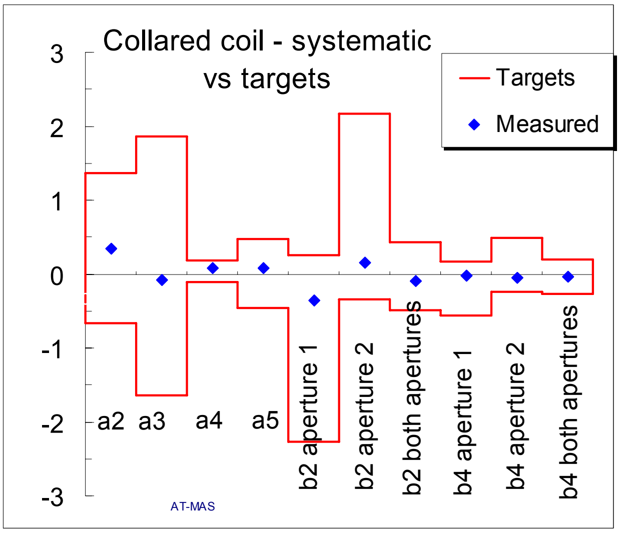

Fig. 3: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (solid red line).

- 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: b_3 is within target and b_5 is larger than the upper target of 0.10 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, 848 have cross-section 3, plus one hybrid 1-2). With cross-section 3, b_3 in the collared coil is 1.0 units below the upper limit (i.e., 2.2 units at high field), and also b_5 is within targets, just at the edge of the upper limit (i.e., 1.1 units at injection). Finally, b_7 in the collared coil is 0.28 units larger than the limits (i.e. 0.34 units at injection).

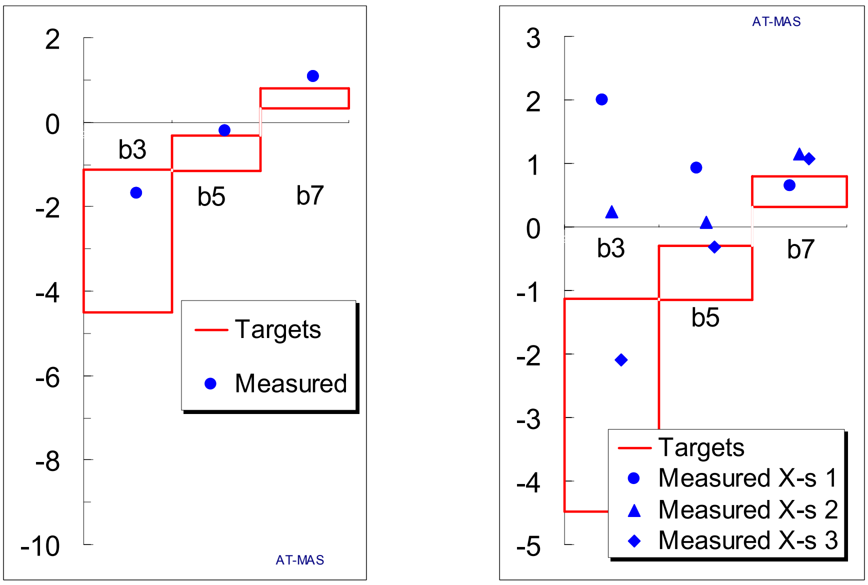

Fig. 4: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (solid red line). Raw data (left) and data separated according to different cross-sections (right).

2.2 Summary of random components

- We first evaluate the standard deviation of the bending strength and multipoles for each Firm and for magnets with cross-section 3 (848 collared coils, see Fig. 5). The standard deviation of multipoles in collared coil is divided by 1.18 (i.e. the increase of the main field due to the iron yoke) and summed in quadrature to the spread of warm-cold correlations in order to give the best estimate of the random at 1.9 K. All values are well within targets, with the exception of the main field in the straight part B; please note that the relevant constraint for beam dynamics is only on the bending strength BdL, which is within targets.

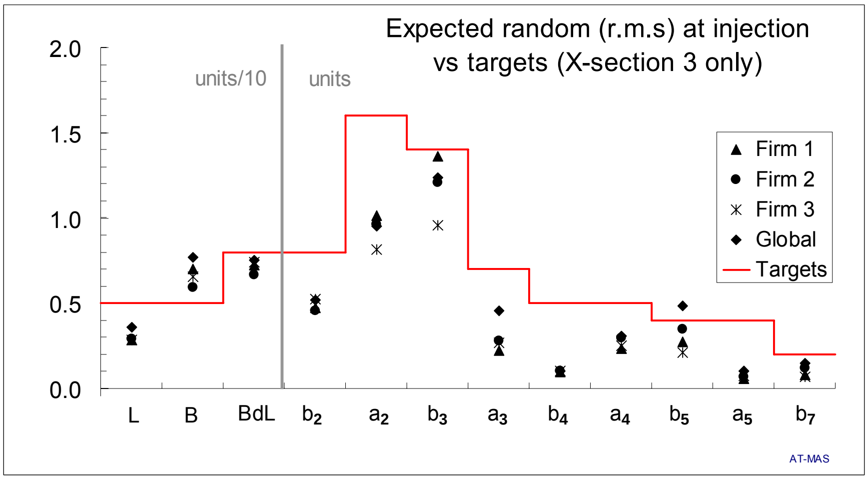

Fig. 5: Expected random component at 1.9 K (cross-section 3 only) compared to targets for random at 1.9 K.

- We then evaluate the expected random component at 1.9 K in each sector. Also in this case, we take the spread in the collared coil, rescale it by 1.18, and sum in quadrature to the spread of the warm-cold correlations. We consider the spread in the first six sectors to be installed, where it has been decided to use magnets with the following features
  - Sector 3-4: diode type L, cross-section 3, inner cable 01B, low b3
  - Sector 4-5: diode type L, cross-section 3, inner cable 01E.
  - Sector 5-6: diode type R, cross-section 3, inner cable 01E.
  - Sector 6-7: diode type R, cross-section 3, inner cable 01B.
  - Sector 7-8: diode type R, cross-section 1 and 2 (mainly), inner cable 01B (mainly)
  - Sector 8-1: diode type L, cross-section 3 (mainly), inner cable 01B, high b3

  In Fig. 6 the expected random component for these five sectors are compared to targets. All expected values are within or close to targets, with the exception of the spread of b3 in sector 7-8 (this is due to the mix of different cross-sections). For Sectors 3-4 to 6-7, which are made of magnets belonging to the mature phase of production, the spread is within targets. The only exception is b5, which is not considered as critical.

