Report on field quality in the main LHC quadrupoles: April-May 2005

E. Todesco, AT-MAS-MA

This report gives data relative to field quality measured at room temperature in quadrupole collared coils and cold masses during the period February-March 2005, comparison to beam dynamics targets. Updated graphs can be found in the LHC-MMS field quality observatory http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/qobs.html.

EDMS n. 598708

The dashboard

- Available measurements: at room temperature we have 570 apertures (285 magnets) and 216 cold masses. At 1.9 K we have measurements of 19 quadrupoles.
- In these two months, 51 apertures (i.e., 25.5 equivalent quadrupoles) and 31 cold masses have been measured at room temperature. Two new measurements are available at 1.9 K.

What's new

Issues critical for beam dynamics:

- **Collar permeability:** The cold mass assembler has been obliged to use the batches of collars with high magnetic permeability due to the lack of collars within specifications. 35 apertures (17.5 magnets) with very high magnetic permeability have been produced: magnetic measurements show strong anomalies in b2, b6 and b10 (see Figs. 7, 11 and 12), compatible with a difference in permeability of 0.01 to 0.03. According to the information provided by the cold mass assembler, three more apertures with high permeability collars will be manufactured. Unfortunately, the advice of the Field Quality Working Group of mixing high permeability collars with collars within specification to reduce the impact on the spread of b2 has not been followed.
- **Spread of focusing strength:** we have 35 apertures with a focusing strength of 30 to 90 units more than average. This has brought the spread of integrated field gradient to 18 units, i.e. 80% more than specified. Without these apertures, the spread is around 14 units.
- **Warm-cold correlations:** In these two months, two magnets have been measured at 1.9 K. Even though they did not have high permeability collars, measurements show anomalies in the offsets of b2 and b6 that are not far from what observed for magnet 120, which was manufactured with high permeability collars. The situation of warm-cold correlations for the integrated field gradient is therefore far from being understood. An additional problem is the warm-cold offset at injection for b6, which is of 2.5 units only in the recent magnets compared to the 4 units measured at the beginning of the production. This could drive the systematic b6 out of targets.

CONTENTS

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 51 new apertures (i.e. 25.5 equivalent quadrupoles) and 31 cold masses have been measured at room temperature (see Fig. 1).

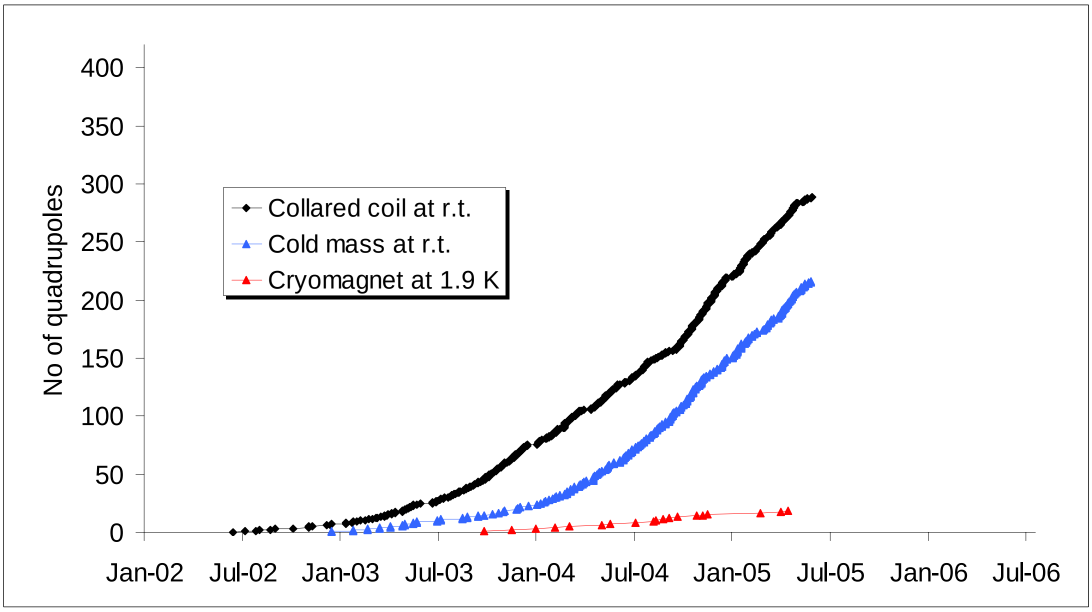


Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

- Cross-section: all apertures have X-section 2, except one aperture (566th).
- Coil protection sheet[1]: all new apertures have a coil protection sheet of 0.87 mm.

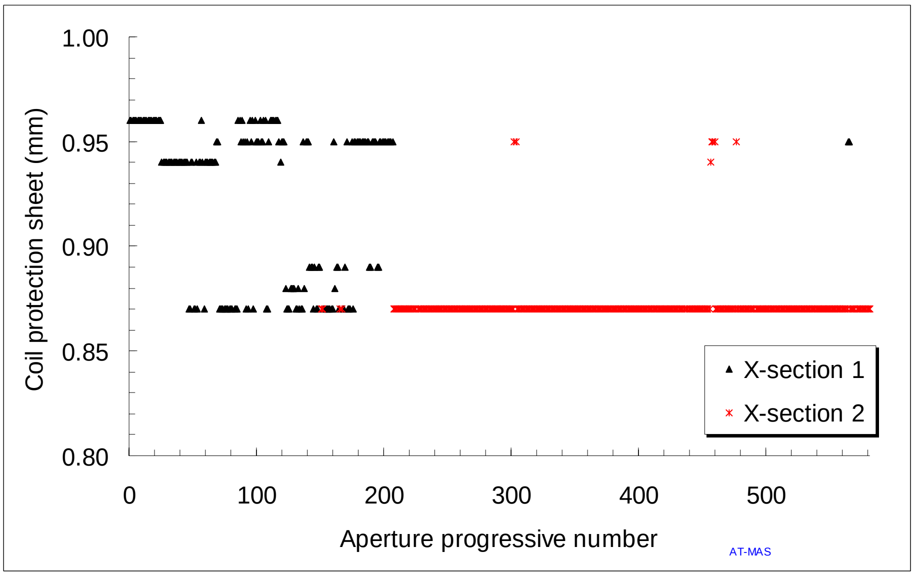


Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[1] The coil protection sheet is a stainless steel sheet between the collar poles and the coils (covering both inner and outer layer) that can be used to optimize pre-stress or field quality.

