Report on field quality in the main LHC dipoles September-October 2006

E. Todesco, AT-MAS-MA

This report gives data relative to field quality measured in collared coils and cold masses during the period September 1 – October 31 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. **807803**

The dashboard

- Available measurements:
  - 1248 collared coils and 1236 cold masses at room temperature,
  - 198.5 equivalent dipoles at 1.9 K[1].
- In these two months we had:
  - 34 new collared coils (7 from Firm1, 27 from Firm2) measured at room temperature,
  - 6.5 dipoles measured at 1.9 K[1].

What's new

- **The production of 1248 dipoles in Firm1, 2 and 3 has been completed.** This corresponds to the pre-series and series contracts of 416 magnets per Firm, providing 1232 dipoles for installation plus 16 spares. 30 additional spares are being assembled by Firm2.
- **Production rate** at Firm2 is at 13.5 collared coils per month.
- **No trends are observed.**
- **An assembly error has been found in 2421:** a strong anomaly in room temperature magnetic measurements has suggested an assembly error in 2421. The decollaring has revealed that a wrong copper wedge has been used over all the magnet length (see pg. 19).

A brief summary of the dipole production (September 2000-October 2006)

- **Summary of field quality**
  - Systematic values: average b3 is at 2.6 units at collision energy, i.e. within the target range of [-3,+3] units. Average b5 is at the target upper limit at injection energy (1.1 units). Average b7 is at 0.34 units at injection energy, i.e. 0.24 units larger than the target of [-0.3, 0.1] units. See pg. 4 for more details. All other systematic multipoles are within targets (see Fig. 3).
  - Random values: spread of the integrated transfer function in each sector is within the 8 units target. The spread of all multipoles is within targets in all sectors, except b3 for sector 7-8 (due to the cross-section change), and b5 in all sectors (random part of 0.5 to 0.7 units versus a target of 0.45 units).
- **Summary of quality control through room temperature magnetic measurements:** 17 cases of wrong assembly have been found through the analysis of magnetic measurements:
  - 5 missing, folded, wrong, or double pieces
  - 2 faulty components
  - 8 cases of bad coil curing
  - 2 cases of bad positioning of cables

  19 electric shorts have been localized through magnetic measurements.

[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 by the same Firm
    - the two collared coils produced afterwards by the same Firm
  - 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

- 34 new collared coils have been measured (collared coils 1215th to 1248th).

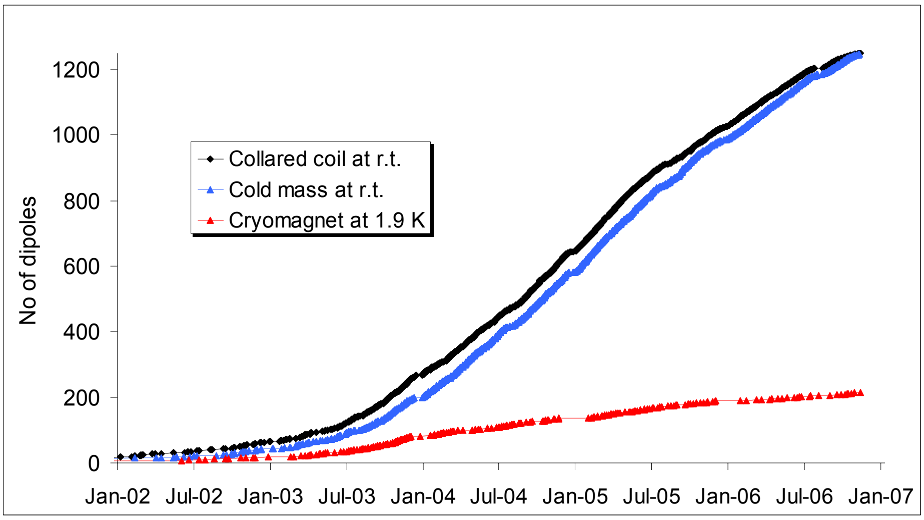

Fig. 1: Number of magnets measured at CERN at 1.9 K and at the manufacturers at room temperature at different stages of assembly procedure.

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

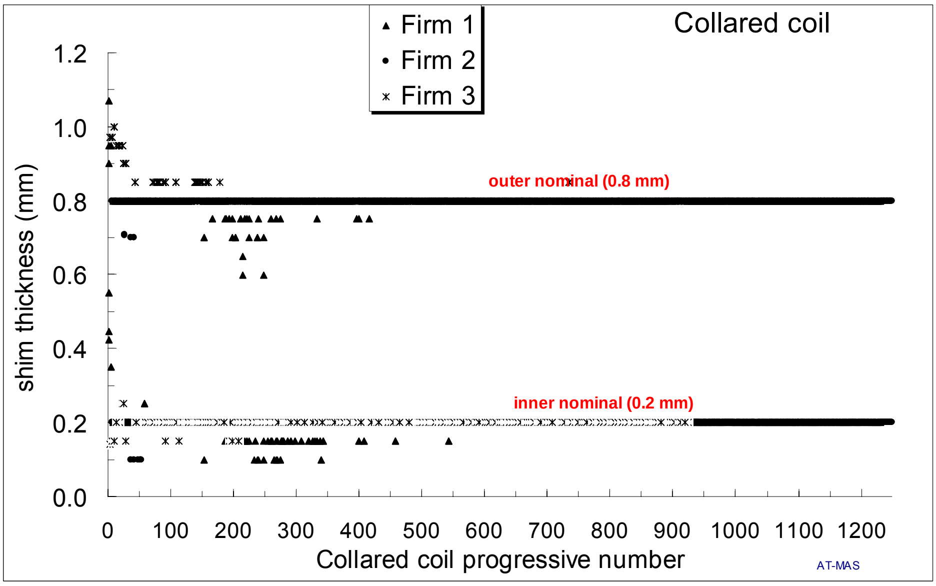

Fig. 2: Thickness of the polar shims used in the collared coils.

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.

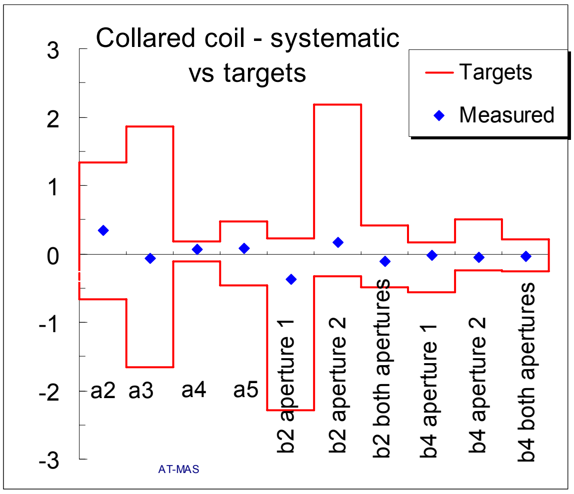

Fig. 3: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (solid red line).

- Best estimates for systematic odd normal multipoles are shown in Fig. 4. In the left part, raw data are plotted. This gives the final situation for global values relative to all manufactured collared coils: b_3 is within target, giving 2.6 units at collision energy. b_5 is larger than the upper target of 0.07 units, corresponding to 1.16 units at injection energy, 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, 1066 have cross-section 3, plus one hybrid 1-2).