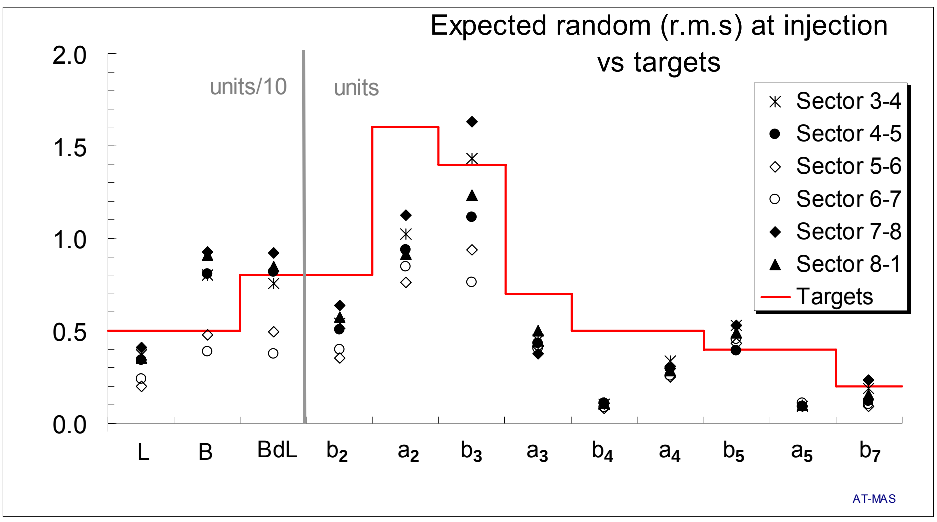

Fig. 6: Expected random component at 1.9 K (markers) compared to targets (solid line), separated according to the provisional allocation to 6 sectors.

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.

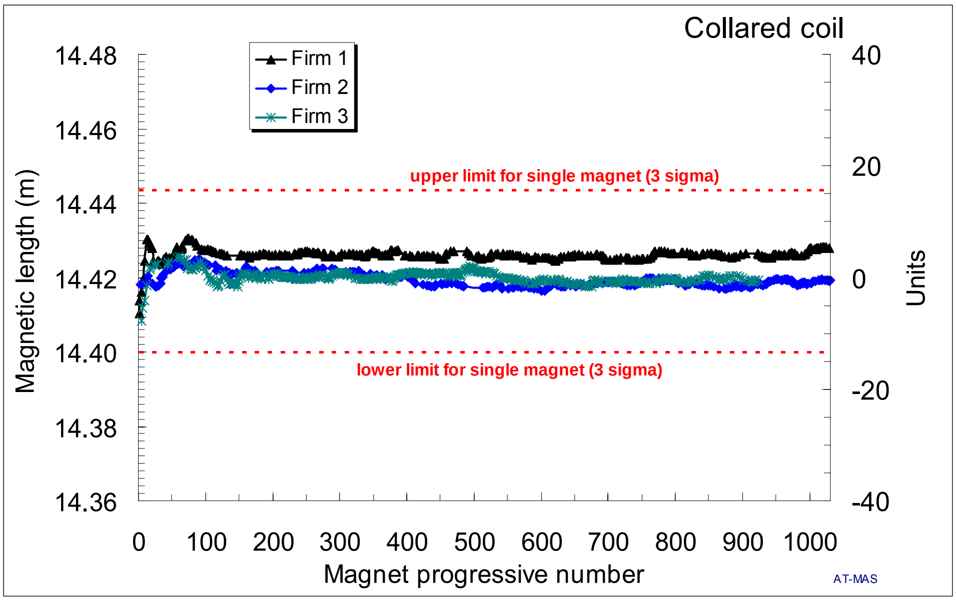

Fig. 7: Magnetic length of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- 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 10 units of difference between Firm1 and Firm3, with Firm2 in between.

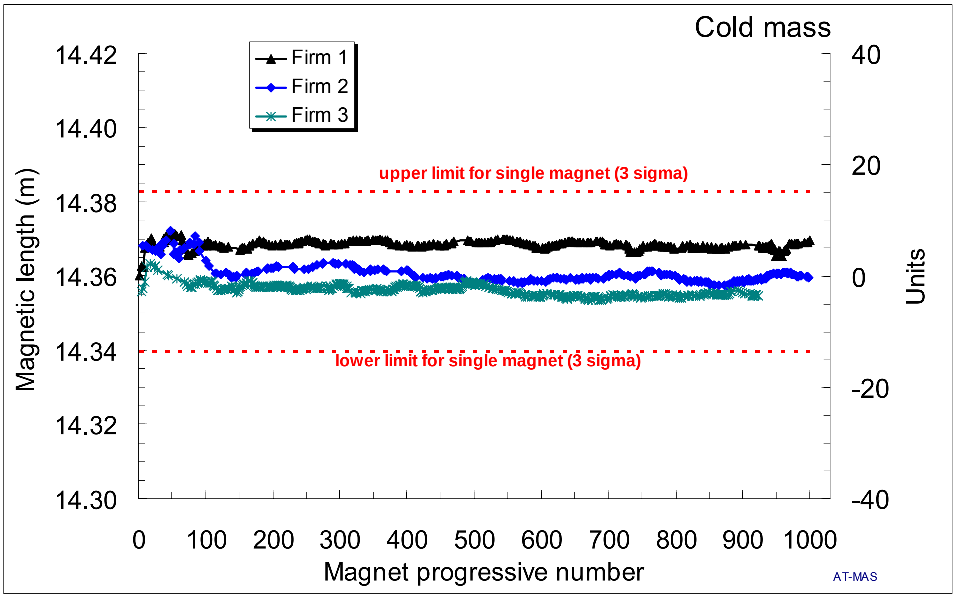

Fig. 8: Magnetic length of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.1.2 Trends in transfer function

- Transfer function in collared coils 982nd to 1030th is stable.

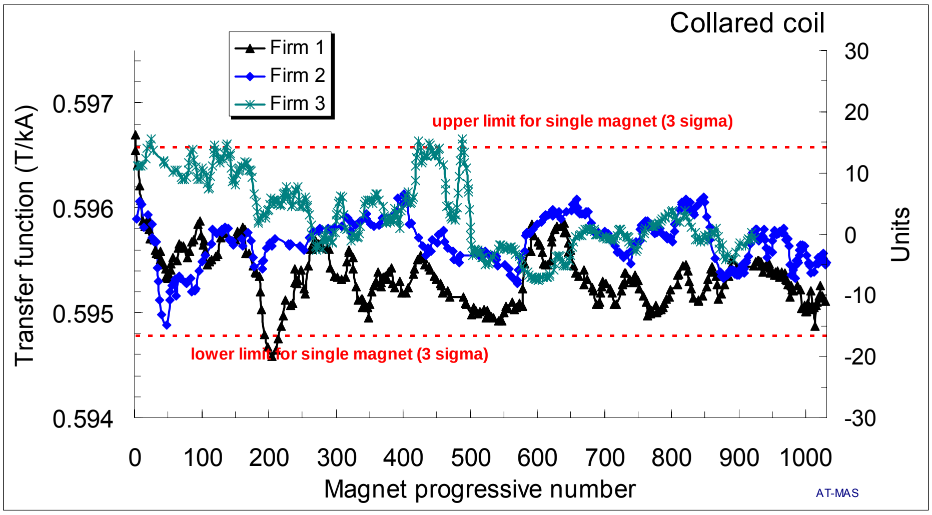

Fig. 9: Transfer function of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- 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).