PART II: MEASUREMENTS VERSUS BEAM DYNAMICS TARGETS

- Best estimates of normal and skew systematic components are given in Fig. 3. All the multipoles are within specifications.
- For b6, the average is carried out over 200 apertures with X-section 1 and 370 with X-section 2: this gives a systematic b6 within the target. When the contribution of the different X-sections is separated, one finds that b6 in X-section 1 is 1.5 units larger than the upper target, and that in X-section 2 it is well centred in the allowed range (see Fig. 3, left).

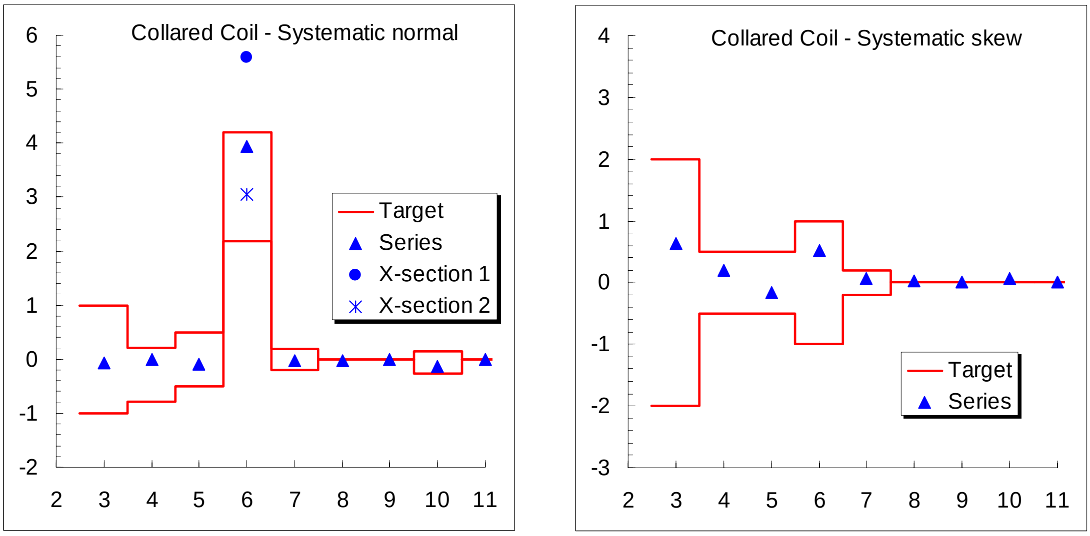


Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (solid lines).

- Best estimates of the random components are given in Fig. 4. All values are within targets with the exception of b2, b6 and a4.
- The standard deviation of b2 (integrated field gradient) is 18.4 units, i.e. 84% more than the target of 10 units. This includes the apertures that have been recently manufactured with high collar permeability (see pg. 4-7). Without the contribution of these apertures, the spread in the apertures is 13.8 units, confirmed by the measurements of cold masses. The measurement of one magnet at 1.9 K suggested that in operational conditions the field anomaly due to collar permeability should be reduced (see pg. 12). Therefore, the values at room temperature probably give a severe overestimate of the spread if the integrated field gradient.
- The spread of b6 over all apertures (1.4 units) is mainly due to the mixing of the two different X-sections. Indeed, the target for beam dynamics on random b6 is not a hard limit.

