Report on field quality in the main LHC dipoles
May-June 2006

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This report gives data relative to field quality measured in collared coils and cold masses during the period May 1 – June 30 2006, 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. **753956**

The dashboard

- Available measurements:
  - 1183 collared coils and 1150 cold masses at room temperature,
  - 189 equivalent dipoles at 1.9 K[1].
- In these two months we had:
  - 52 new collared coils (24 from Firm1, 28 from Firm2) measured at room temperature,
  - 7 dipoles measured at 1.9 K[1].

What's new (not much)

- **Production rate** is at 26 collared coils per month. The rate is 2.8 and 3.2 collared coils per week in Firm1, Firm2, respectively.
- **Firm1** is close to the end of the production (10 more collared coils to be assembled).
- **Measurement of transfer function in Firm1:** The calibration problem in Firm1 has been solved.
- **b3 spread:** Average b3 in Firm1 is still around 2.5-3 units larger than in Firm2. Nevertheless, the spread in the last two months is still within target. No corrective action has been taken, after discussion with AB-ABP.

[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

- 52 new collared coils have been measured (collared coils 1132nd to 1183rd).

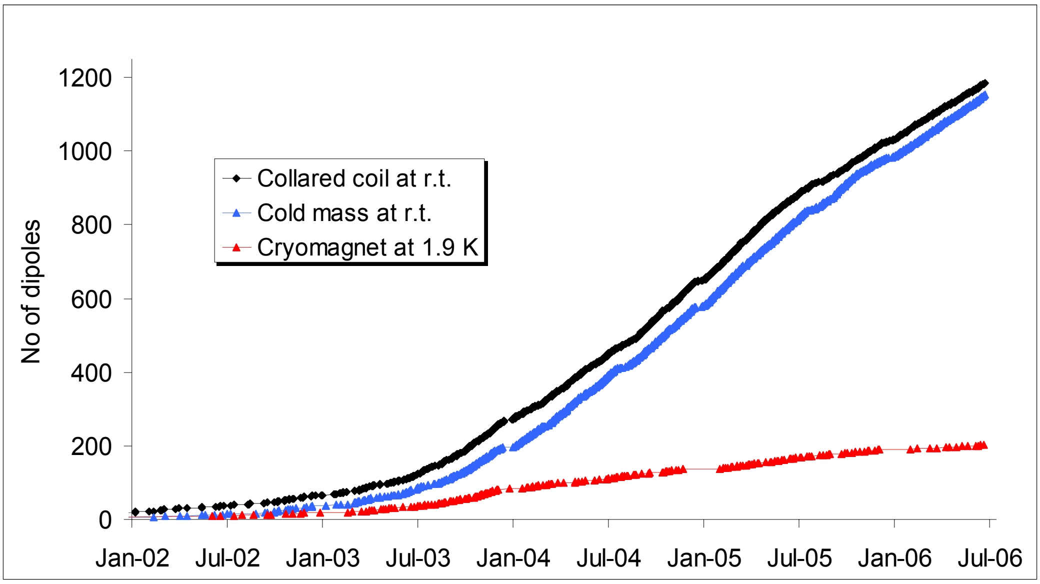

Fig. 1: Number of magnets measured at CERN at 1.9 K and at the manufacturers at room temperature at different stages of assembly procedure.

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

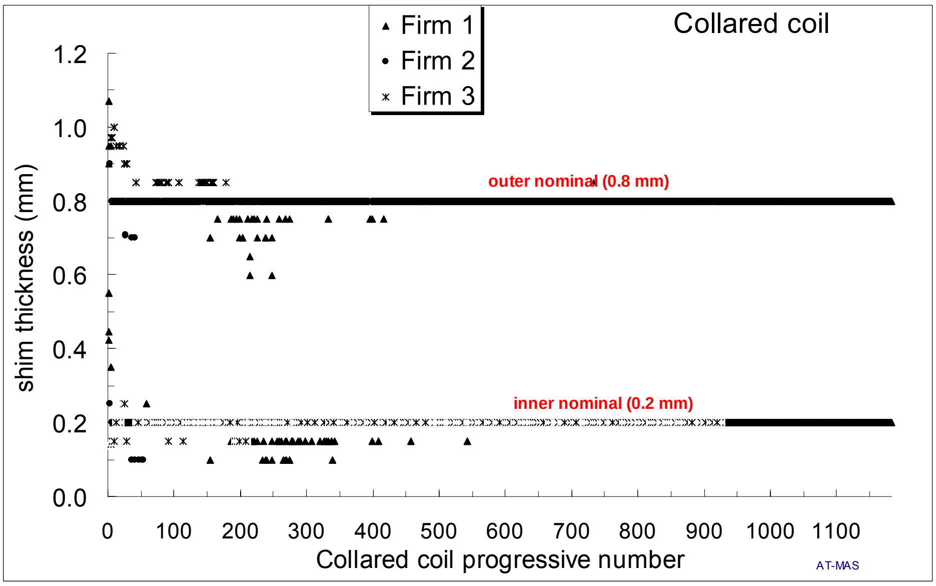

Fig. 2: Thickness of the polar shims used in the collared coils.

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.

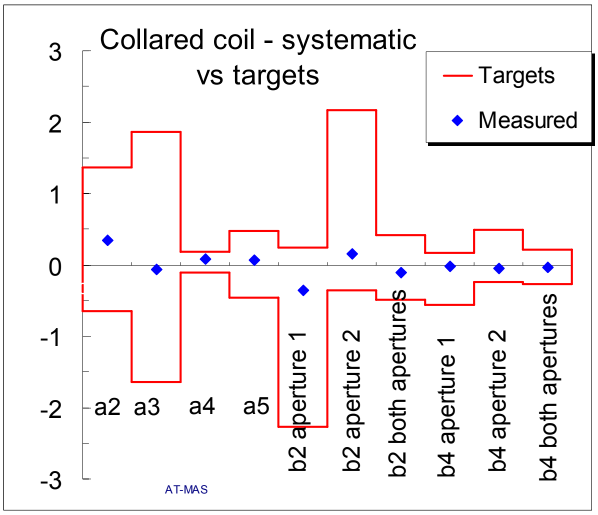

Fig. 3: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (solid red line).

- 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, giving 2.6 units at high field. b_5 is larger than the upper target of 0.08 units, corresponding to 1.17 units at injection, and b_7 is 0.28 units larger than target, corresponding at 0.34 units at injection.
- 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, 1001 have cross-section 3, plus one hybrid 1-2). With cross-section 3, b_3 in the collared coil is 0.80 units below the upper limit, and also b_5 is within targets, just below the upper limit. Finally, b_7 in the collared coil is 0.29 units larger than the limits.