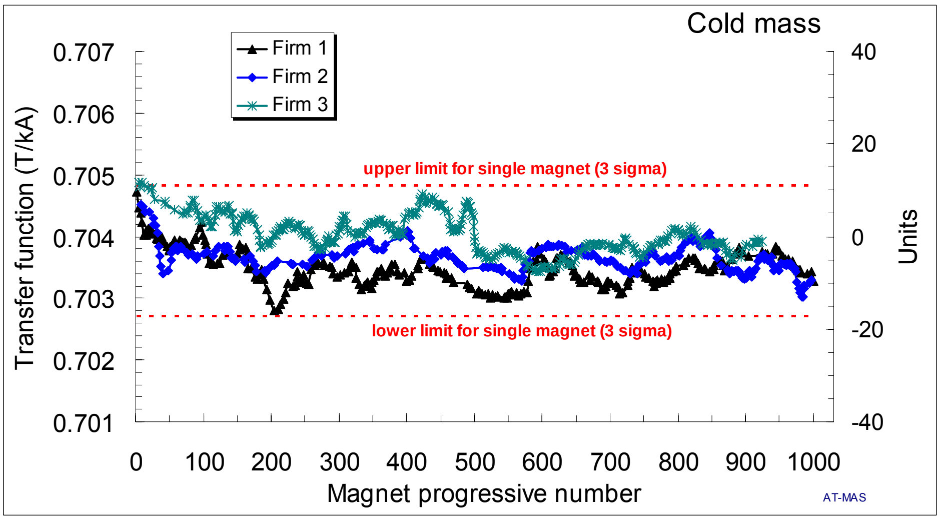

Fig. 10: Transfer function of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.1.3 Trends in integrated transfer function

- The integrated transfer function is stable in the recent production (see Fig. 11).

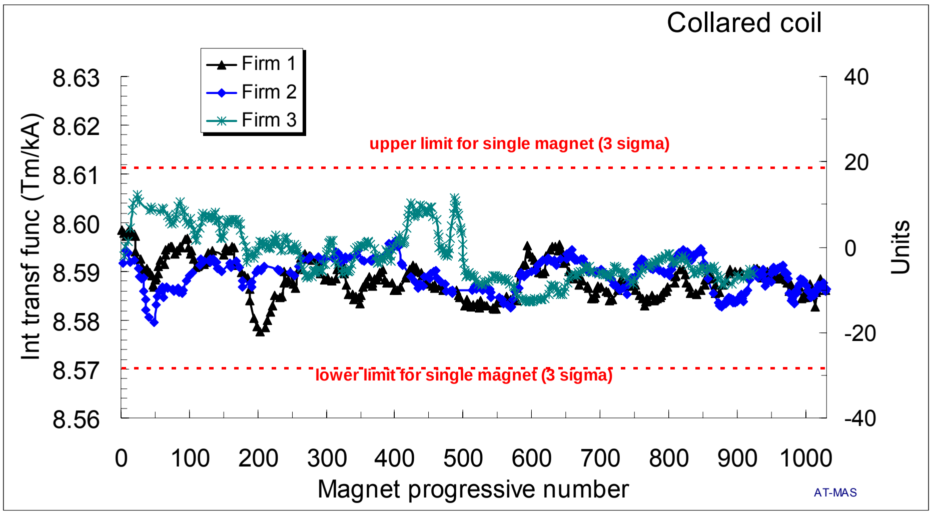

Fig. 11: Integrated transfer function of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- In the **cold masses,** the spread of the integrated transfer function between Firms is reduced by 20% (see Fig. 12), as expected, and confirms the collared coil results.

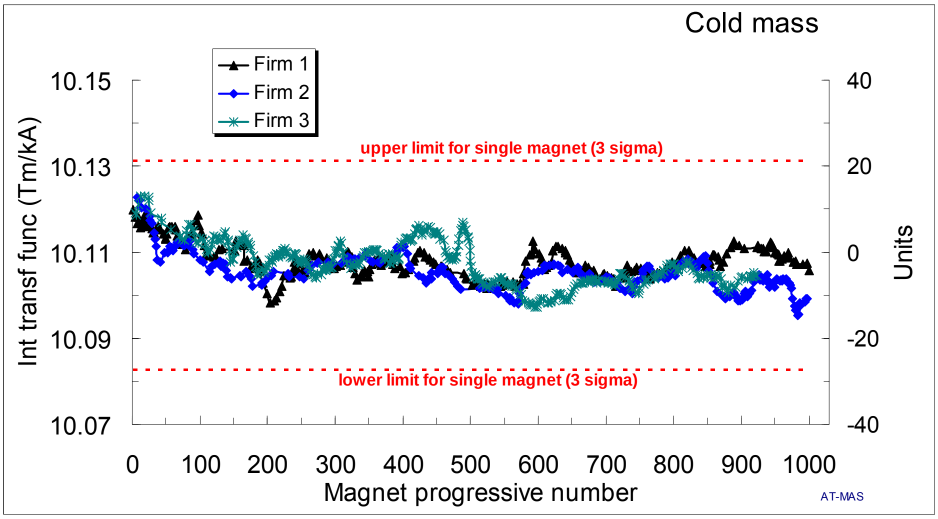

Fig. 12: Integrated transfer function of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.2 Trends in odd normal multipoles

- Average b3 in Firm2 in the collared coils is within targets. The recent production shows a small positive trend in Firm1, whose recent values are 2 units larger than targets. However, the systematic b3 is well within targets.