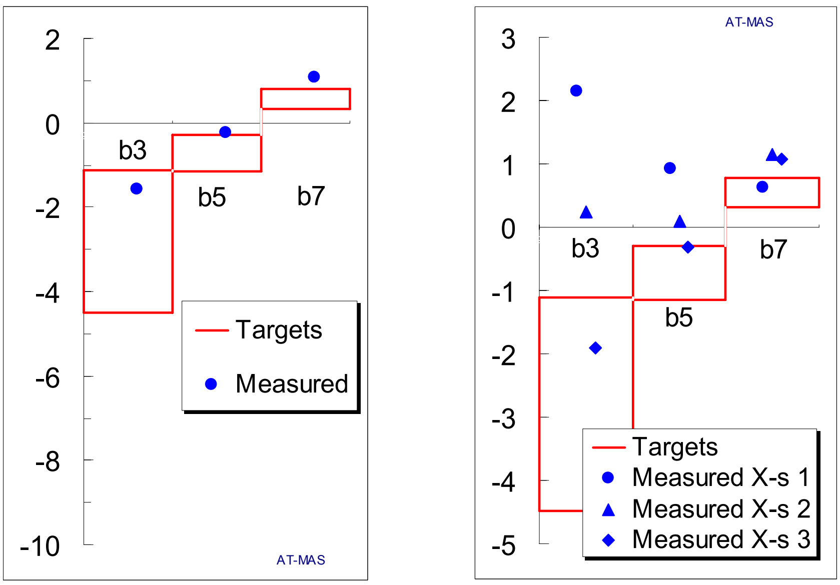

Fig. 4: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (solid red line). Raw data (left) and data separated according to different cross-sections (right).

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 (1066 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 b5 when all firms are mixed (marker “Global” in Fig. 5).

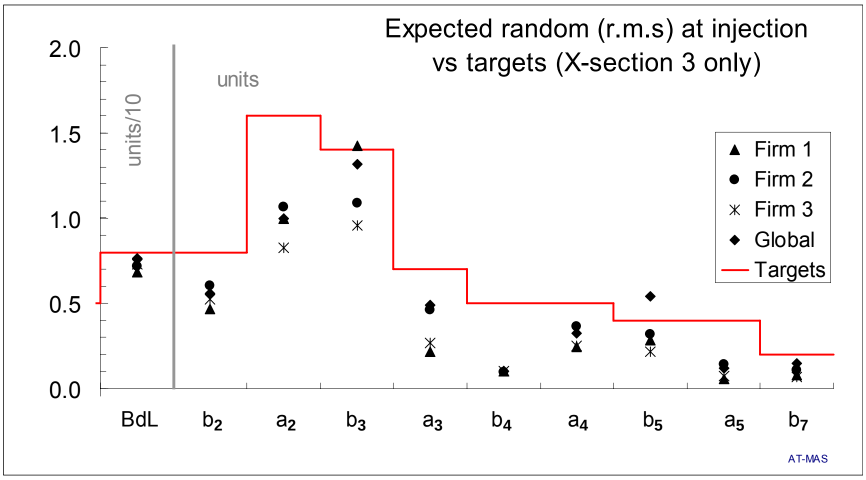

Fig. 5: Expected random component at 1.9 K (cross-section 3 only) compared to targets for random at 1.9 K.

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[3], 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 the random part of b5, which is 0.5 to 0.65 units, versus a target of 0.45 units; this large value, which is not considered as critical for the beam, is due to large differences in the systematic between firms (see Fig. 15).

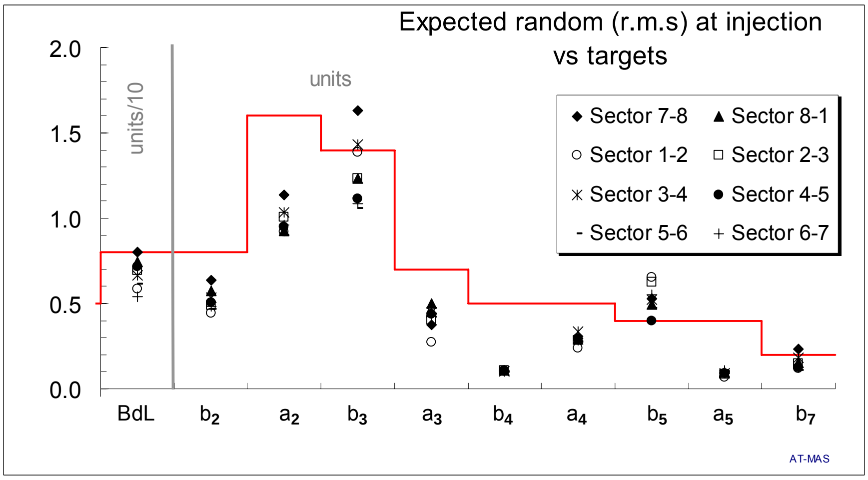

Fig. 6: Expected random component at 1.9 K (markers) compared to targets (solid line), separated according to the provisional allocation to 6 sectors.

[3] Please note that BdL r.m.s. values given in previous reports were erroneously ~15% higher.

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.

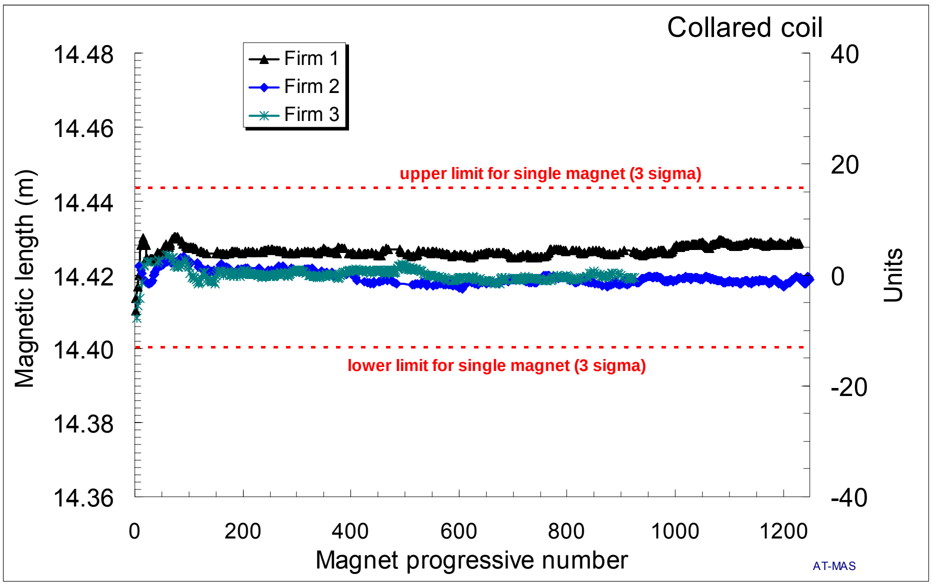

Fig. 7: Magnetic length of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- 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.

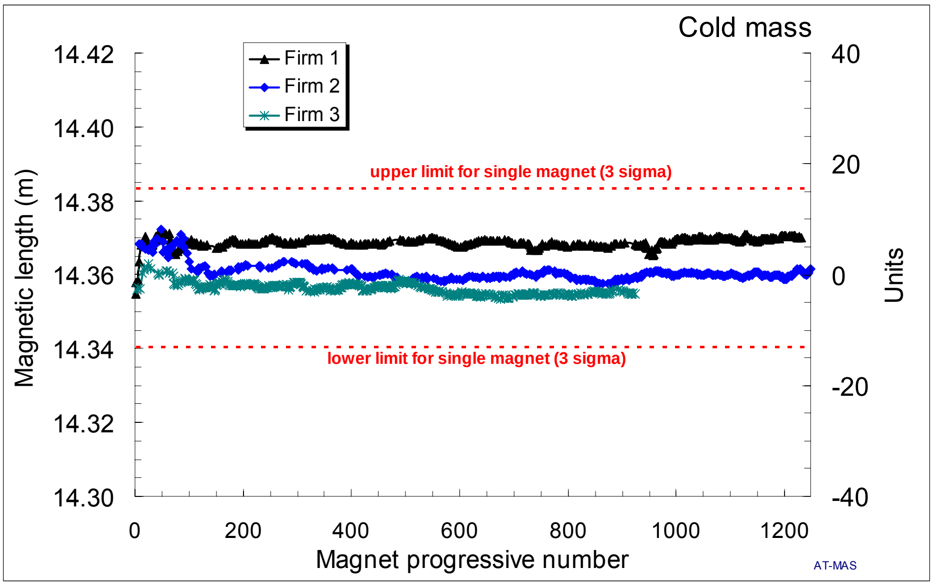

Fig. 8: Magnetic length of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.1.2 Trends in transfer function

- Transfer function in collared coils 1215th to 1248th is stable around the central values of the whole production.