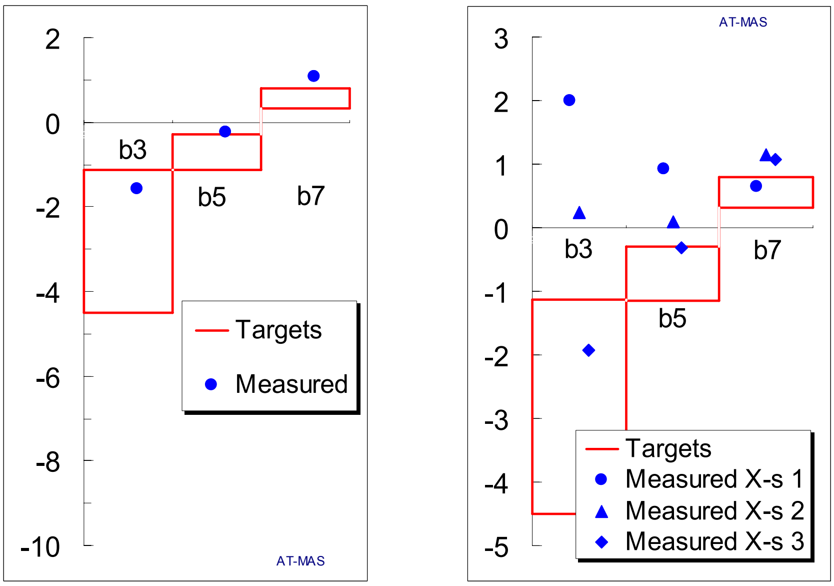

Fig. 4: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (solid red line). Raw data (left) and data separated according to different cross-sections (right).

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 (1001 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.

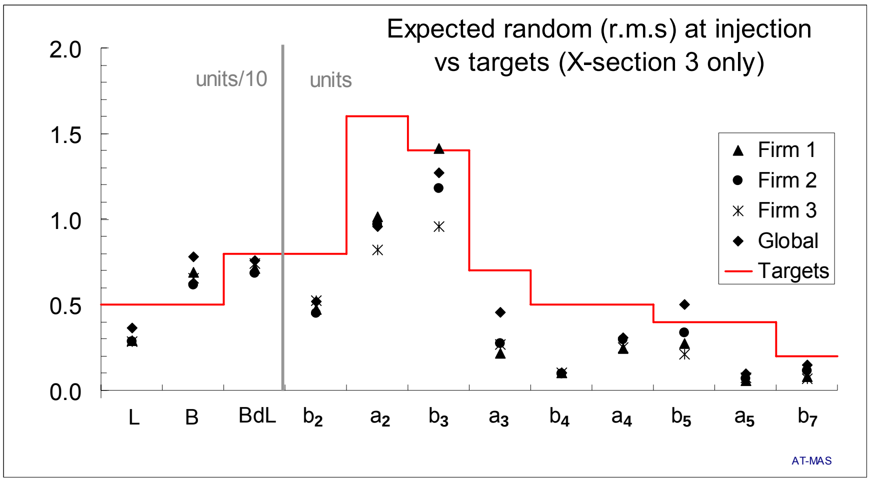

Fig. 5: Expected random component at 1.9 K (cross-section 3 only) compared to targets for random at 1.9 K.

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.

In Fig. 6 the expected random components for each sector 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 1-2 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. The impact of the recent trends in b3 is visible in Sectors 1-2 and 3-4, where its spread is at the target value.

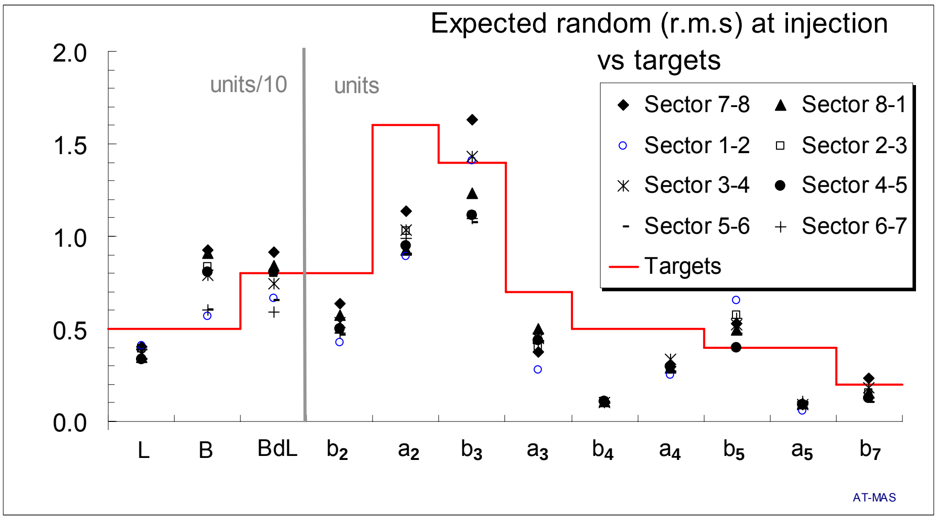

Fig. 6: Expected random component at 1.9 K (markers) compared to targets (solid line), separated according to the provisional allocation to 6 sectors.

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.

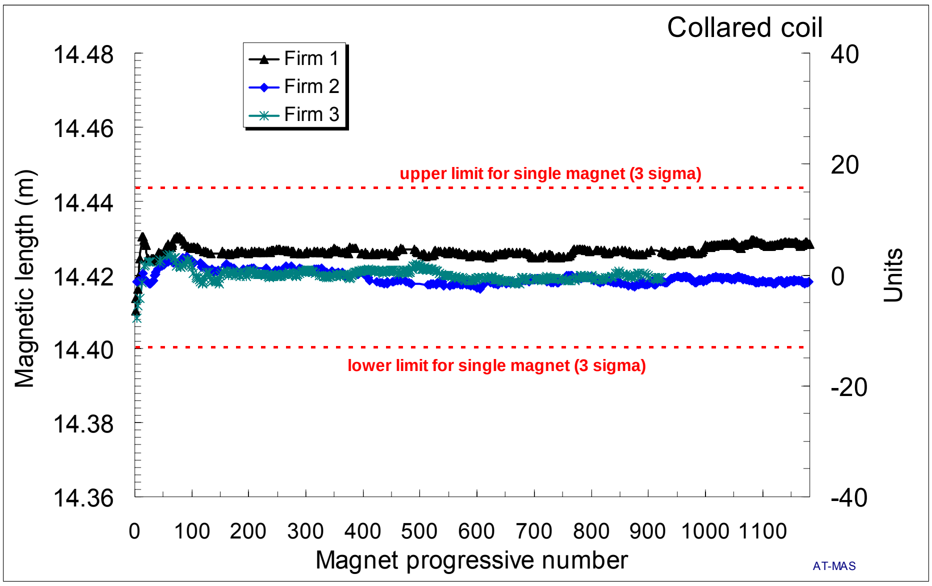

Fig. 7: Magnetic length of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- 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.

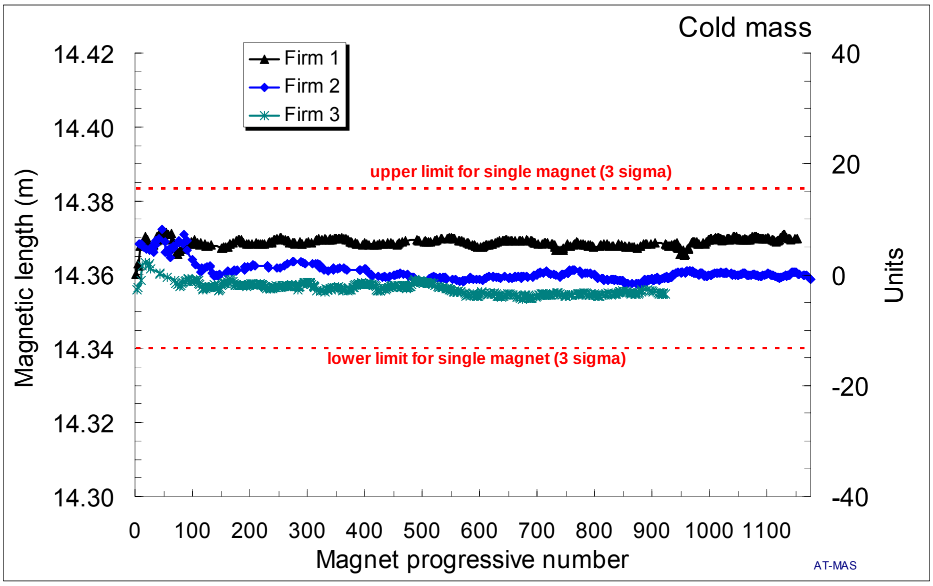

Fig. 8: Magnetic length of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.1.2 Trends in transfer function

- Transfer function in collared coils 1032nd to 1183rd is stable in Firm1, and has a negative trend in Firm2.