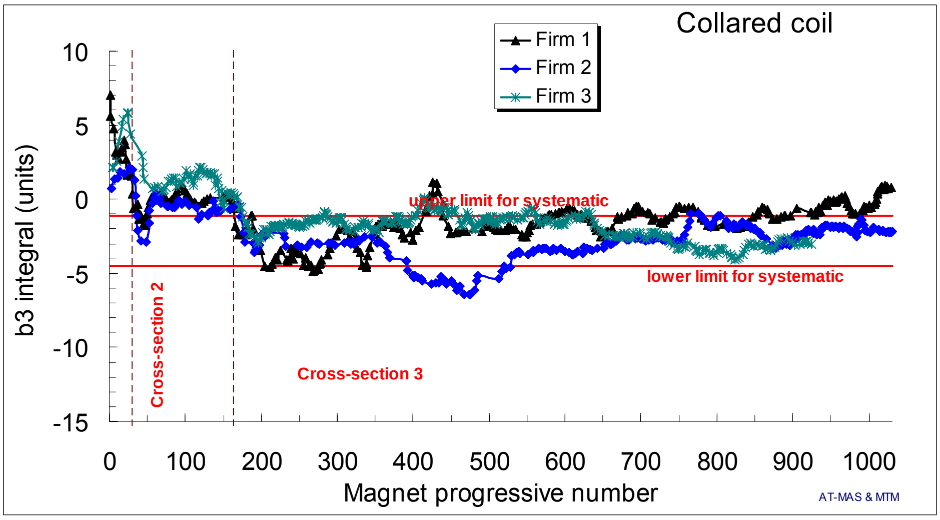

Fig. 13: Average b3 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

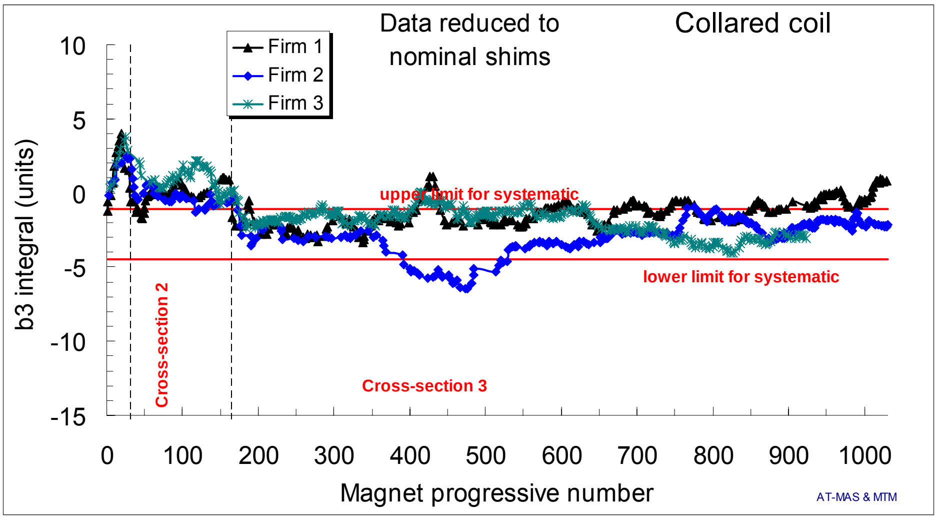

Fig. 14: Average b3 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles. Data normalised to nominal shims[3].

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

- Normal decapole b5 is stable in both Firms.

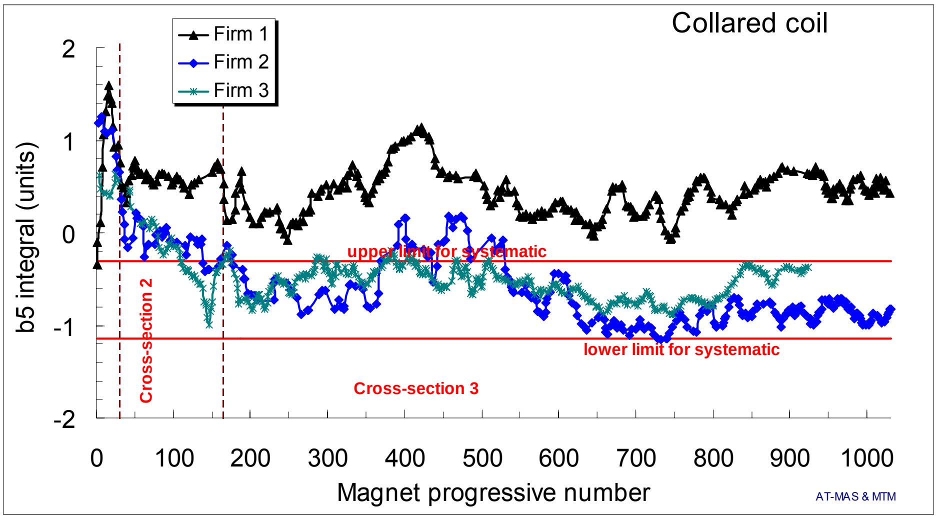

Fig. 15: Average b5 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

- Normal 14th pole b7 is stable both Firms.

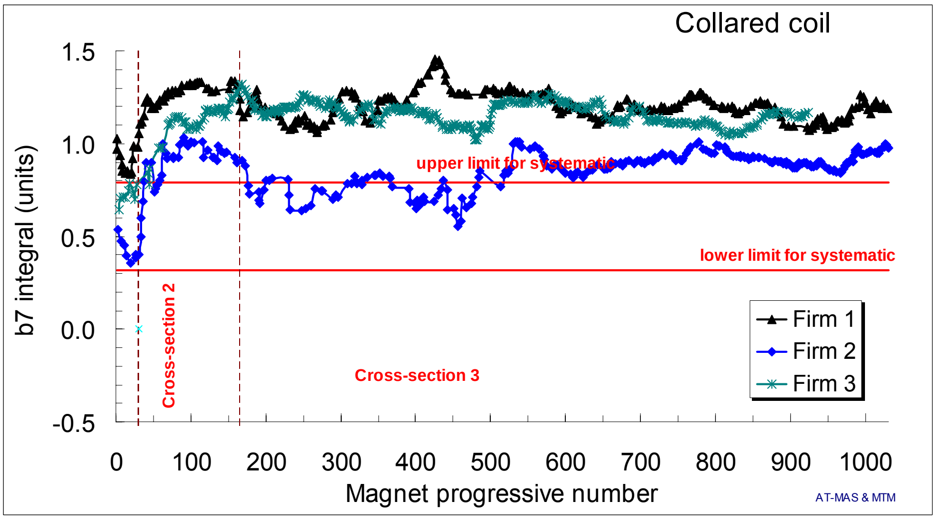

Fig. 16: Average b7 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

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 cancel each other due to the two-in-one symmetry).

3.3.1 Trends in normal quadrupole

- All measured values are within targets (see Figs. 17-19).

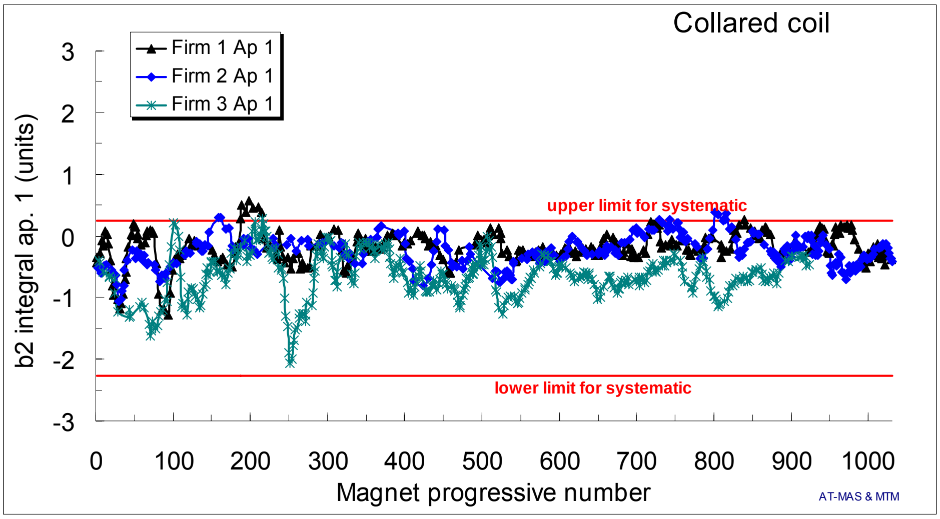

Fig. 17: Average b2 in straight part of the collared coils (aperture 1), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