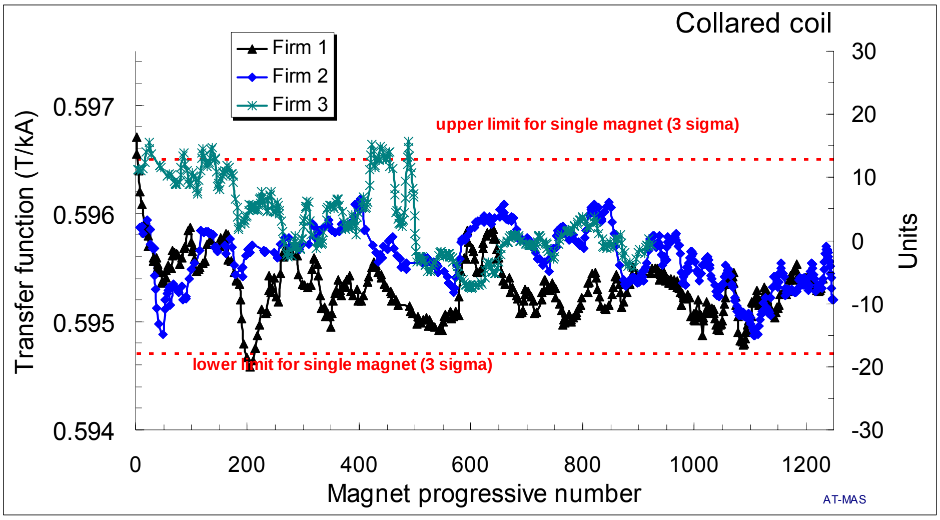

Fig. 9: Transfer function of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

- **Cold mass** data confirm the collared coil ones.

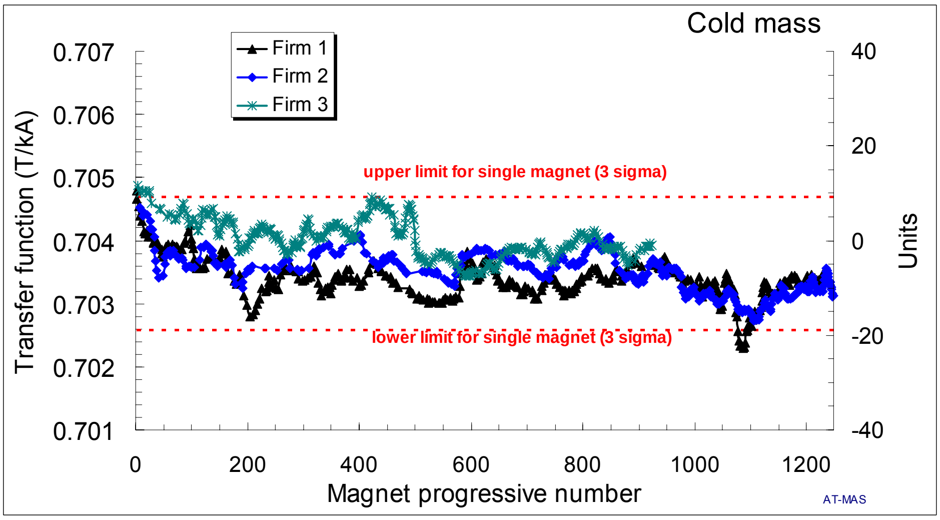

Fig. 10: Transfer function of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.1.3 Trends in integrated transfer function

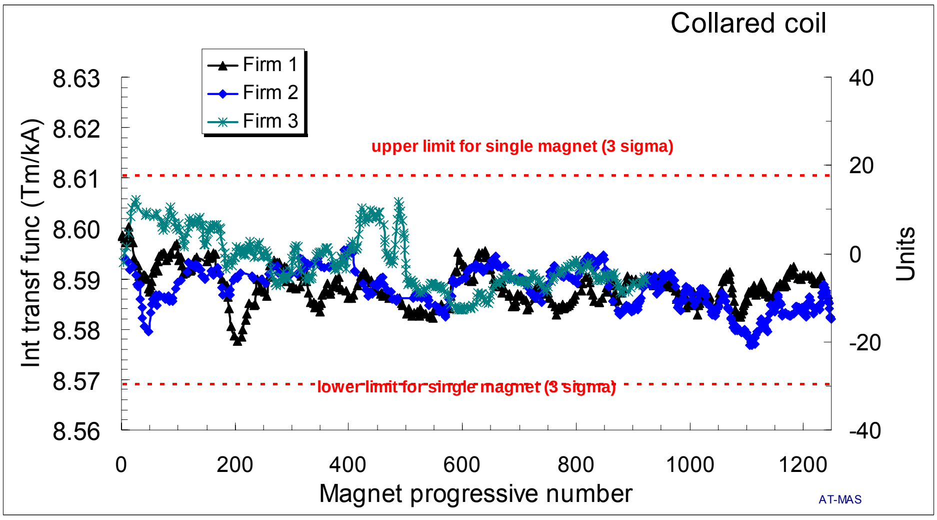

Fig. 11: Integrated transfer function of the measured collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

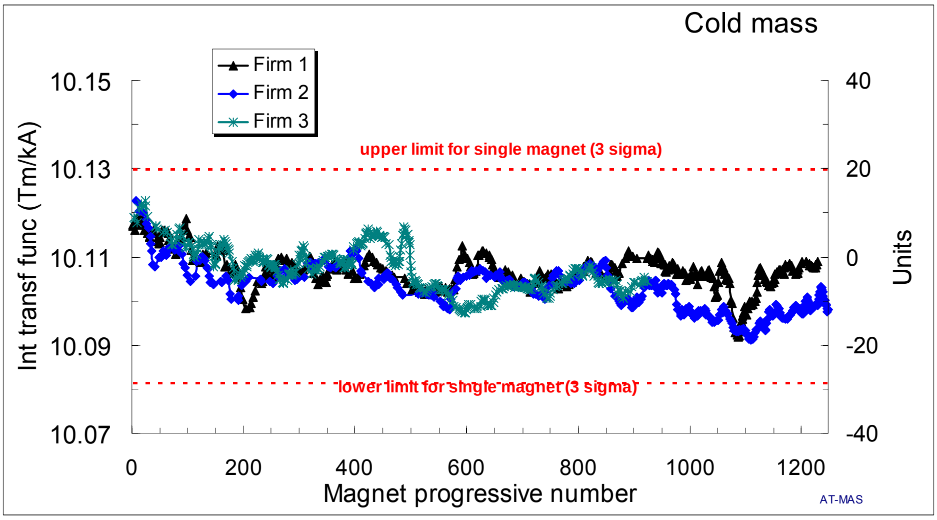

Fig. 12: Integrated transfer function of the measured **cold masses**, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm).

3.2 Trends in odd normal multipoles

- The situation is stable: at the end of the production, we have a difference in normal sextupole of about 3 units (two to three times the standard deviation per Firm) between Firm1 and Firm2.