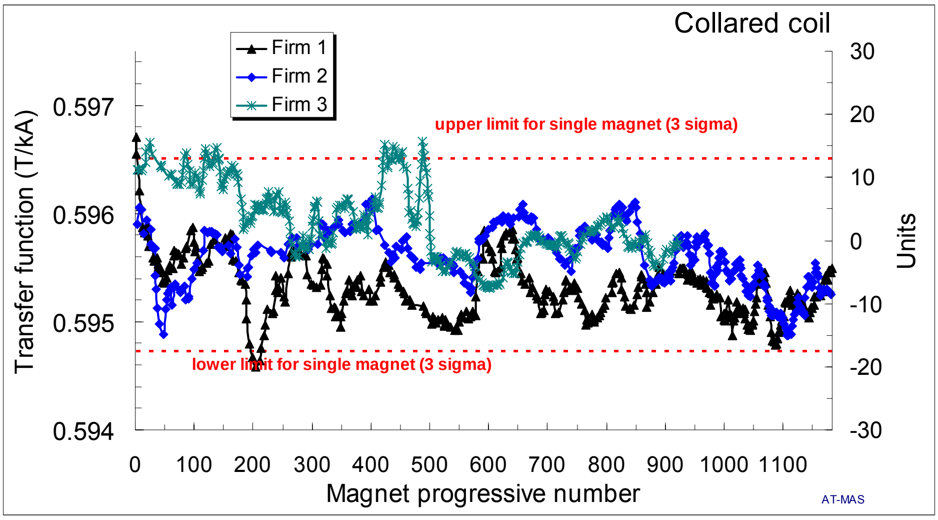

Fig. 9: Transfer function of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- 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). Consistency between collared coil and cold mass data has been confirmed, after a calibration of the moles in Firm1.

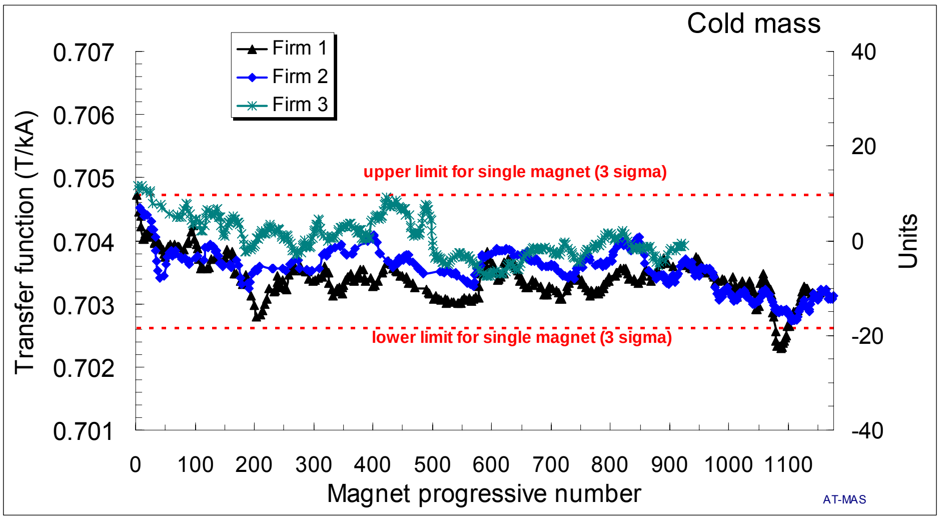

Fig. 10: Transfer function of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.1.3 Trends in integrated transfer function

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

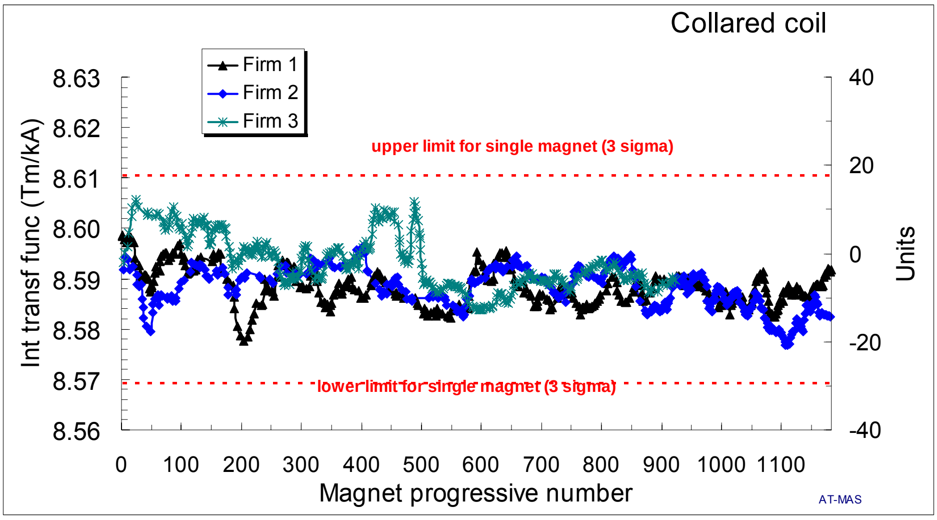

Fig. 11: Integrated transfer function of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- In the **cold masses** (see Fig. 12), recent values show a systematic difference of about 10 units between Firm1 and Firm2.

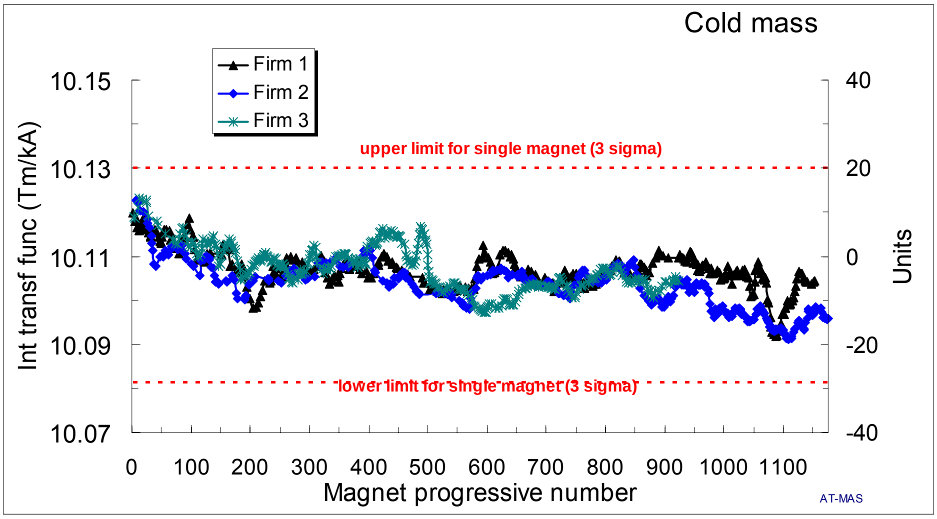

Fig. 12: Integrated transfer function of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.2 Trends in odd normal multipoles

- Average b3 in Firm2 in the collared coils is within targets. The recent positive trend in Firm1 has been confirmed by more recent data. Since a few months, average b3 in Firm1 is around 0.5 units, i.e. 2.5 units more than in Firm2. This brings the standard deviation of the b3 in the last six months (Firm1 and Firm2 together) to 1.62 units in collared coils and 1.37 units in cold masses. This is larger than what obtained in the last year (0.9 units for all cold masses in 2005), but still within the target of 1.4 units (for cold masses). The systematic b3 is not affected by these trends, and is well within targets. The trend is not associated to variations of b5 and b7, see next page.