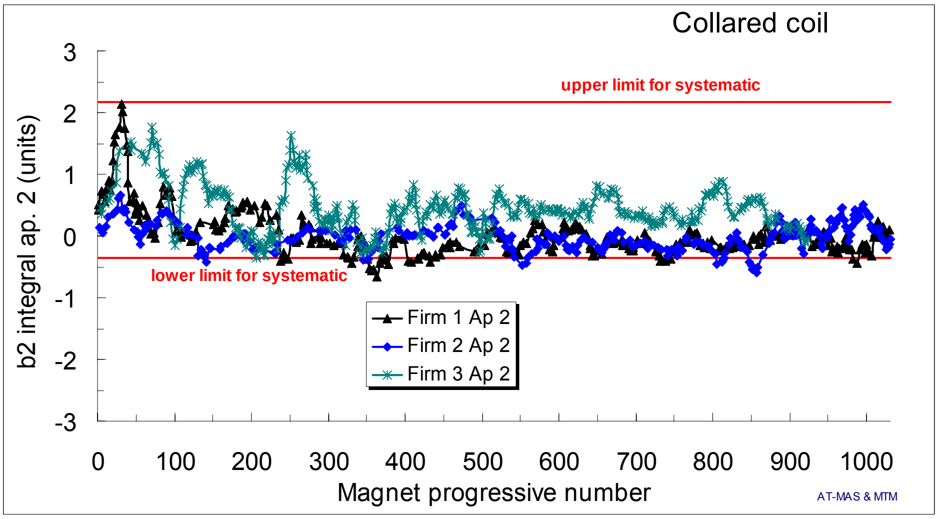

Fig. 18: Average b2 in straight part of the collared coils (aperture 2), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

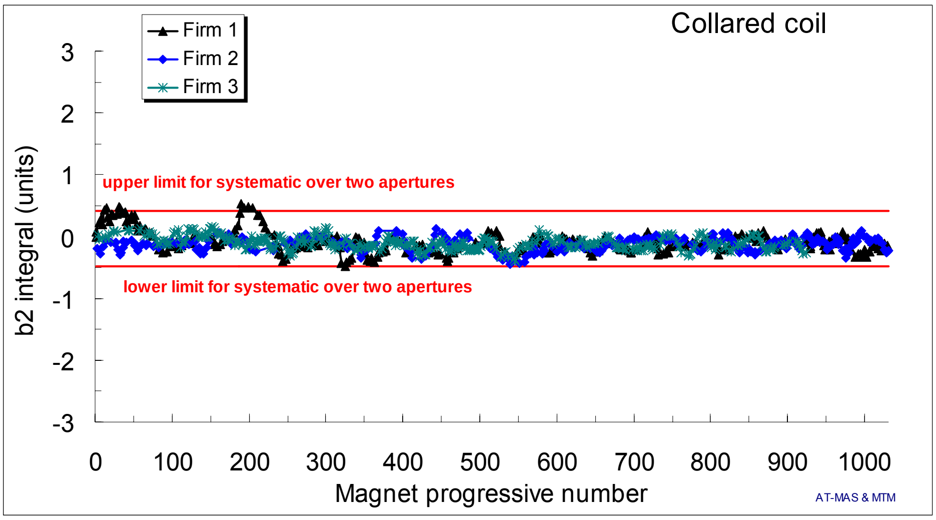

Fig. 19: Average b2 in straight part of the collared coils (average of both apertures), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

3.3.2 Trends in normal octupole

- All measured values are within targets (see Figs. 20-22).

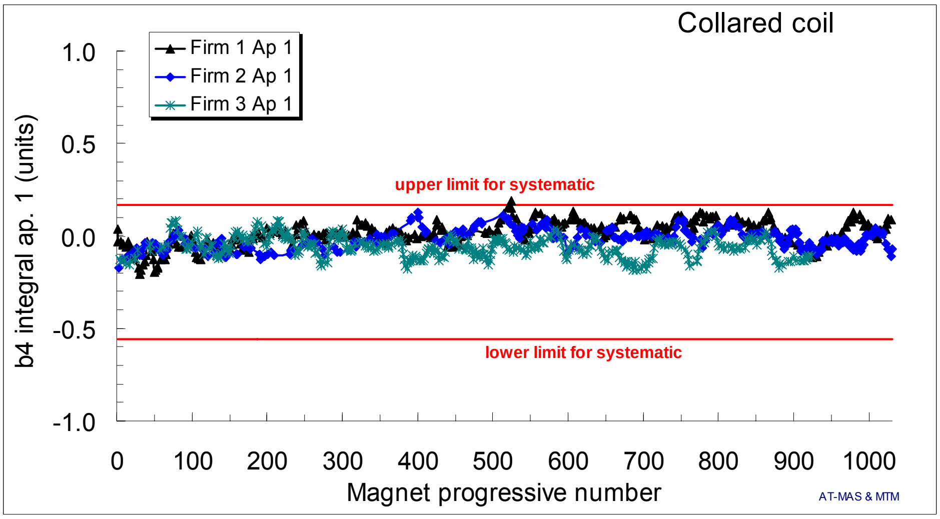

Fig. 20: Average b4 in straight part of the collared coils (aperture 1), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

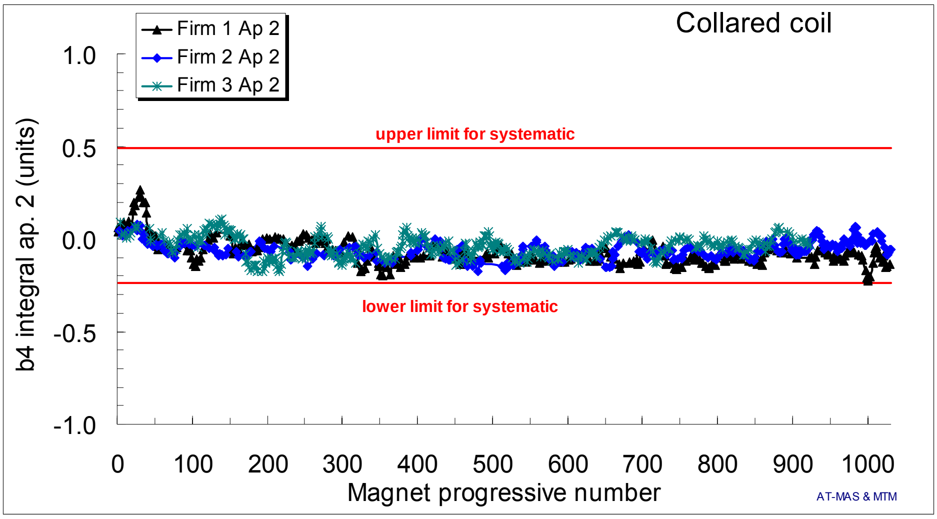

Fig. 21: Average b4 in straight part of the collared coils (aperture 2), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

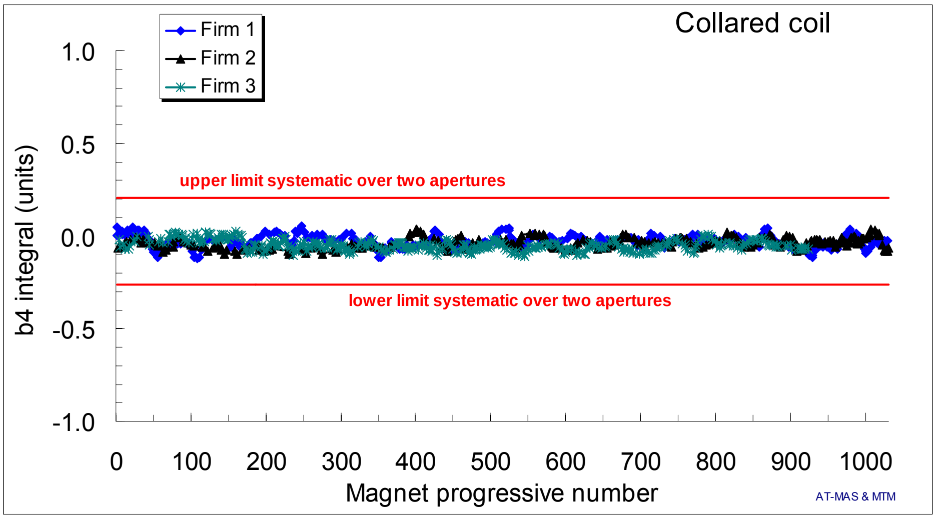

Fig. 22: Average b4 in straight part of the collared coils (average of the apertures), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

3.4 Trends in skew multipoles

- Systematic skew quadrupole and octupole a2 and a3 are within targets (see Fig. 23-24), and the production of these two months is stable.