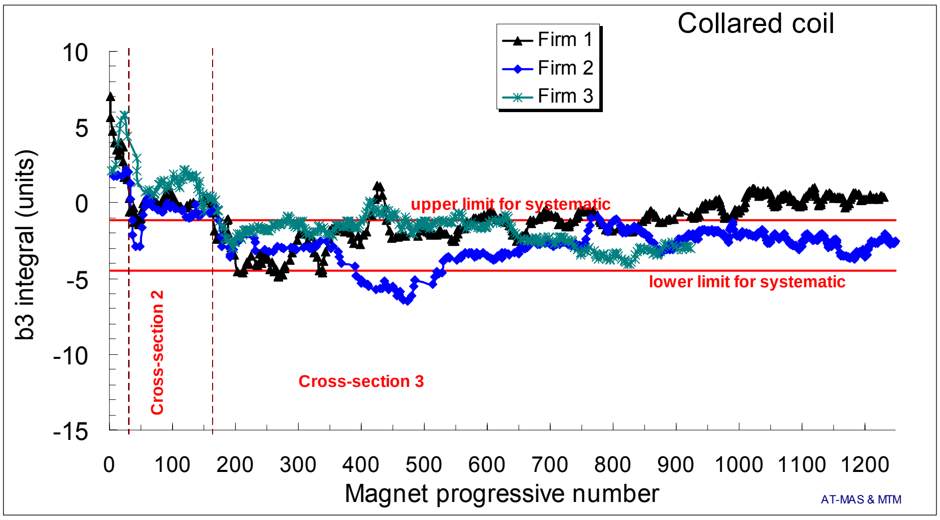

Fig. 13: Integral b3 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

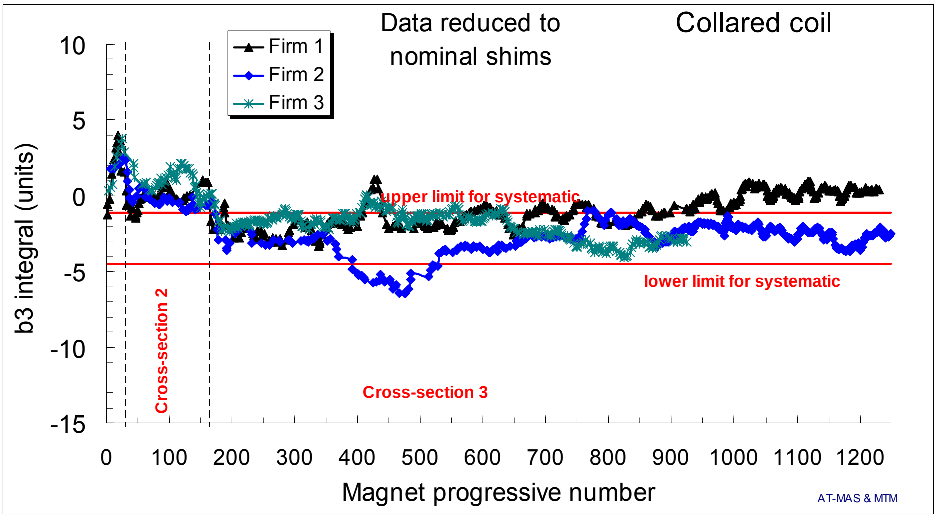

Fig. 14: Integral b3 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles. Data normalised to nominal shims[4].

[4] 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.

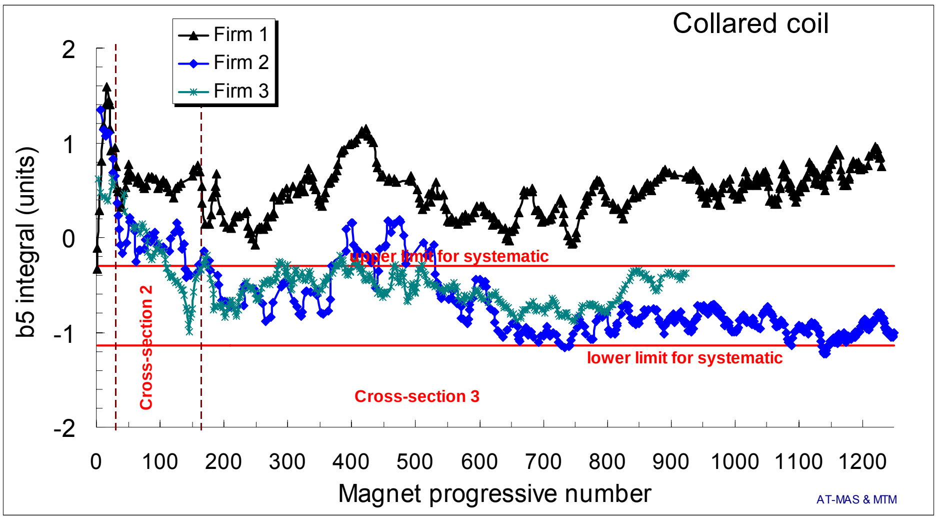

Fig. 15: Integral b5 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

- Normal 14th pole b7 is stable.

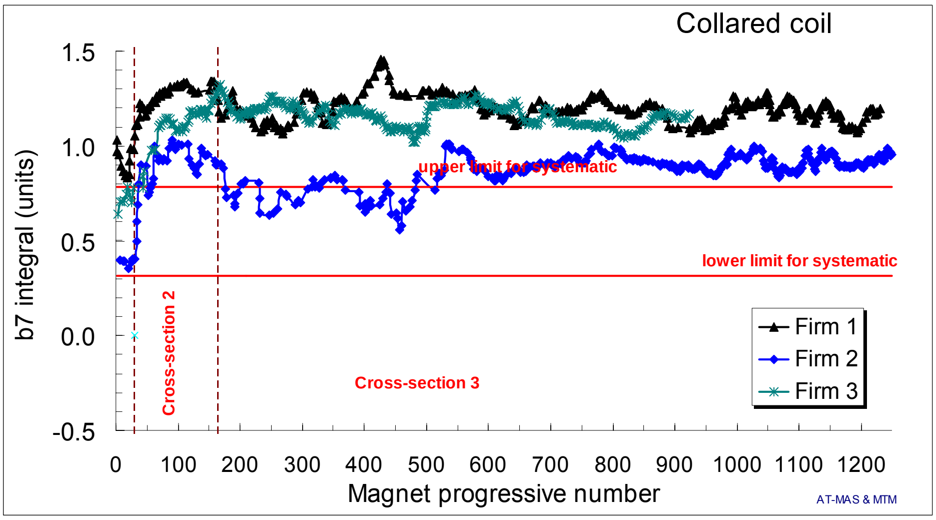

Fig. 16: Integral b7 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

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).

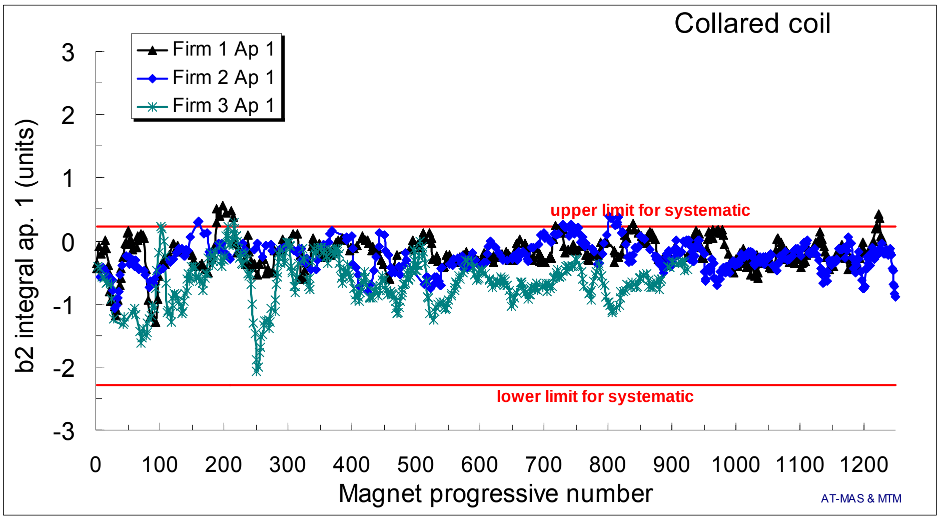

Fig. 17: Integral b2 in the collared coils (aperture 1), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