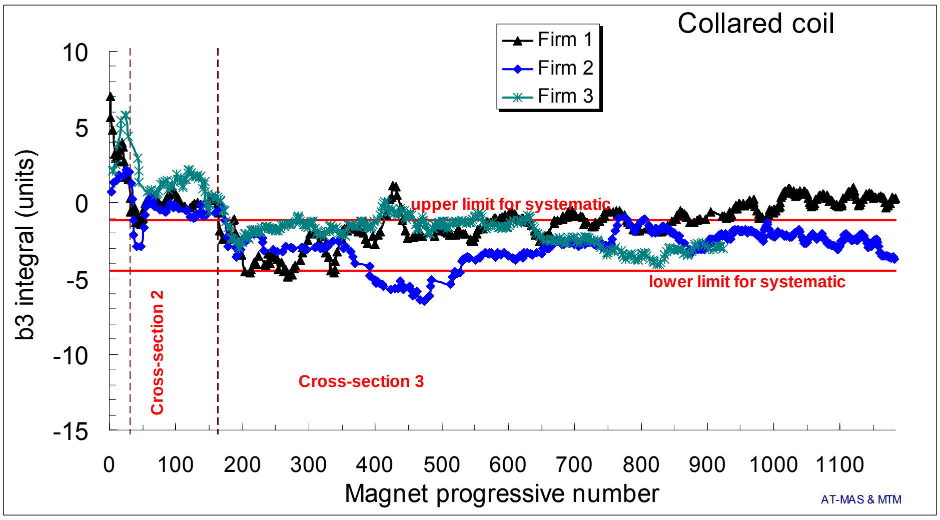

Fig. 13: Integral b3 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

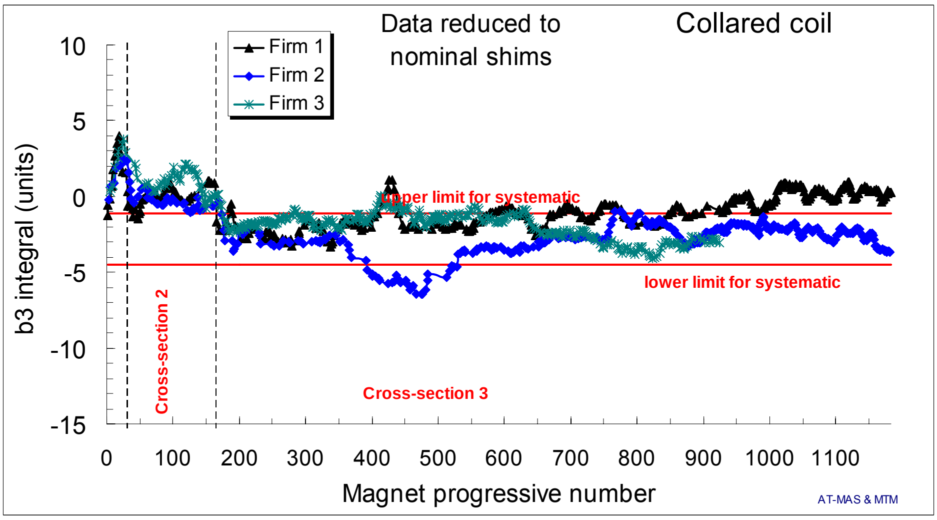

Fig. 14: Integral b3 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles. Data normalised to nominal shims[3].

[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.

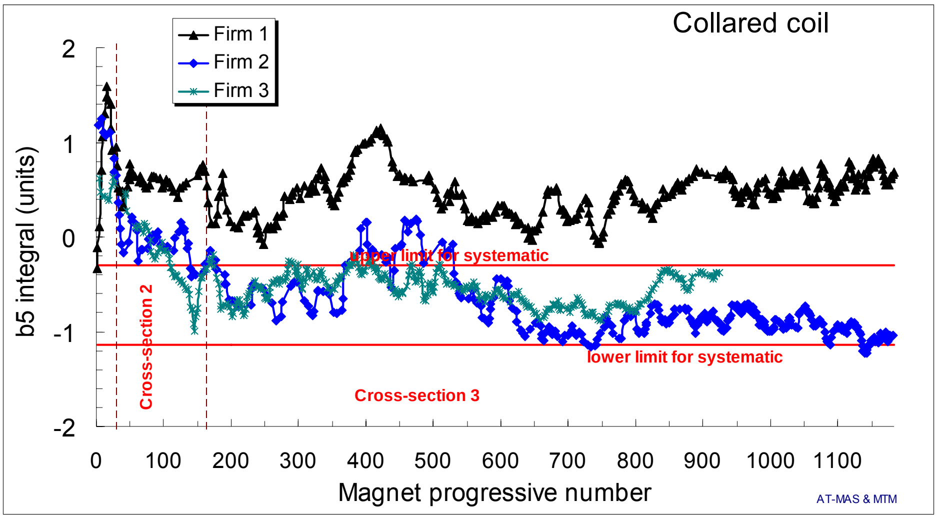

Fig. 15: Integral b5 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

- Normal 14th pole b7 is stable in both Firms.

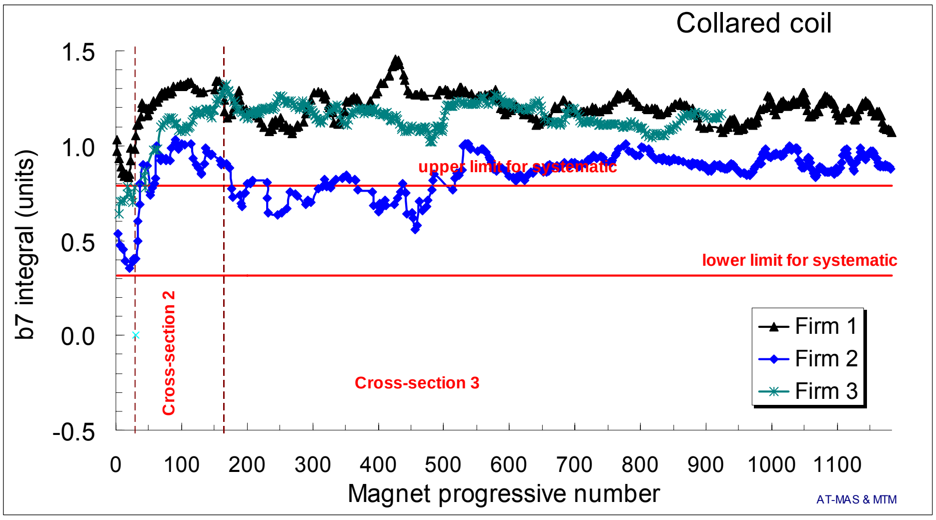

Fig. 16: Integral b7 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

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).