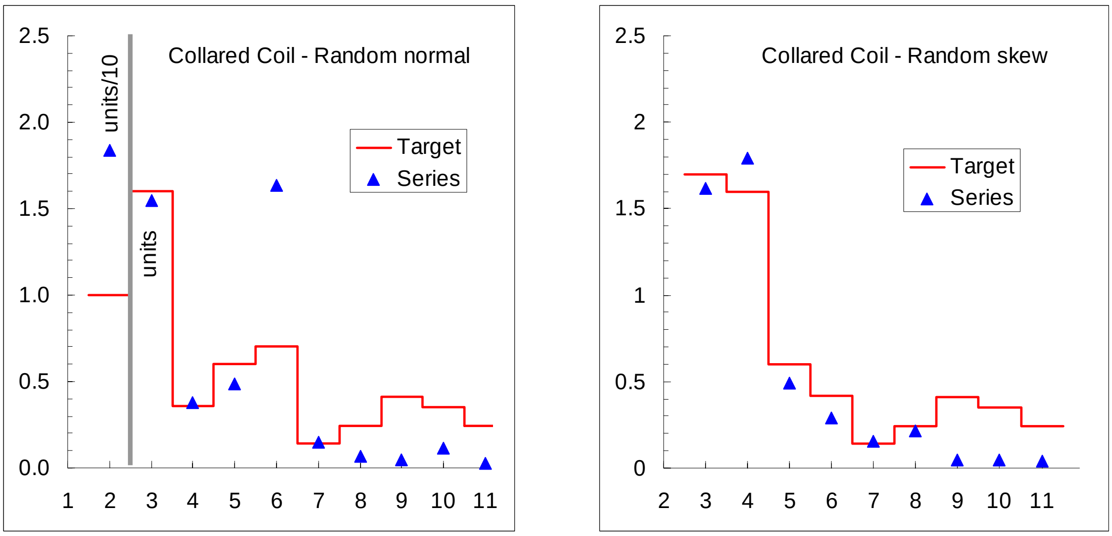


Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

PART III: TRENDS IN FIELD QUALITY

3.1 Trends in focusing strength

3.1.1 Trends in magnetic length

- The magnetic length of the apertures has a very low spread (2 units). Apertures 520th to 541st and 13 apertures between 567th and 582nd (see Fig. 5) have a magnetic length of around 5 to 10 units less than previous production. These apertures have been manufactured with collar permeability out of tolerance, thus leading to high field gradient, low b6 and high b10 (see Figs. 7, 11 and 12). This slightly shorter magnetic length could be due to the fact that the absence of pole in the head collars reduces the impact of high permeability on field quality in the heads[2].

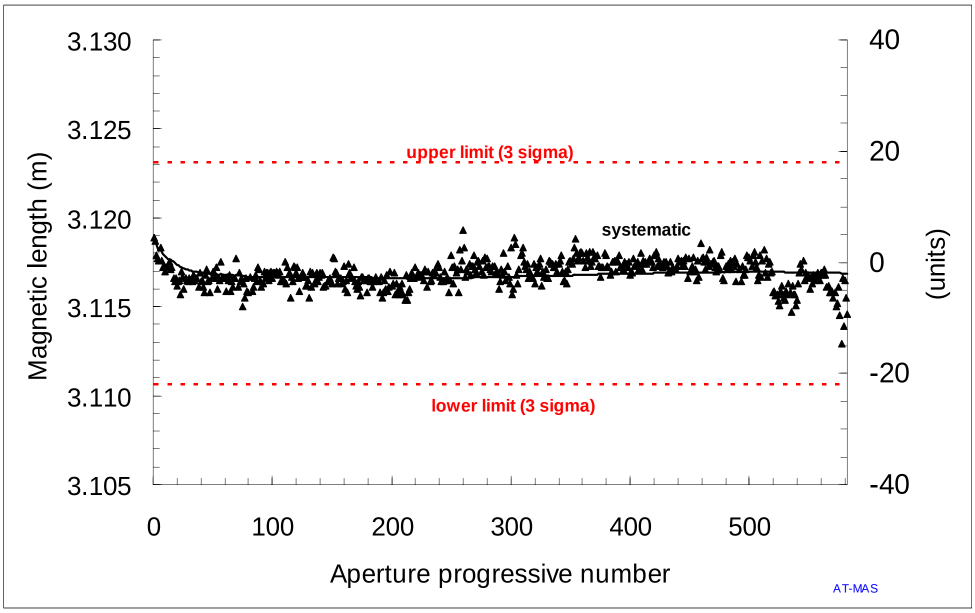
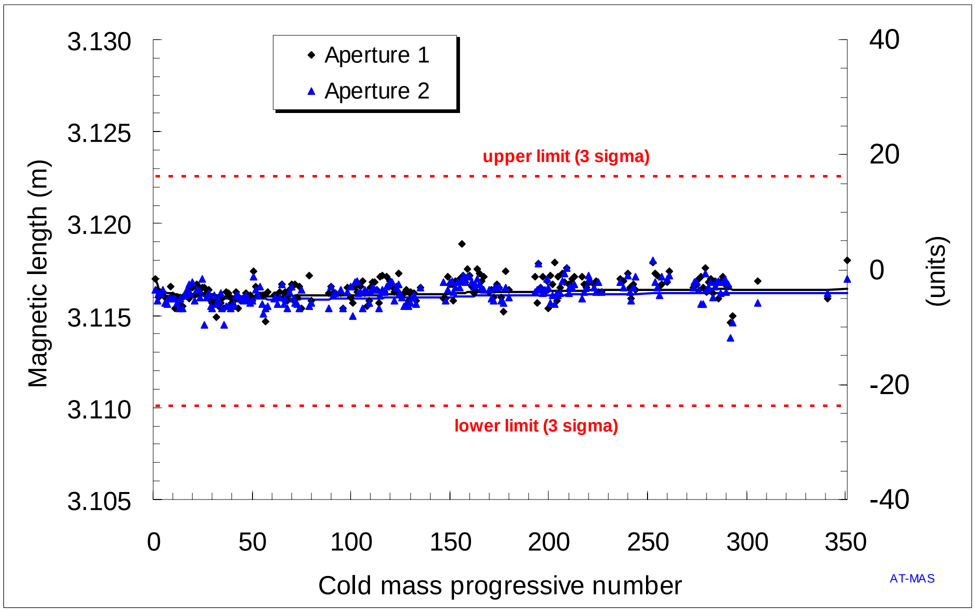


Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

- Standard deviation of magnetic length of **cold masses** is 1.8 units.



.

Fig. 6: Magnetic length of the measured **cold masses** and running average (solid line).

[2] F. Simon, private communication

3.1.2 Trends in field gradient

- 22 apertures between 520th and 541st and 13 apertures between 567th and 582nd (see Fig. 7) have been manufactured with high permeability collars. The first 22 apertures have a higher field gradient of about 20 to 60 units, and the other 13 of 40 to 90 units. The trend plots of b6 and b10 confirm the hypothesis that these field gradient anomalies are due to the out of tolerance in the permeability of the collars: they feature a lower b6 and a higher b10 in agreement with the model and the permeability measurements (see Figs. 11 and 12). A higher field gradient of 30 to 90 units corresponds to a higher permeability of 0.01 to 0.03.
- The spread of the field gradient excluding apertures 520th-541st and 567th-582nd is 14 units, and it becomes 19.4 units if these apertures are included in the statistics.