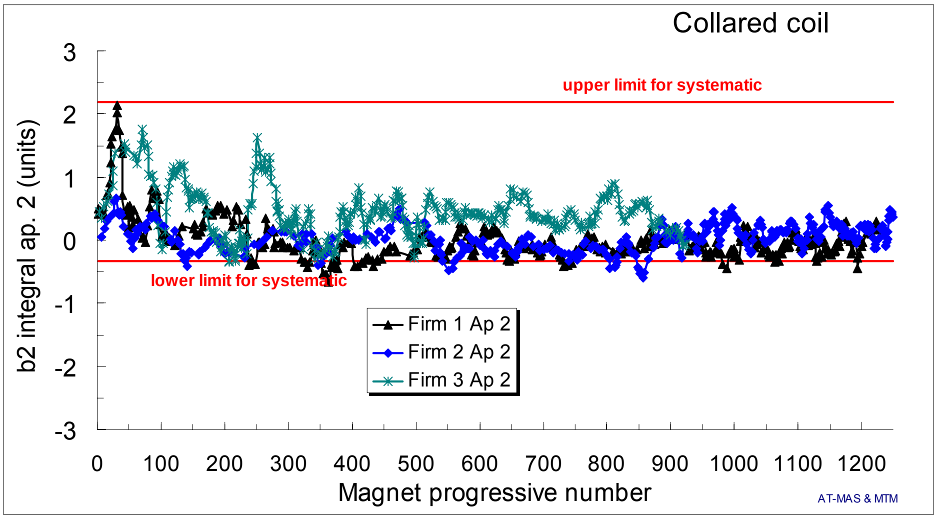

Fig. 18: Integral b2 in the collared coils (aperture 2), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

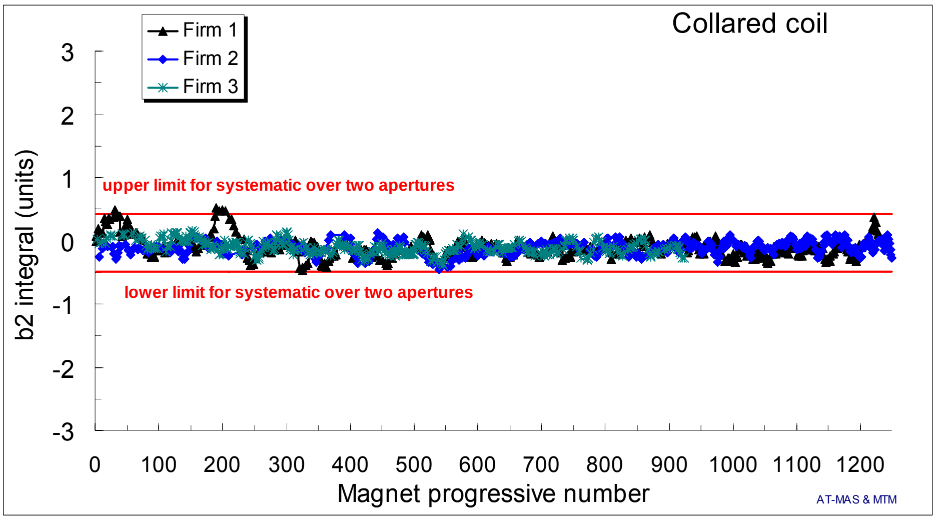

Fig. 19: Integral b2 in the collared coils (average of both apertures), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

3.3.2 Trends in normal octupole

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

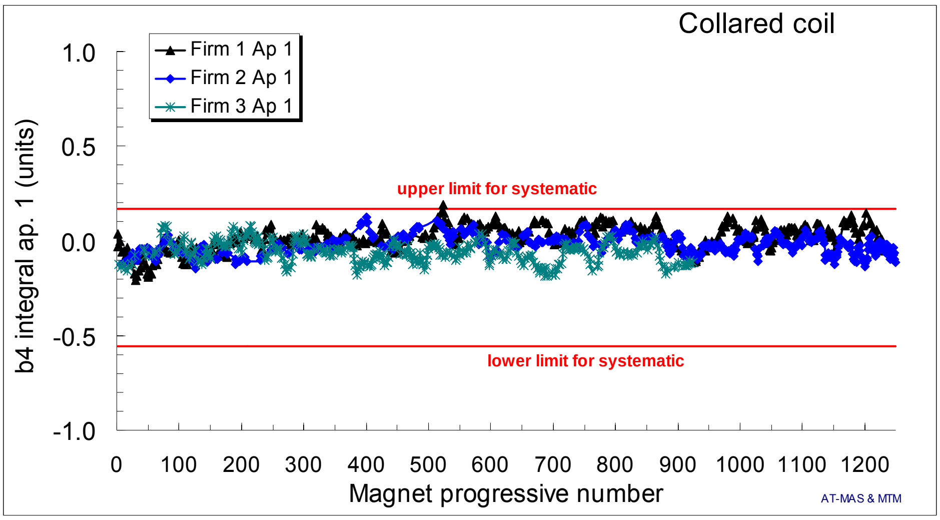

Fig. 20: Integral b4 in the collared coils (aperture 1), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

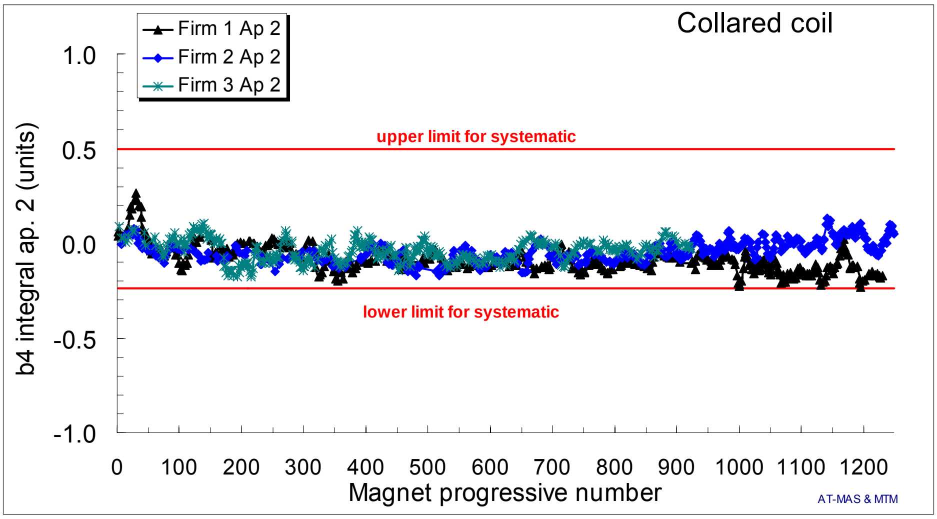

Fig. 21: Integral b4 in the collared coils (aperture 2), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

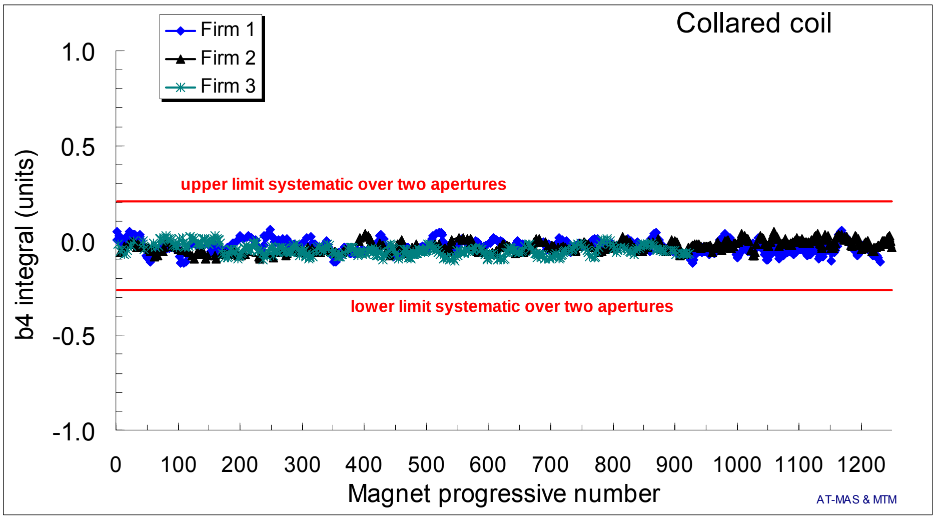

Fig. 22: Integral b4 in the collared coils (average of the apertures), separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

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.