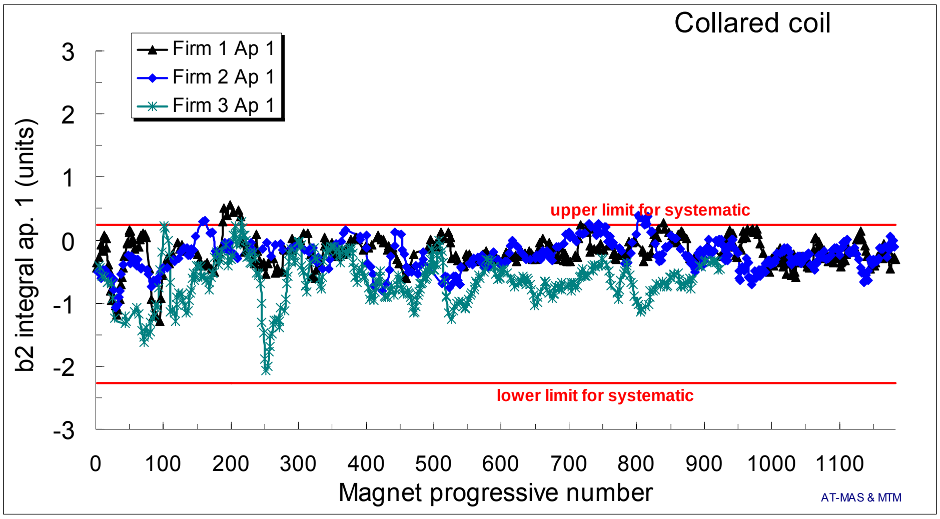

Fig. 17: Integral b2 in the collared coils (aperture 1), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

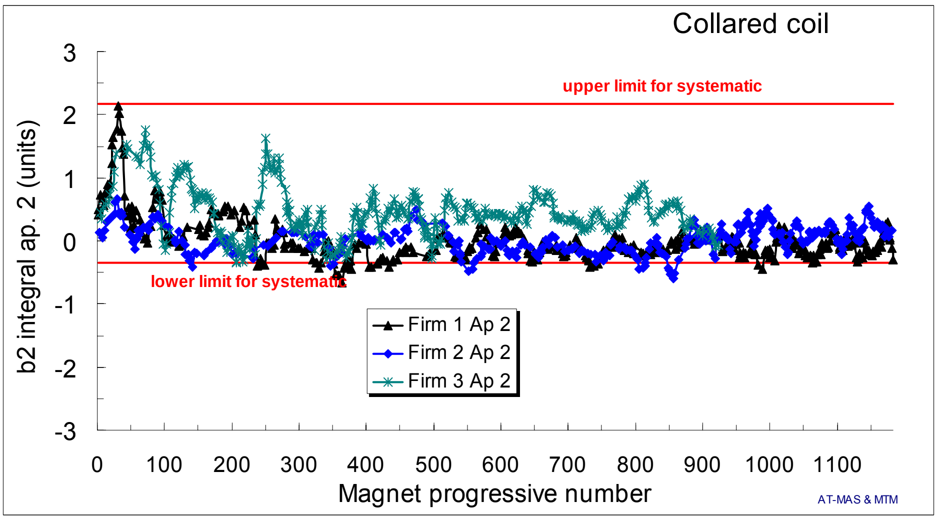

Fig. 18: Integral b2 in the collared coils (aperture 2), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

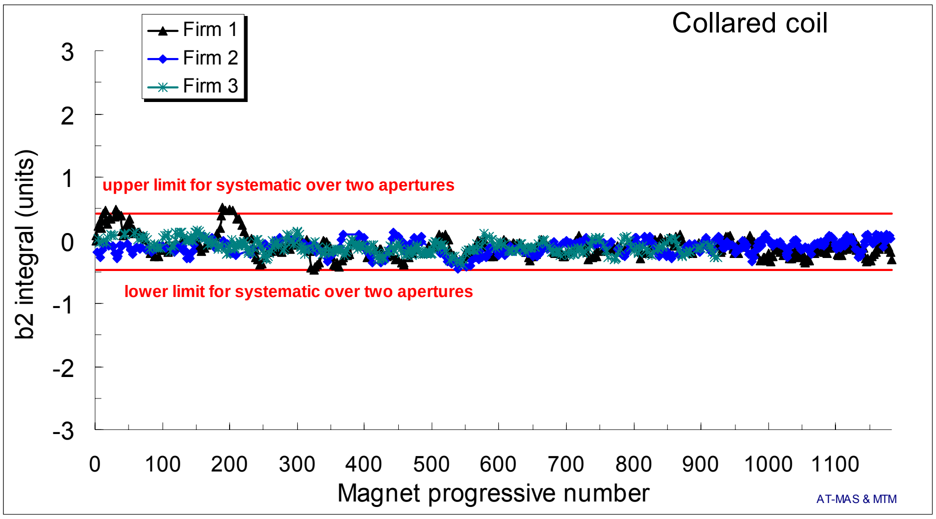

Fig. 19: Integral b2 in the collared coils (average of both apertures), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

3.3.2 Trends in normal octupole

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

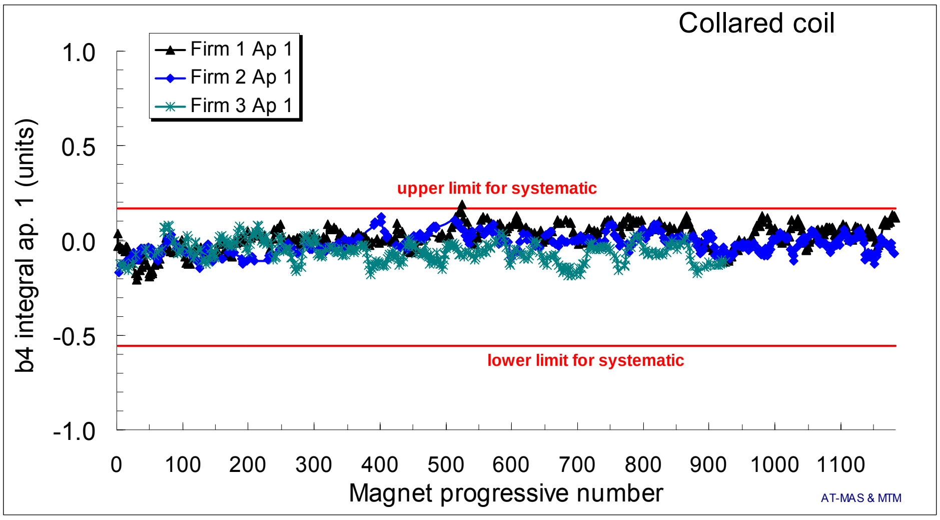

Fig. 20: Integral b4 in the collared coils (aperture 1), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