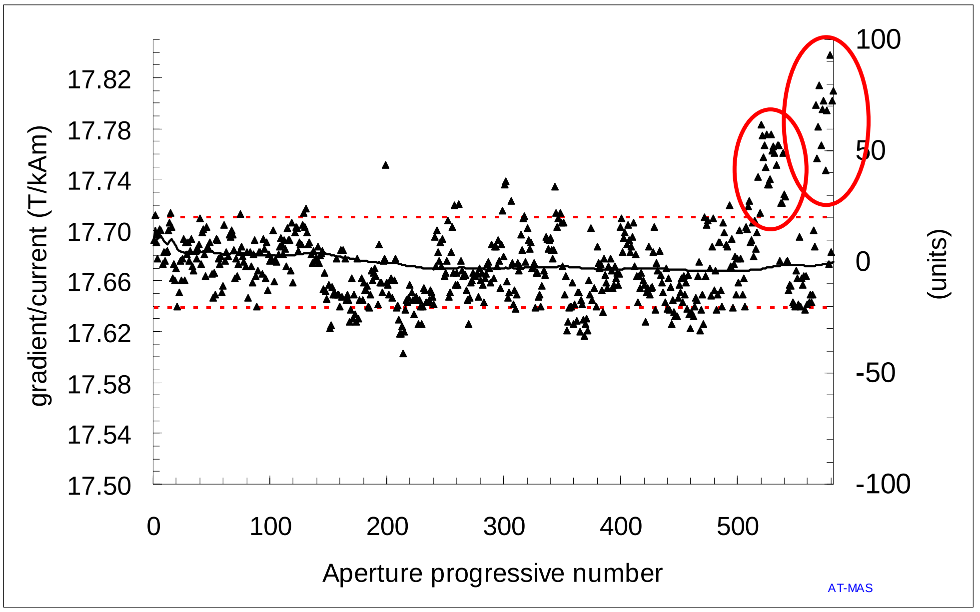


Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines). Recent apertures manufactured with high permeability collars are marked by a circle.

- The spread observed in apertures is confirmed by **cold mass** data. Four apertures recently manufactured with high permeability collars (523rd, 525th, 531st and 534th) have been assembled in cold masses. The magnetic measurements of the cold mass confirm the higher gradient already observed in the apertures (see Fig. 8, red circle).

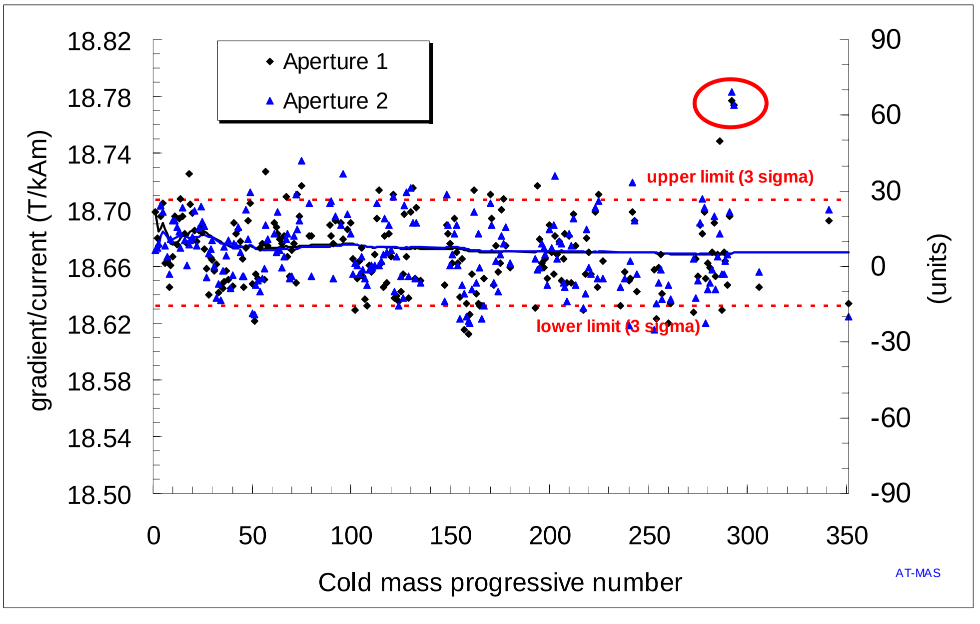


Fig. 8: Field gradient of the measured **cold masses** and running averages (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

3.1.3 Trends in integrated field gradient

- The spread of the integrated field gradient (or focusing strength) is dominated by the spread in the field gradient, since the magnetic length is very stable, both in apertures and in cold masses (see Figs. 9 and 10). For the apertures, the spread is 13.8 units (18.4 units including the apertures 520th-541st and 567th-582nd), and for the cold masses is 13.3 units.