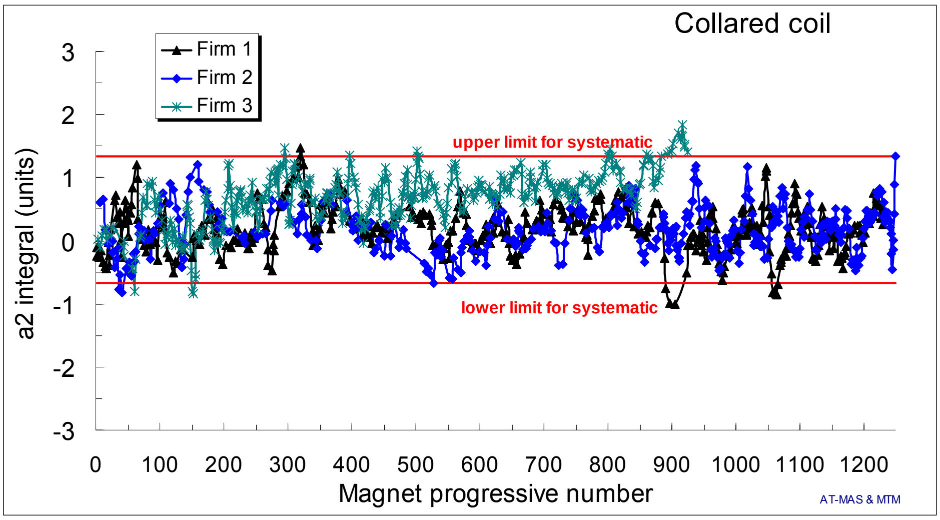

Fig. 23: Integral a2 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

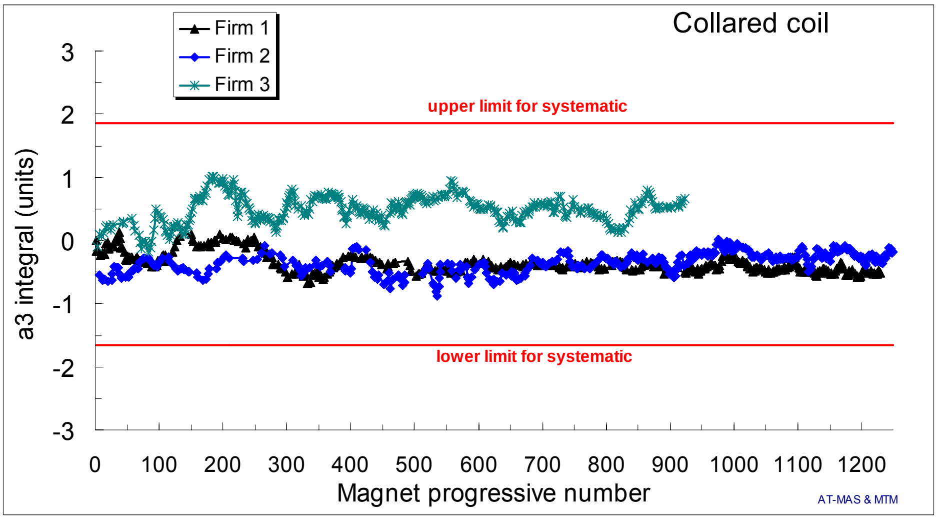

Fig. 24: Integral a3 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

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

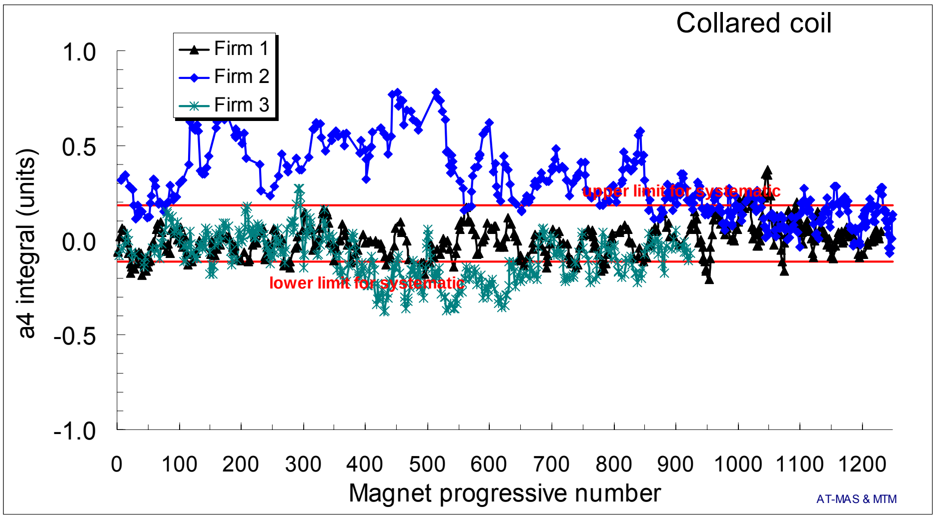

Fig. 25: Integral a4 in the collared coils, separated per Firm (each dot is the average of 5 consecutive magnets of the same Firm), and beam dynamics targets for the systematic (red lines) based on correlations with 198.5 cryodipoles.

3.5 Trends in systematic differences between Firms

See previous reports.

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 1222nd, thus implying that there is no more delay with respect to the last manufactured collared coil.

- 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.
- The r.m.s. of the "warm-cold" offsets is 5 units at injection field and 4.6 units at high field.

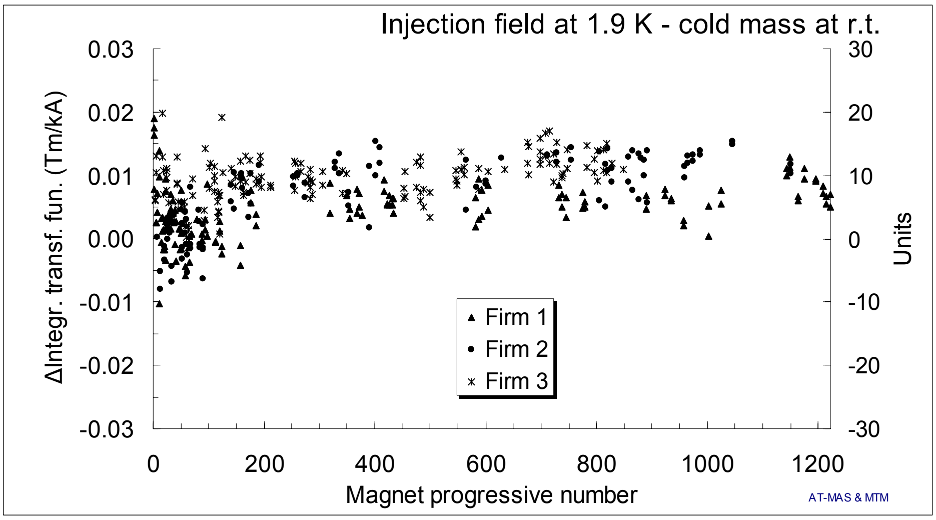

Fig. 26: Difference for the integrated transfer function between measured values at 1.9 K, injection field, and **cold mass at r.t.** along the magnet production.