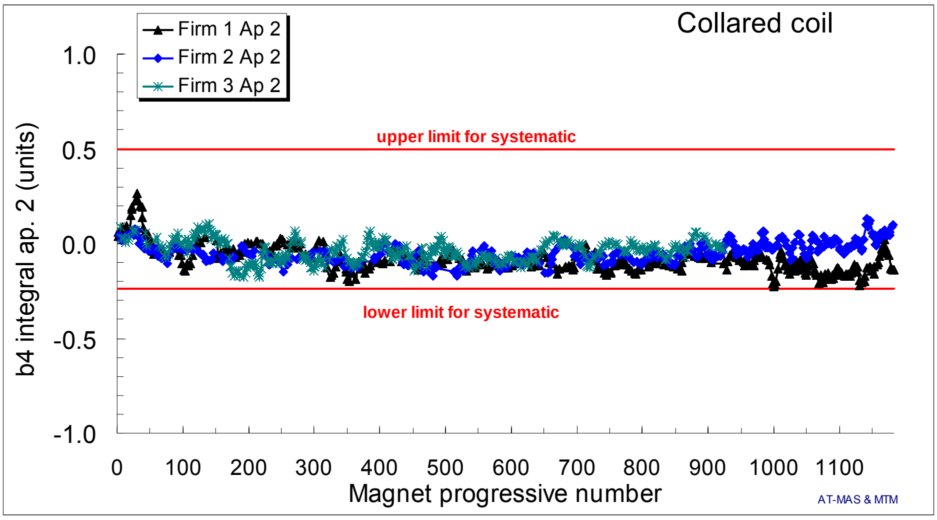

Fig. 21: Integral b4 in the collared coils (aperture 2), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

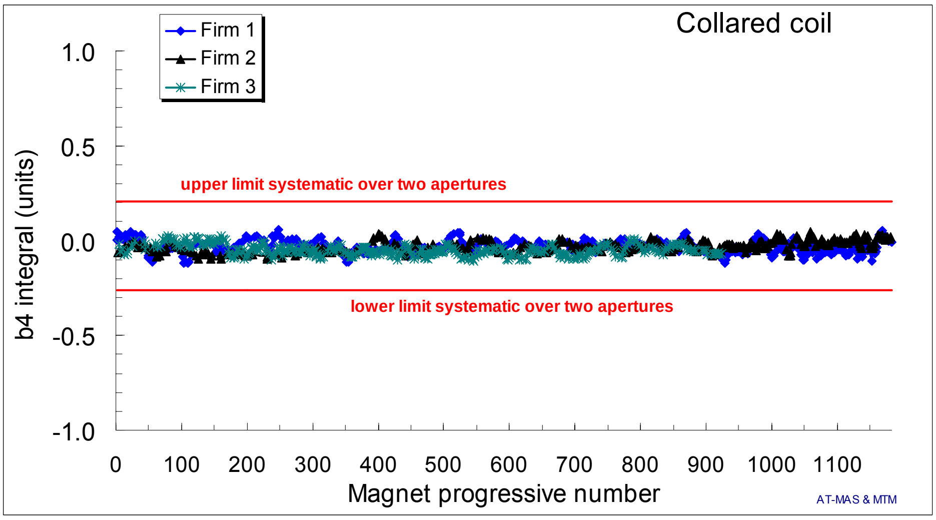

Fig. 22: Integral b4 in the collared coils (average of the apertures), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

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.

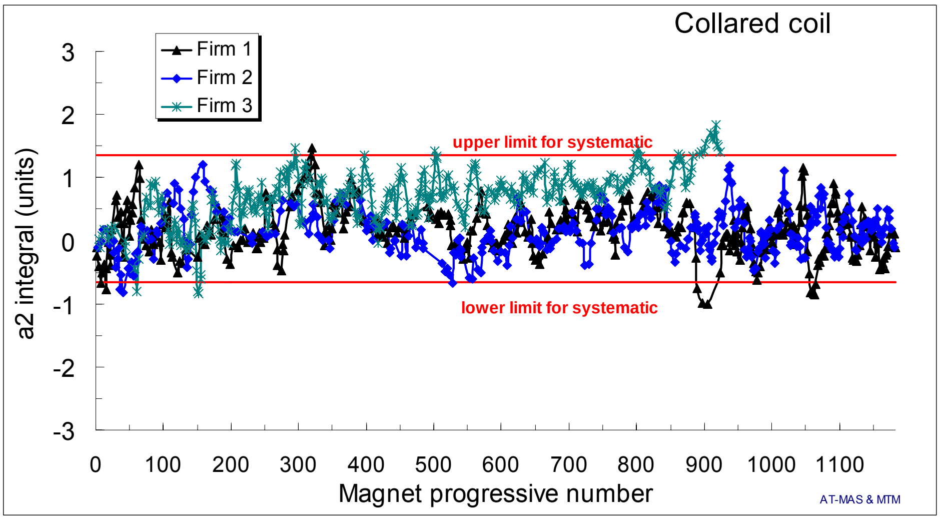

Fig. 23: Integral a2 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

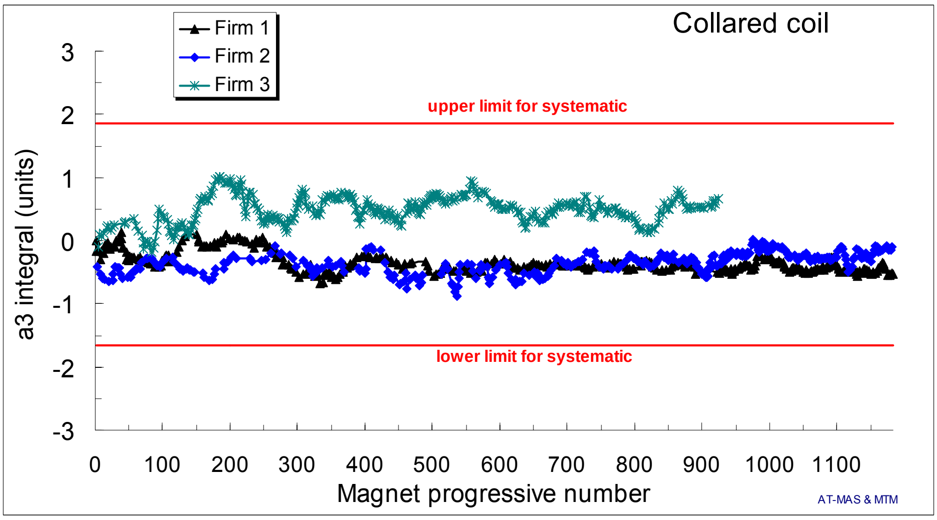

Fig. 24: Integral a3 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

- 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, has disappeared.

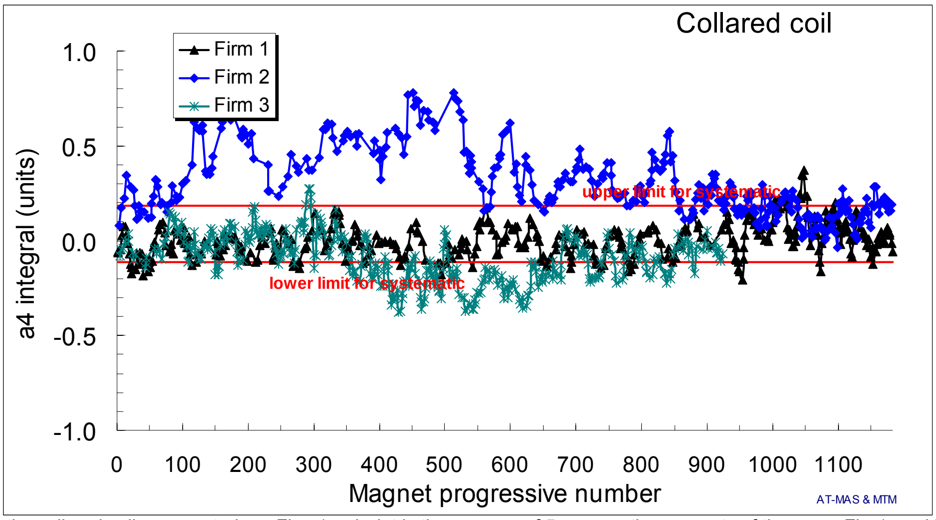

Fig. 25: Integral a4 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 183 cryodipoles.