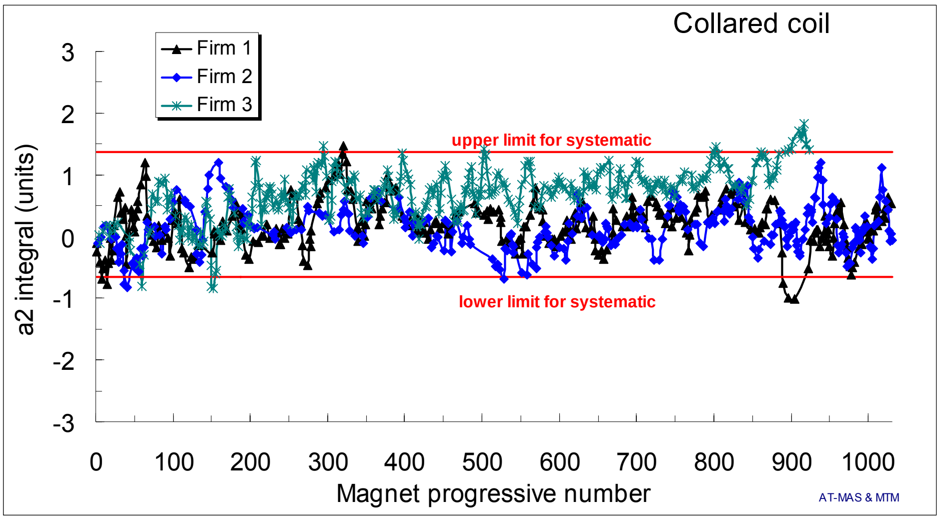

Fig. 23: Average a2 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

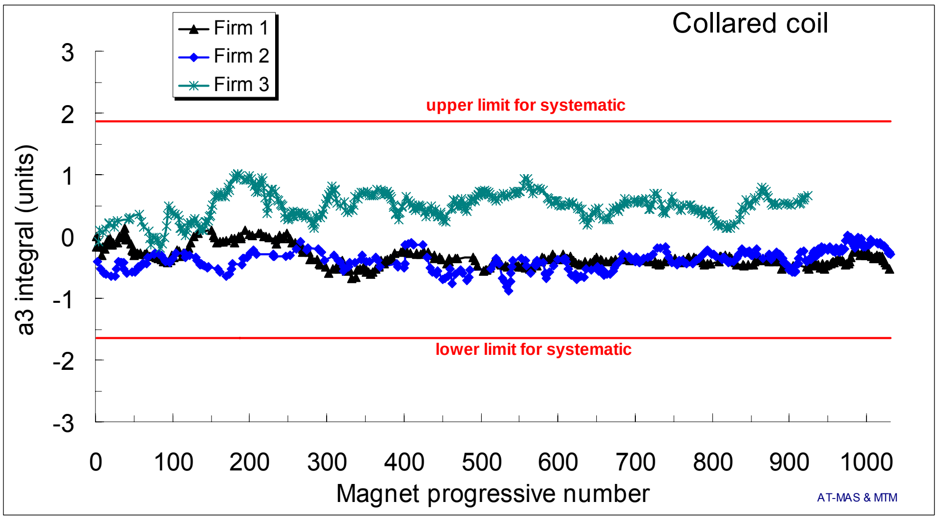

Fig. 24: Average a3 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

- Average skew octupole a4 is within the tight beam dynamics targets in Firm1.
- The strong systematic component (around 0.5 units in average) in Firm2 observed between magnet progressive number 100 and 600 is disappearing.

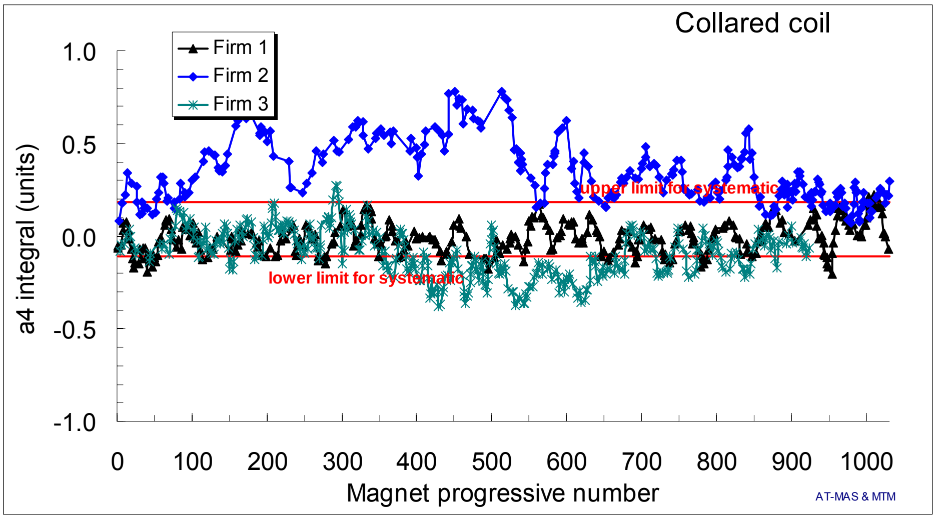

Fig. 25: Average a4 in straight part of the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 176 cryodipoles.

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 0.5 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.

We observe some 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, b_3 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 cold mass measured at room temperature. The offsets are given versus the magnet progressive number. This gives a hint on the sampling rate 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 965th, thus implying a delay of 65 collared coils with respect to the last manufactured collared coil (i.e. the 1030th), which corresponds to three 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.

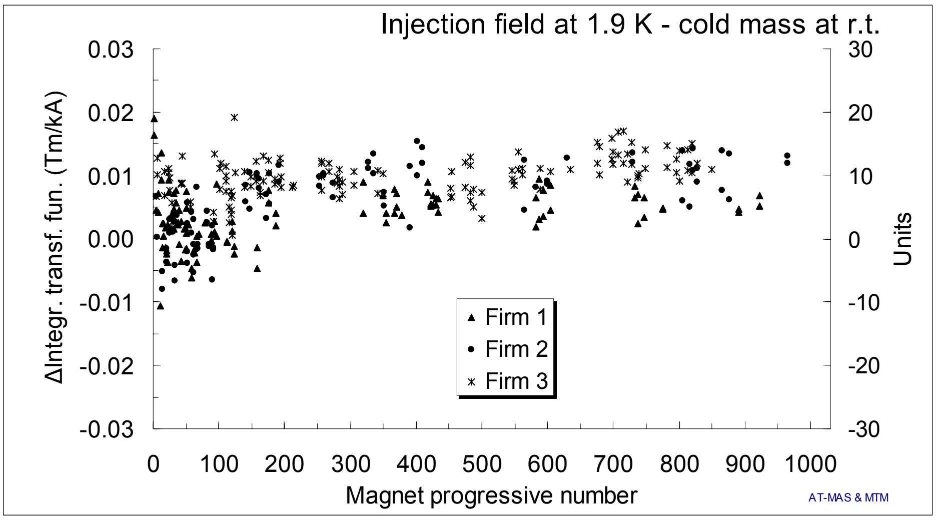

Fig. 26: Difference for the integrated transfer function between measured values at 1.9 K, injection field, and **cold mass at r.t.** along the magnet production.