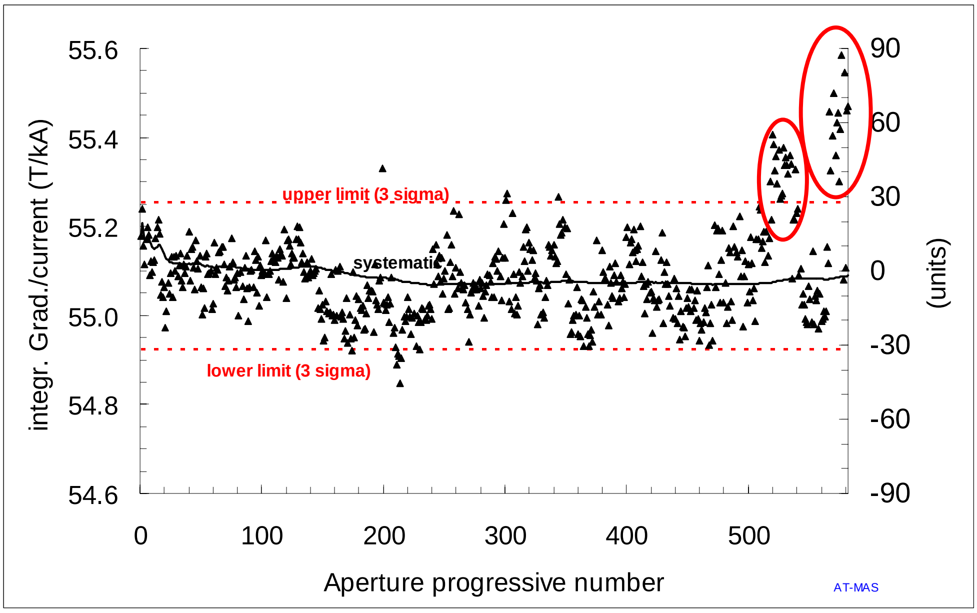


Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

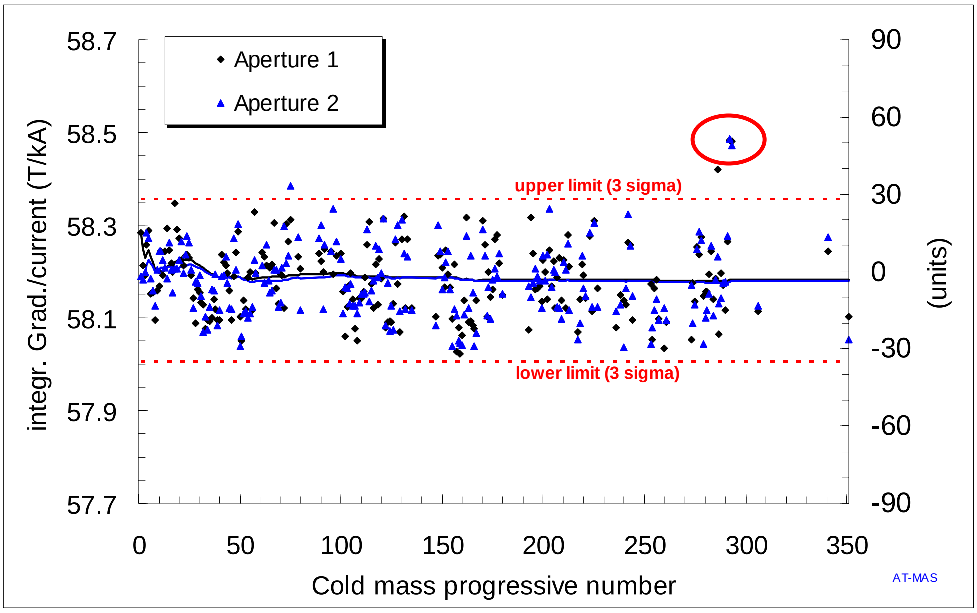


Fig. 10: Integrated field gradient of the measured **cold masses** and running averages (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

3.2 Trends in allowed multipoles

- The systematic value of cross-section 2 is within targets. Systematic b6 has dropped from 5.5 units to about 3 units with the introduction of cross-section 2 (see Fig. 11). An upper trend is being observed since aperture 400th.
- Apertures 520th-541st and 13 apertures between 567th and 582nd have manufactured with high permeability collars (solid circles in Fig. 11). These apertures have a b6 of 2 to 6 units lower than the recent production, corresponding to a higher permeability of 0.01 to 0.02.

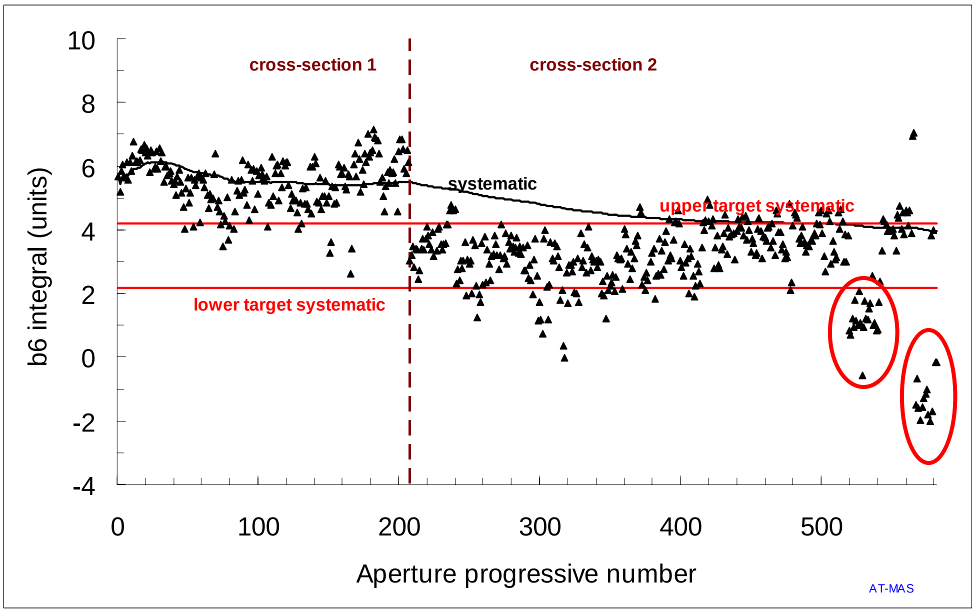


Fig. 11: Integral b6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations measured at 1.9 K on 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a circle.