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 0.3 units, against -0.09 and 0.01 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.. Recent data show a b_3 difference of about 3 units between Firm1 and Firm2.

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 1046th, thus implying a delay of 136 collared coils with respect to the last manufactured collared coil (i.e. the 1182nd), which corresponds to five months of production at present rates.

- 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.

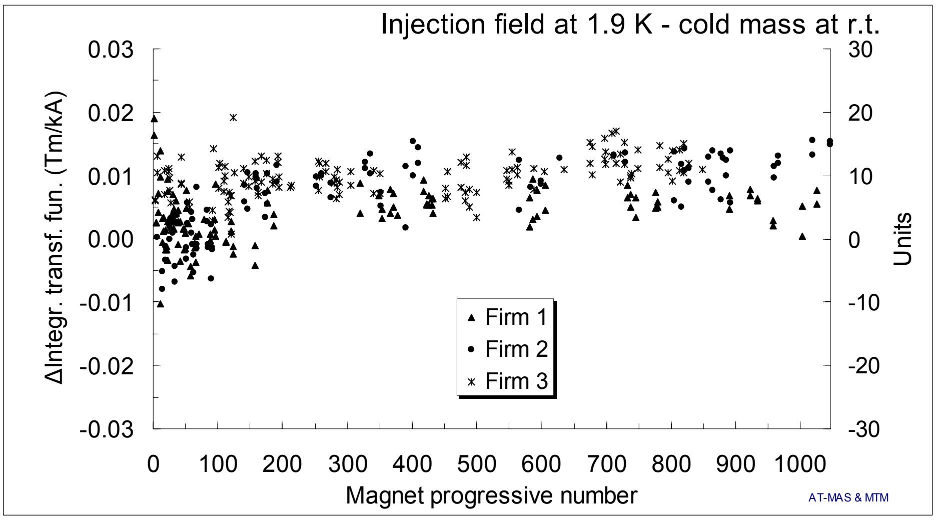

Fig. 26: Difference for the integrated transfer function between measured values at 1.9 K, injection field, and **cold mass at r.t.** along the magnet production.

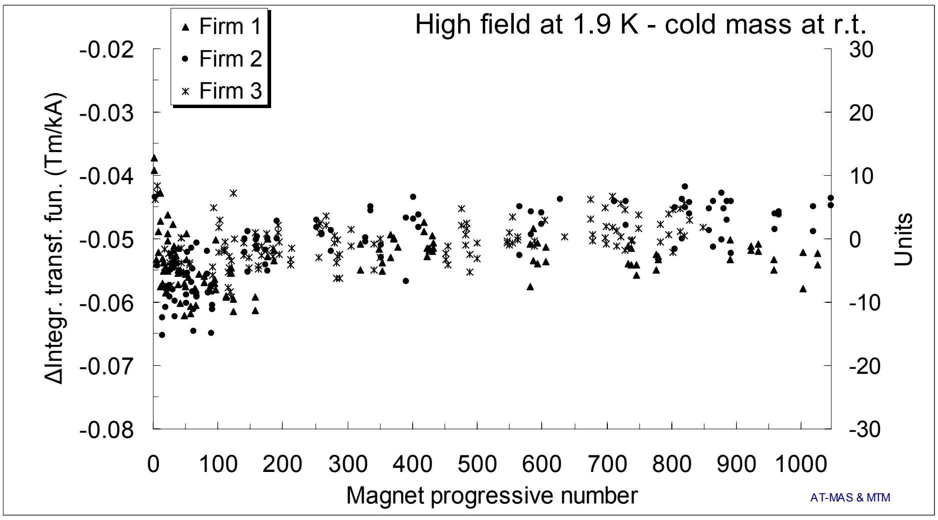

Fig. 27: Difference for the integrated transfer function between measured values at 1.9 K, high field, and **cold mass at r.t.** along the magnet production.

- 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.

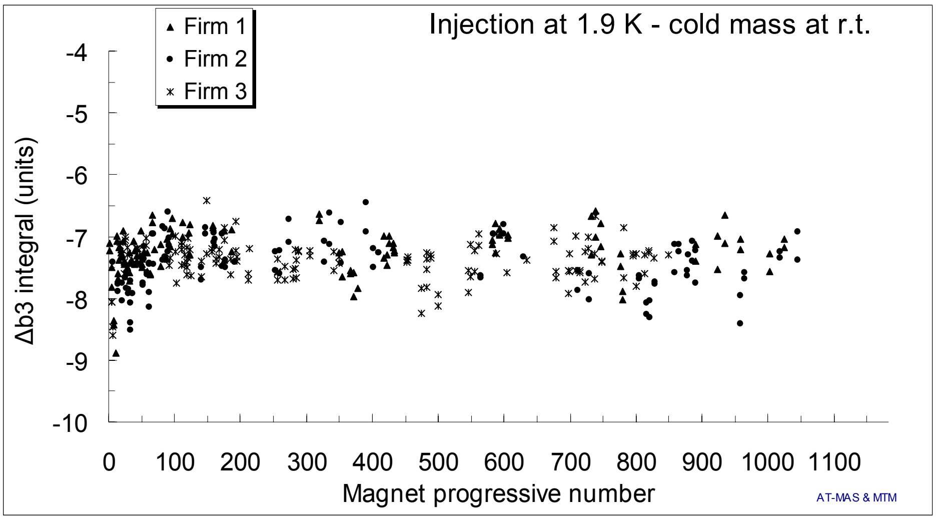

Fig. 28: Difference for the b3 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

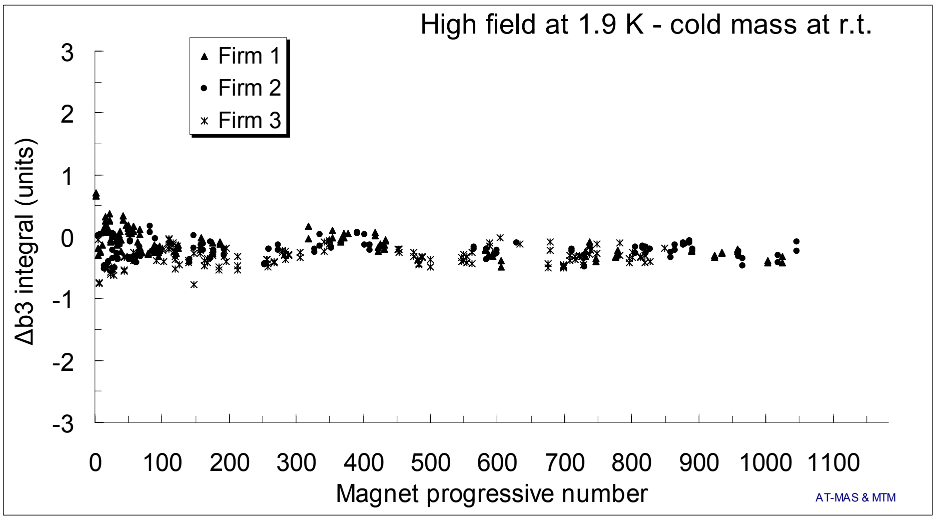

Fig. 29: Difference for the b3 between measured values at 1.9 K, high field, and **cold mass at r.t.**, along the magnet production.

- 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.