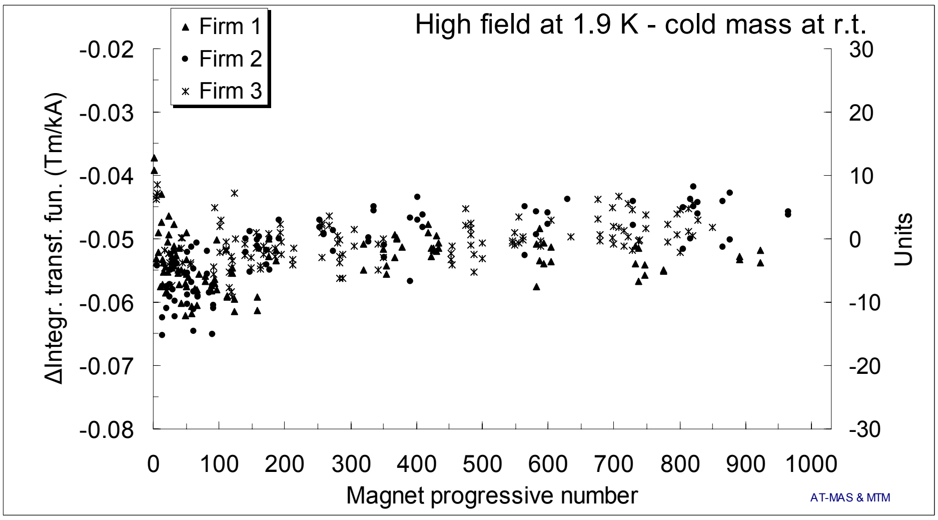

Fig. 27: Difference for the integrated transfer function between measured values at 1.9 K, high field, and **cold mass at r.t.** along the magnet production.

- 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. Offsets are stable, and are within a range of ±0.7 units at injection, and ±0.5 units at high field.

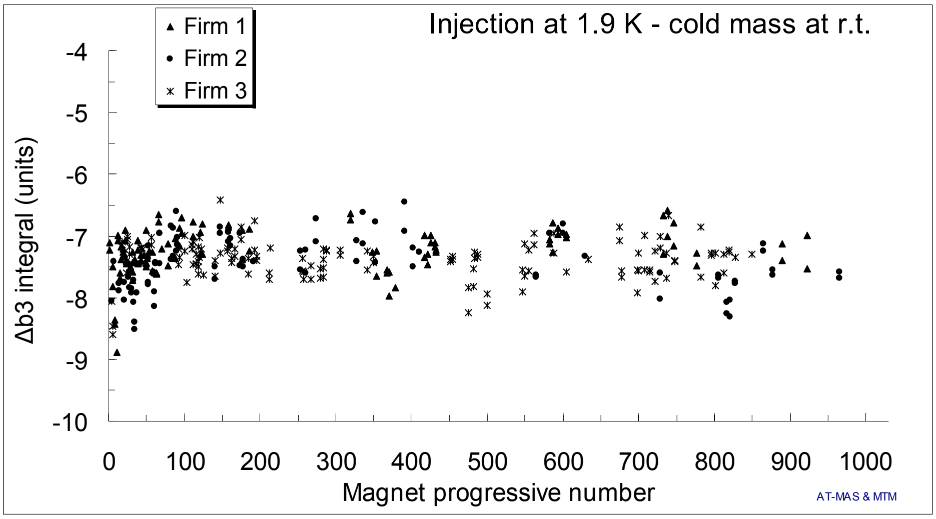

Fig. 28: Difference for the b3 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

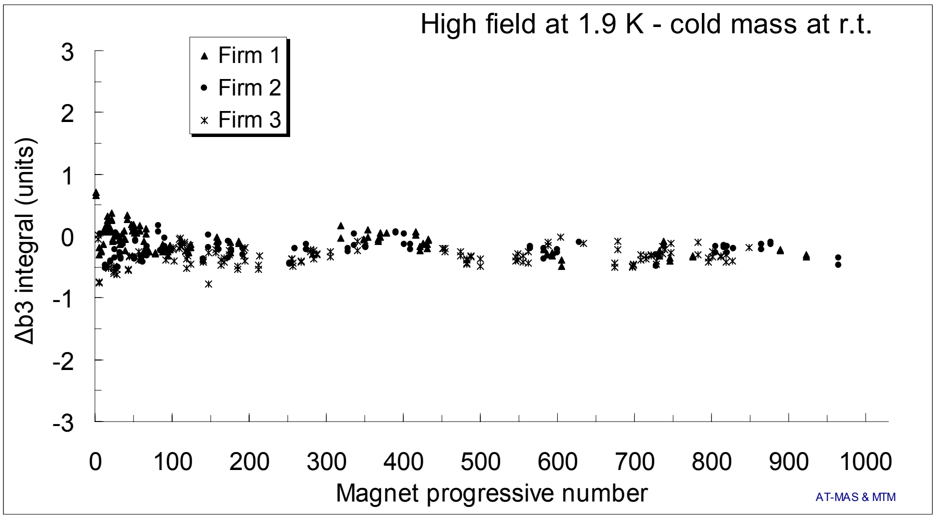

Fig. 29: Difference for the b3 between measured values at 1.9 K, high field, and **cold mass at r.t.**, along the magnet production.

- Trends for the b5 and b7 offsets between injection and cold mass are given in Fig. 30 and 31. The situation is stable in both cases.

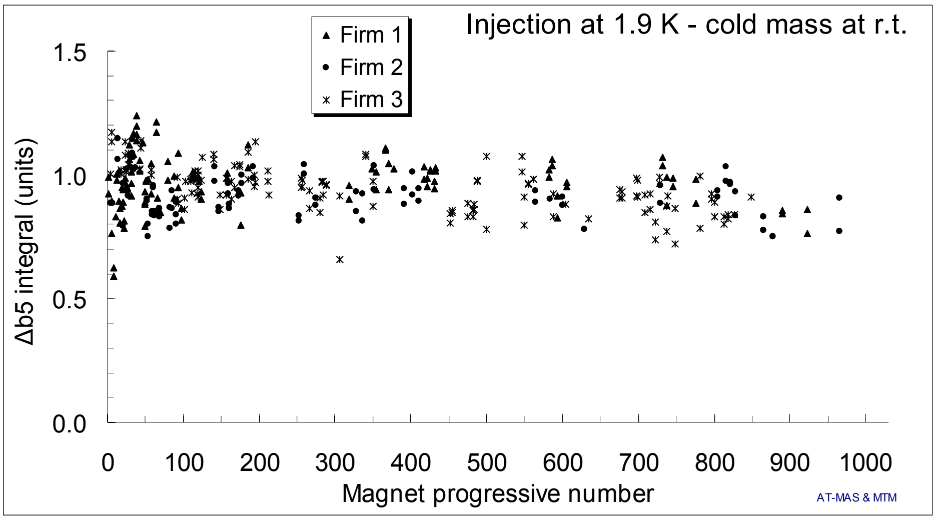

Fig. 30: Difference for the b5 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