- Systematic b10 is well within targets (see Fig. 12). Apertures 520th-541st and 13 apertures between 567th and 582nd have manufactured with high permeability collars (solid circles in Fig. 12). These apertures have a b10 of 0.2 to 0.7 units higher than the recent production, corresponding to a higher permeability of 0.01 to 0.03.

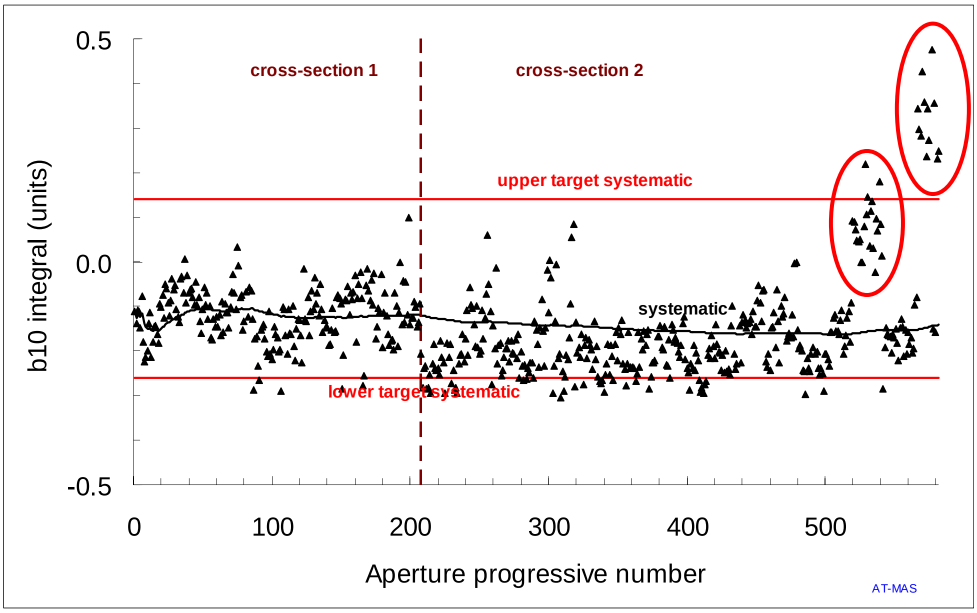


Fig. 12: Integral b10 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations with 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a red circle.

3.3 Trends in non-allowed multipoles

3.3.1 Normals: b3, b4, b5, b7

- Systematic value of b3 is close to zero as expected by the symmetry, and is within targets (see Fig. 13). No trends are observed.

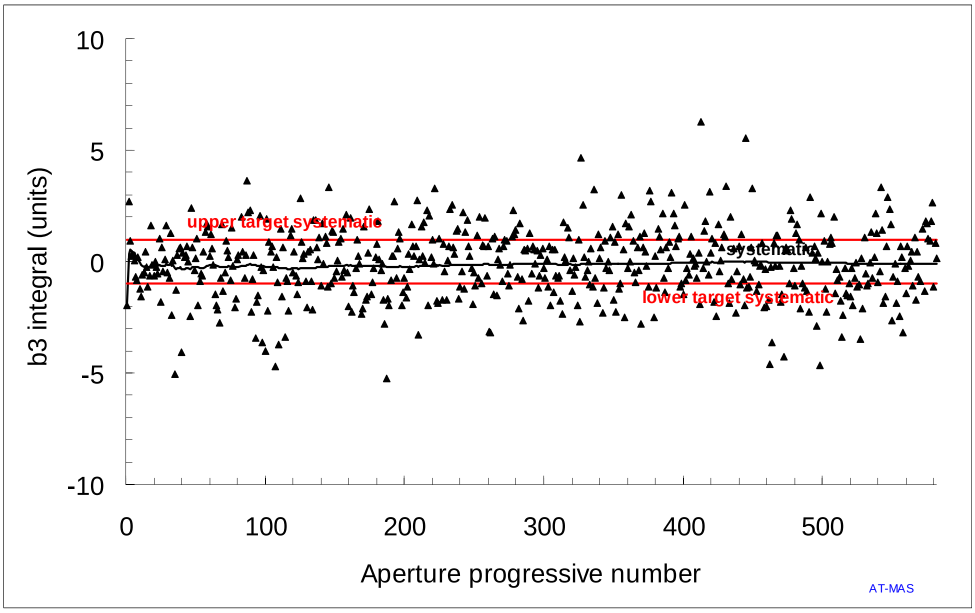


Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- The multipole b4 had a systematic component of about 0.5 units at the beginning of the production that disappeared since aperture 200th (see Fig. 14). Analysis of measurements at 1.9 K suggests that the systematic component is due to a problem of the early measurements at room temperature.