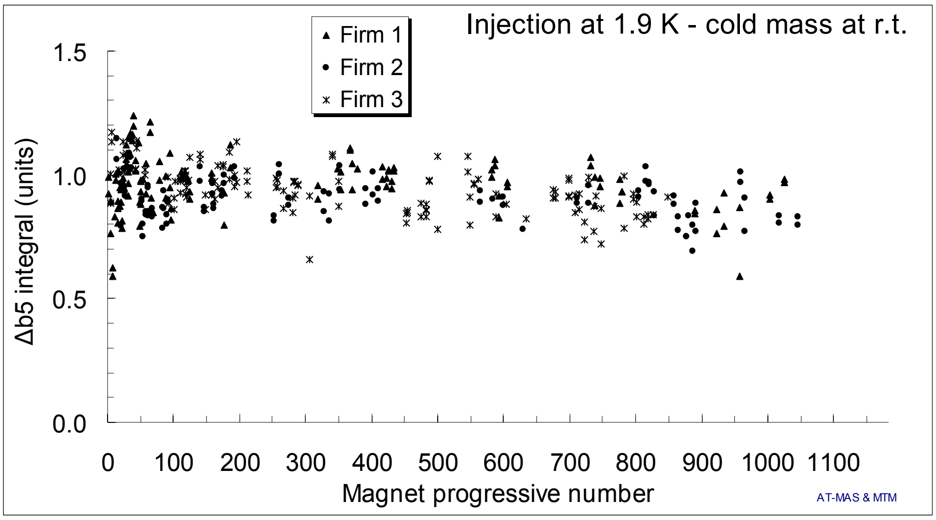

Fig. 30: Difference for the b5 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

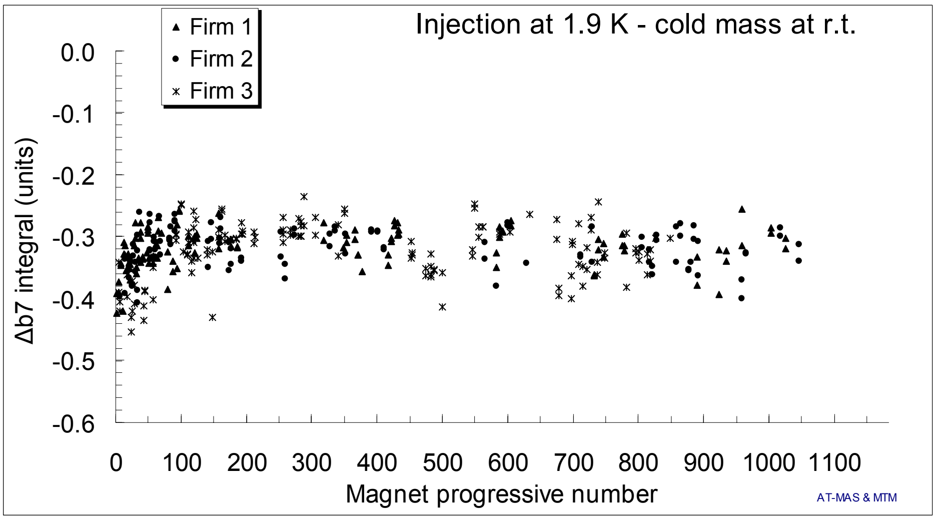

Fig. 31: Difference for the b7 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

PART IV: QUALITY CONTROL

4.1 Holding point results

Some field anomalies have been detected in the recent production of Firm1: two cases of large variations of b2 along the axis (1366 and 1405), one case of b4 and b6 variations (1371), indicating a small block6 movement, and one case with anomalies in skew multipoles in several positions along the axis (1373). In the first cases, the pattern of the signal suggested that the anomaly is related to the outer layer (no impact on high multipoles); since only a few multipoles are affected, it becomes difficult to identify the quadrant and the direction of the possible coil displacement. The project engineer opted for de-collaring the worst case (1366), which showed several small irregularities in the conductor positions of the outer layer, but no clear defect. The other collared coils have been released. Ten more coils will be produced in Firm1 before the end of the production.

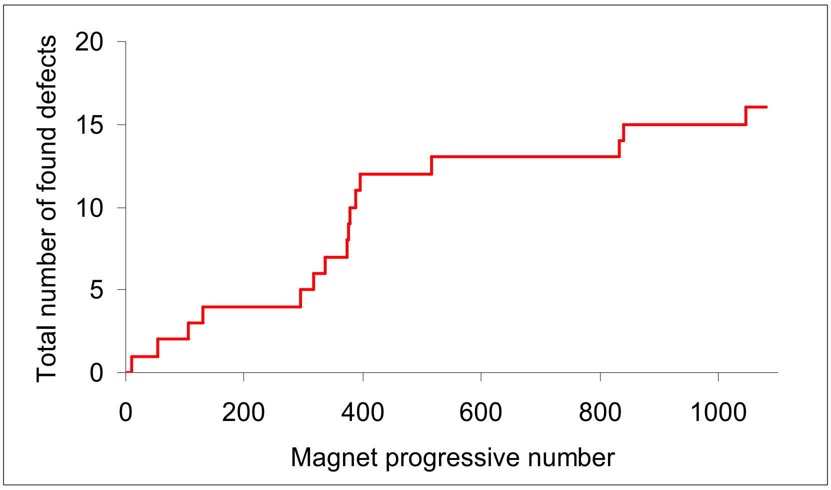

Fig. 32: Total number of defects found with room temperature magnetic measurements versus magnet progressive number.

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

Magnet	Measured on	Analysis	Opened on	Result
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
2303	20-Jan-2006	Inward movement of block6	10-Feb-2006	Good glue, 1.2 mm 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.

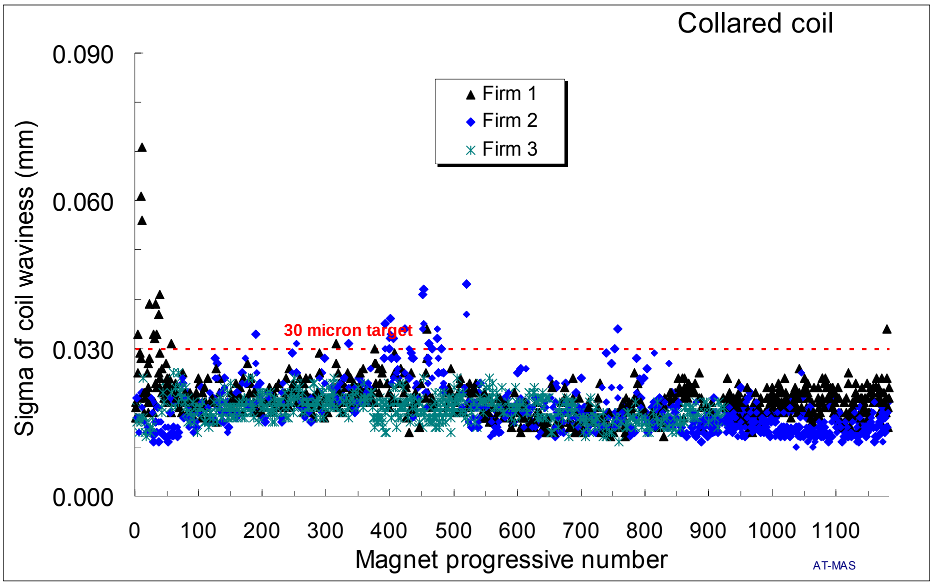

Fig. 33: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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