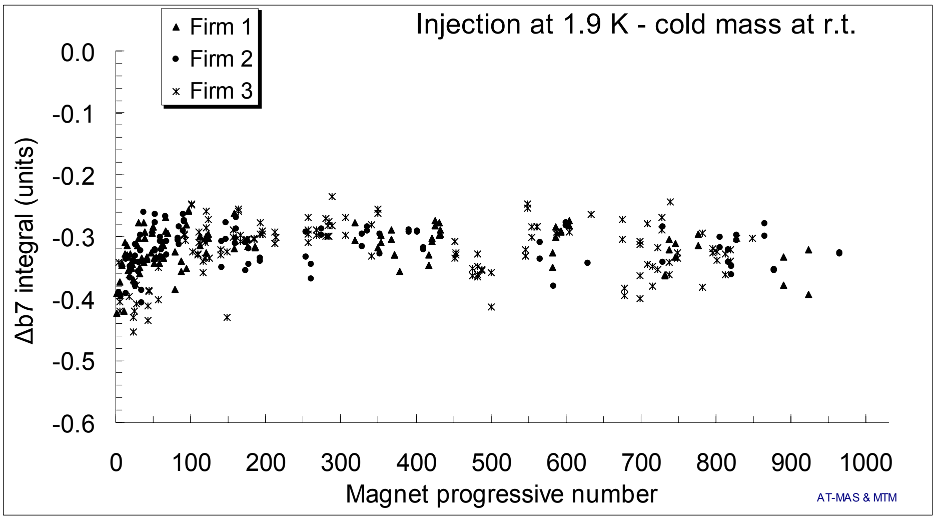

Fig. 31: Difference for the b7 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

PART IV: QUALITY CONTROL

4.1 Holding point results

Two different types of problems have been found:

- A problem with the measurement system (the data of two different positions being exactly the same), already reported in the previous report, for magnets 1274, 1303, 1304, 1305. Measurements have been repeated to get a reliable set of data. The problem has now disappeared.
- A problem with the measurement system (wrong magnetic length due to a fault in the longitudinal positioning of the mole), for magnets 1302 and 1305. Measurements have been repeated to get a reliable set of data. The problem has now disappeared.
- A suspect of block6 onward movement of 0.15 mm for 1310: a short mole measurement to have the detail of the anomaly has been required.

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 15 over 1030 collared coils, i.e. 1.5%. A large fraction of these defects (8 over 14) has been found in collared coil 300th to 400th (see Fig. 32).

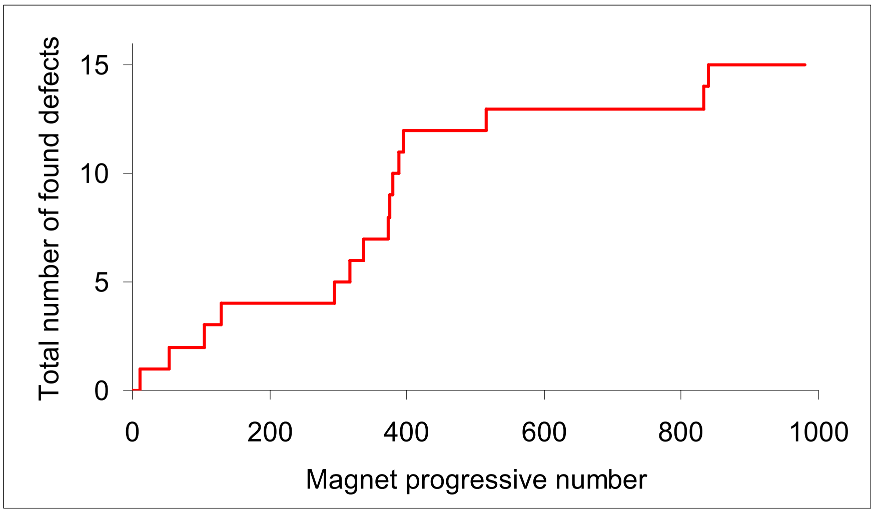

Fig. 32: Total number of defects found with room temperature magnetic measurements versus magnet progressive number.

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

Magnet	Measured on	Analysis	Opened on	Result
		Bad assembly cases		
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
3254	06-Sep-2004	Inward movement of block5 and 6	14-Sep-2004	Folded outer shim
		Faulty components		
Magnet	Measured on	Analysis	Opened on	Result
1251	12-May-2005	Strong field anomalies in high order	08-Jun-2005	Cold bore with high magn. permeability
1253	20-May-2005	Strong field anomalies in high order	-	Cold bore with high magn. permeability
		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.

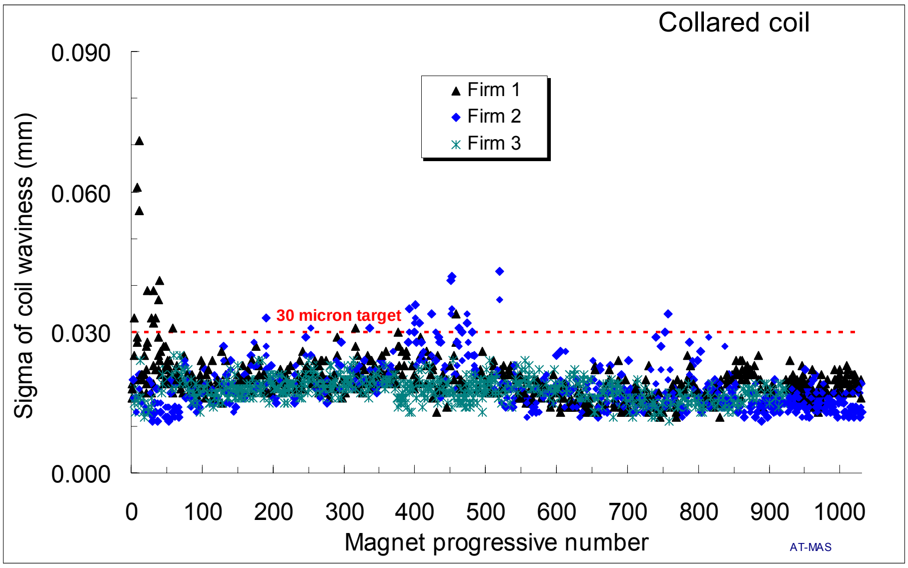

Fig. 33: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

Acknowledgements

We wish to acknowledge all colleagues involved in the measurements at room temperature and at 1.9 K, and the Firm personnel involved in magnetic measurements. We thank P. Hagen, and C. Vollinger for data validation and analysis, and C. Vollinger for carefully reading the manuscript and valuable suggestions. We finally acknowledge the project engineers and MTM-AS for discussions and support in the analysis.