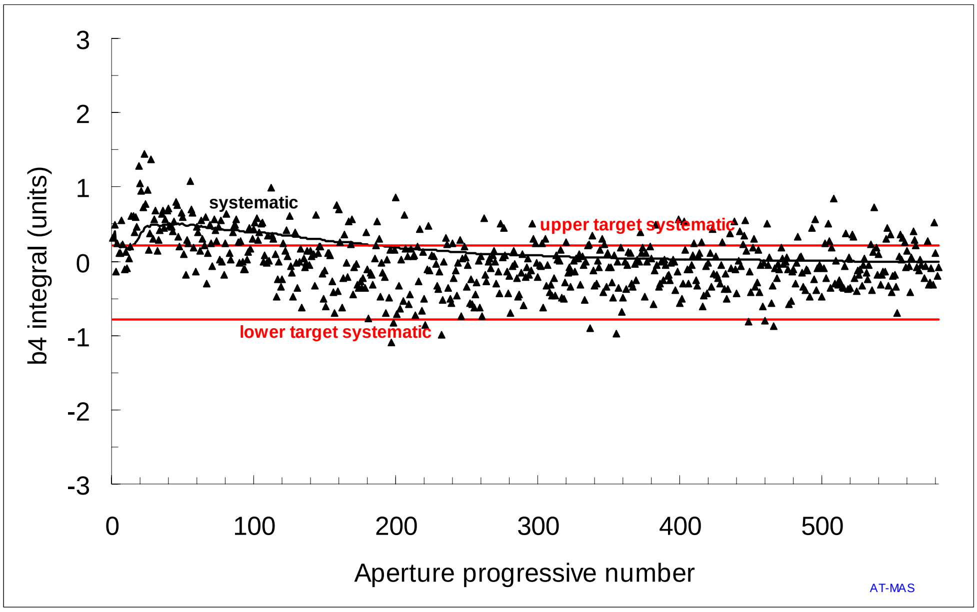


Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- Systematic values of b5 and b7 are close to zero as expected by the symmetry, and well within targets (see Figs. 15 and 16). No trends are observed.

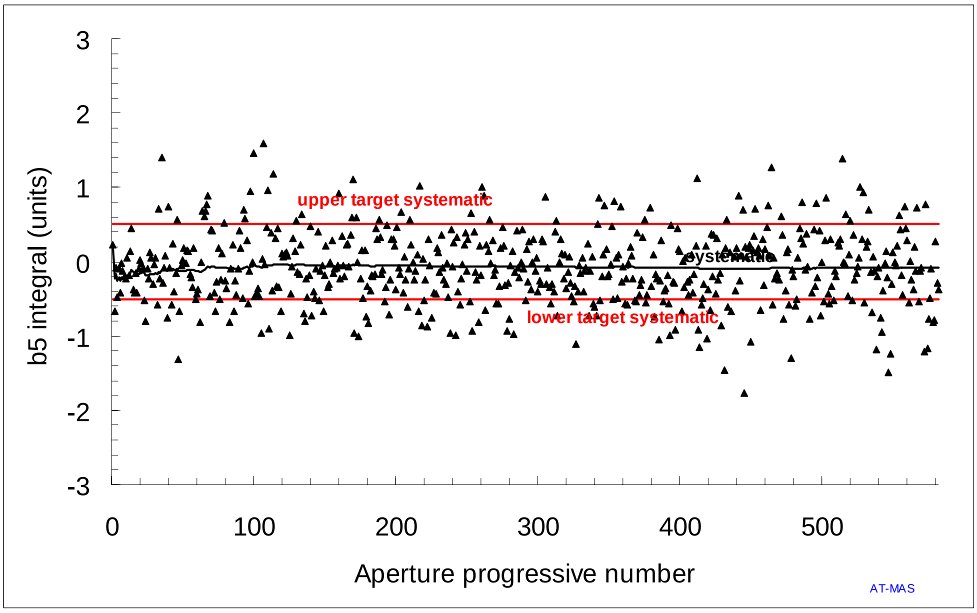


Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

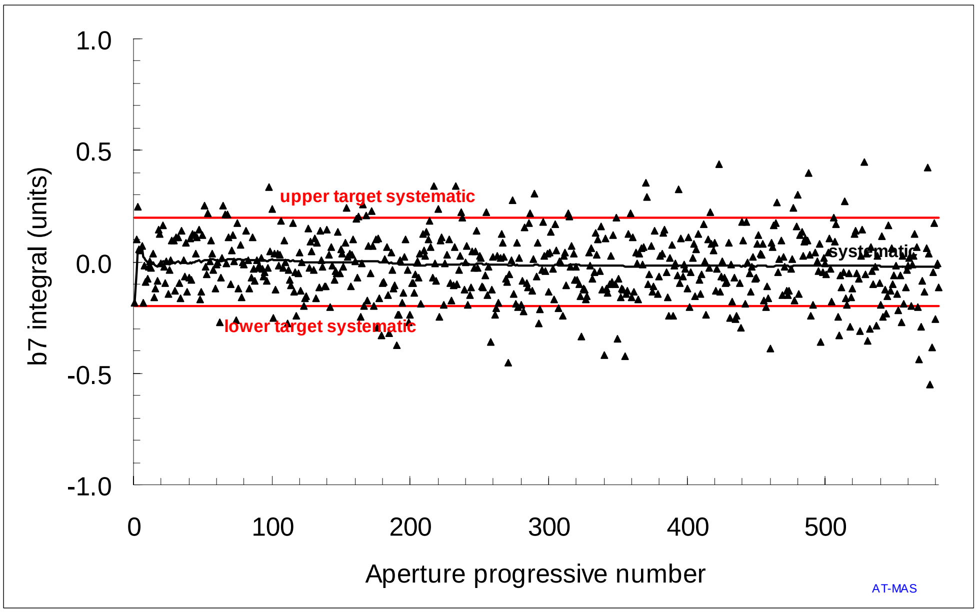


Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

3.3.2 Skews: a3, a4, a5, a6

- Systematic values of a3, a4 and a5 are close to zero as expected by the symmetry, and well within targets (see Figs. 17-19).
- The multipole a6 has a systematic component of about 0.5 units since the beginning of the production (see Fig. 20). This unexplained component, which had trends at the beginning of the production, is not critical for beam dynamics since it is within targets.