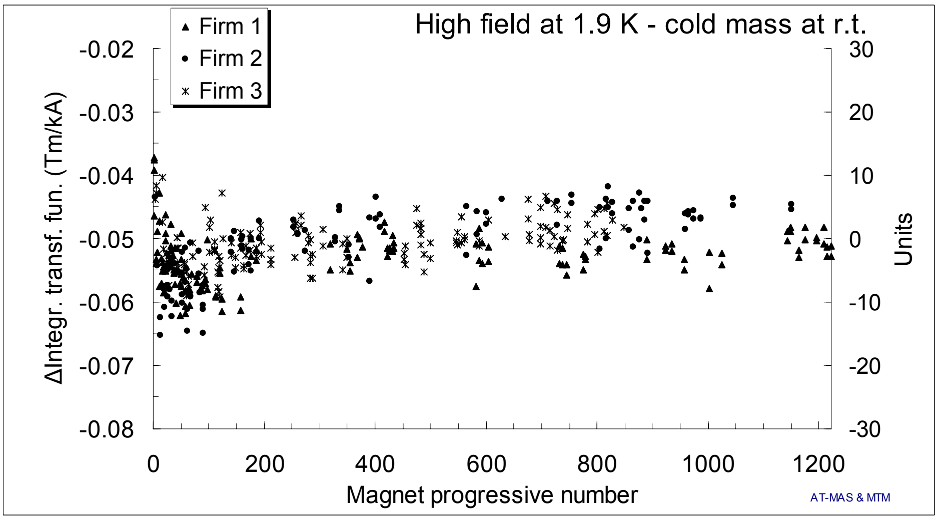

Fig. 27: Difference for the integrated transfer function between measured values at 1.9 K, high field, and **cold mass at r.t.** along the magnet production.

- 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.
- The r.m.s. of the "warm-cold" offsets is 0.38 units at injection field and 0.19 units at high field.

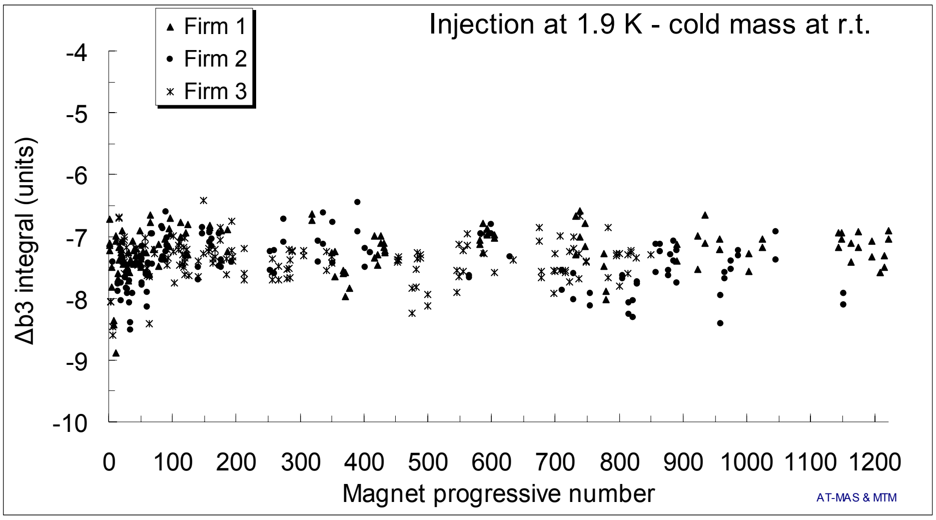

Fig. 28: Difference for the b3 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

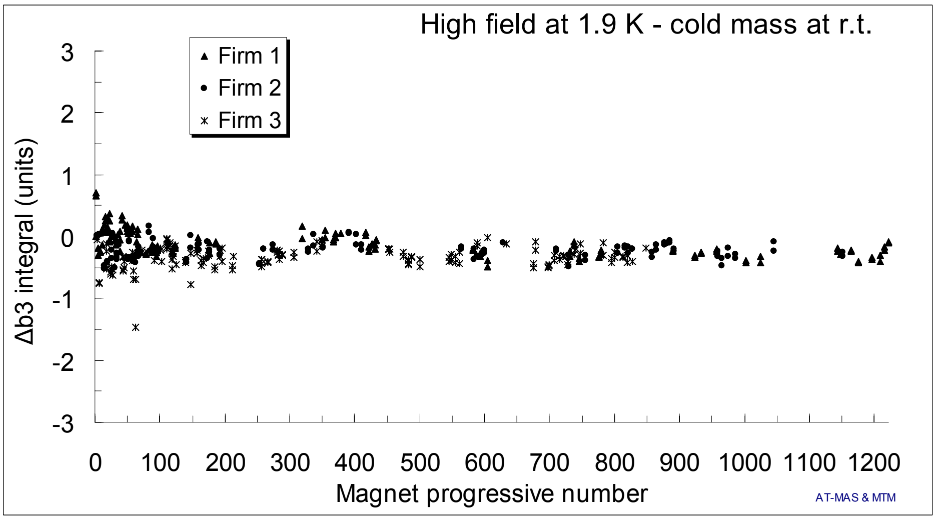

Fig. 29: Difference for the b3 between measured values at 1.9 K, high field, and **cold mass at r.t.**, along the magnet production.

- 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.
- The r.m.s. of the “warm-cold” offsets at injection field is 0.10 units for b5 and 0.04 units for b7.

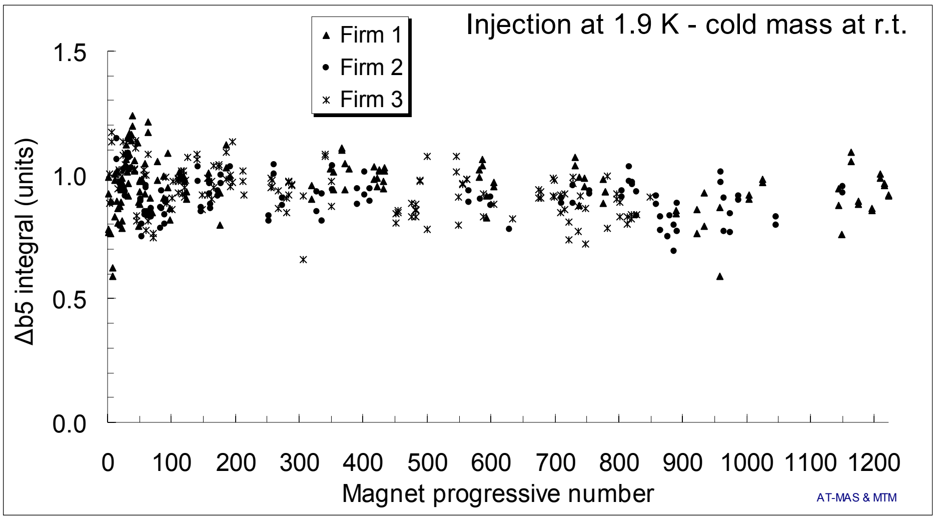

Fig. 30: Difference for the b5 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

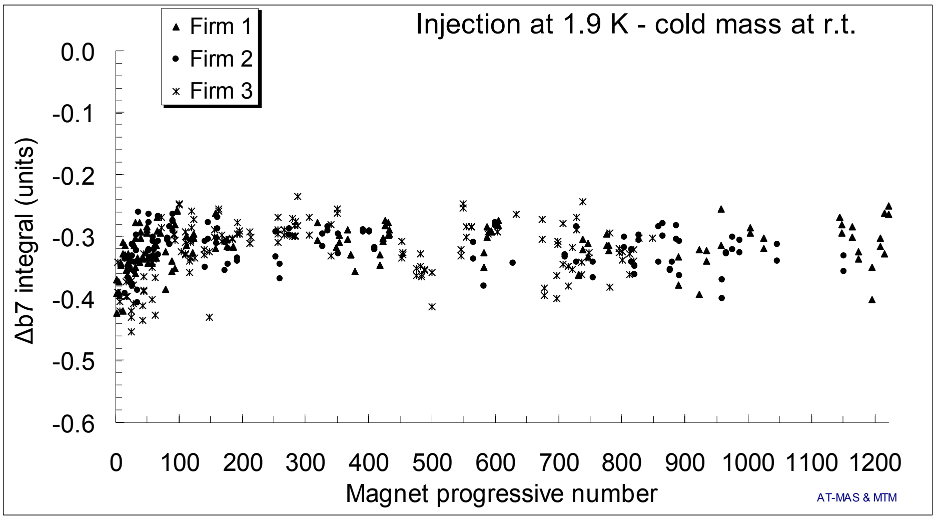

Fig. 31: Difference for the b7 between measured values at 1.9 K, injection field, and **cold mass at r.t.**, along the magnet production.

PART IV: QUALITY CONTROL

4.1 Holding point results

Collared coil 2421 has shown strong anomalies all along the magnet axis (-13 units of b2, -5 units of b3, 16 units of a2, 12 units of a3, 7 of a4, …). The analysis has suggested a large assembly error (of the order of 1 mm) in one quadrant, affecting also the inner layer. After decollaring, it has been found that a copper wedge of type 2 has been put at the place of the type 1 wedge (see Fig. 32).

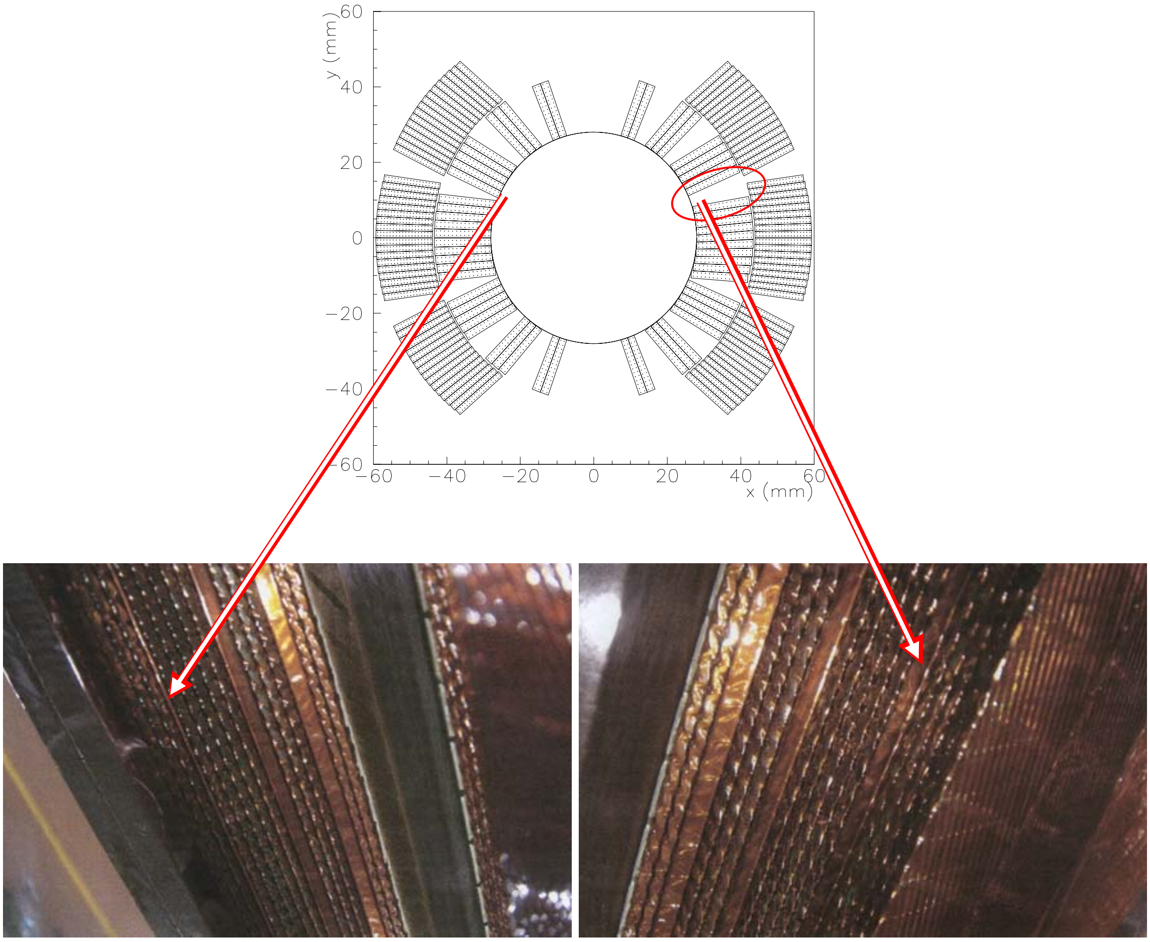

Fig. 32: Assembly defect found in 2421: cross-section sketch (upper part) with wrong copper wedge (red circle), internal side of the inner coil, left part with no defect (left) and right part with defect (right).

The total number of defects found along the production is given in Fig. 33 and Table I.

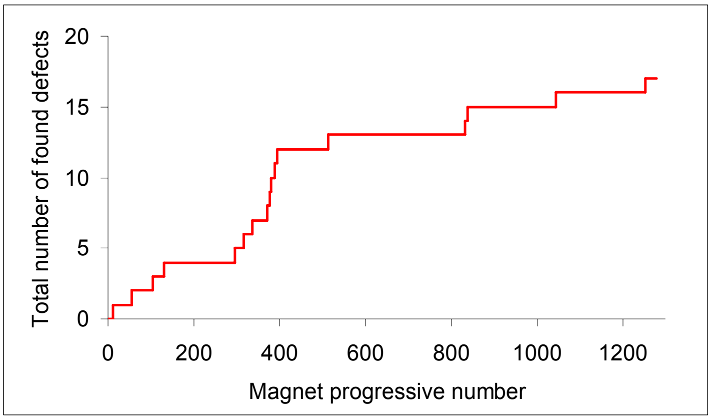

Fig. 33: Total number of defects found with room temperature magnetic measurements versus magnet progressive number.

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

Magnet	Measured on	Analysis	Opened on	Result
Bad assembly cases				
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
2421	21-Nov-2006	Displacement of around 1 mm in one quadrant	10/28/2006	wrong copper wedge
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
ity 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.

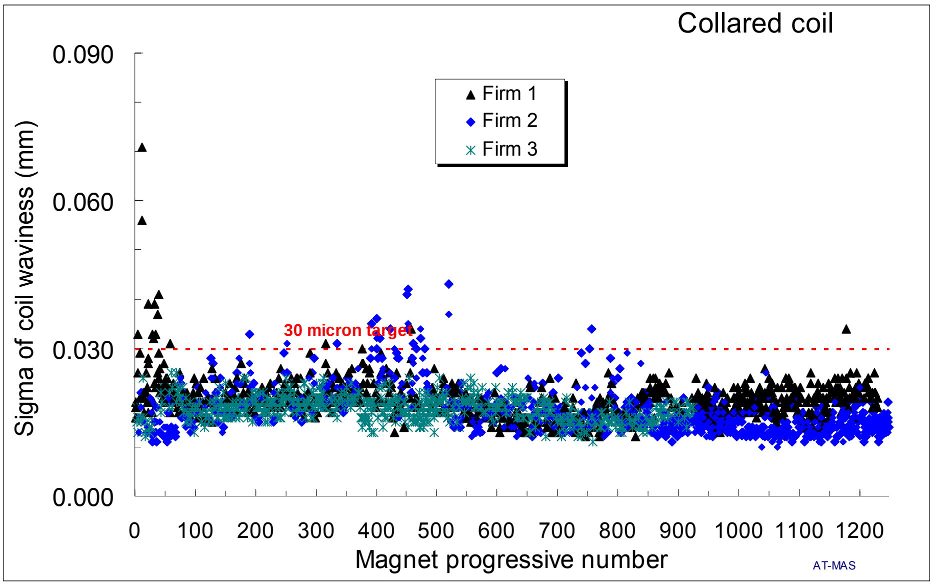

Fig. 34: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

Acknowledgements

We wish to thank all colleagues involved in the measurements at room temperature and at 1.9 K, and the Firm personnel that carried out the magnetic measurements. P. Hagen and C. Vollinger analysed around 2/3 of the whole LHC main dipole warm magnetic measurements (cold mass and collared coils, respectively), i.e. more than 3000 apertures. The rest of the data has been analysed by a team including R. Chamizo, V. Remondino, D. Richter and E. Wildner. We acknowledge the project engineers, MTM-AS for discussions and support in the analysis. We wish to acknowledge S. Fartoukh and the ABP-LOC magnet evaluation team for the work carried out to set out the beam dynamics targets, and for the fruitful collaboration on the follow-up of field quality versus targets.