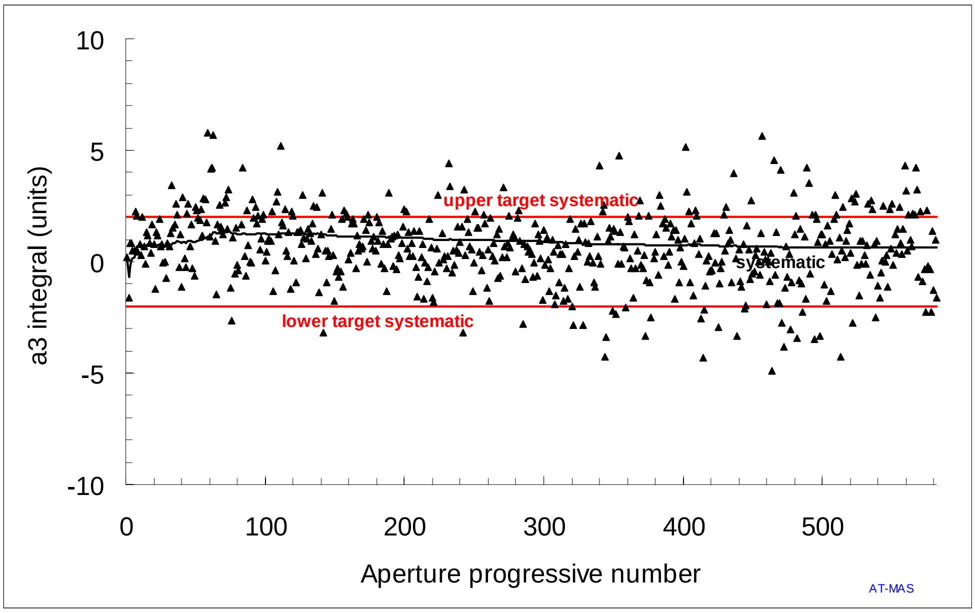


Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

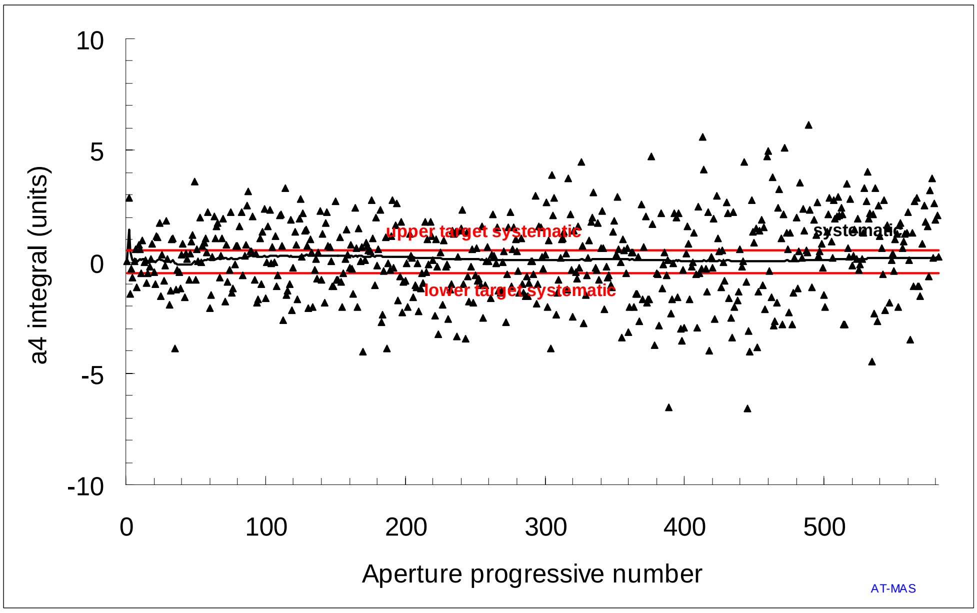


Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

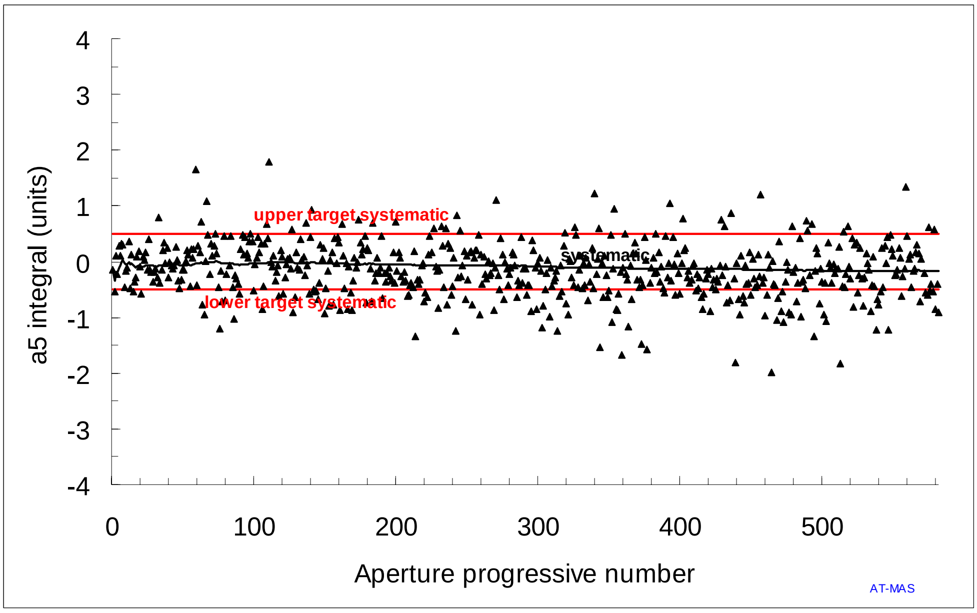


Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

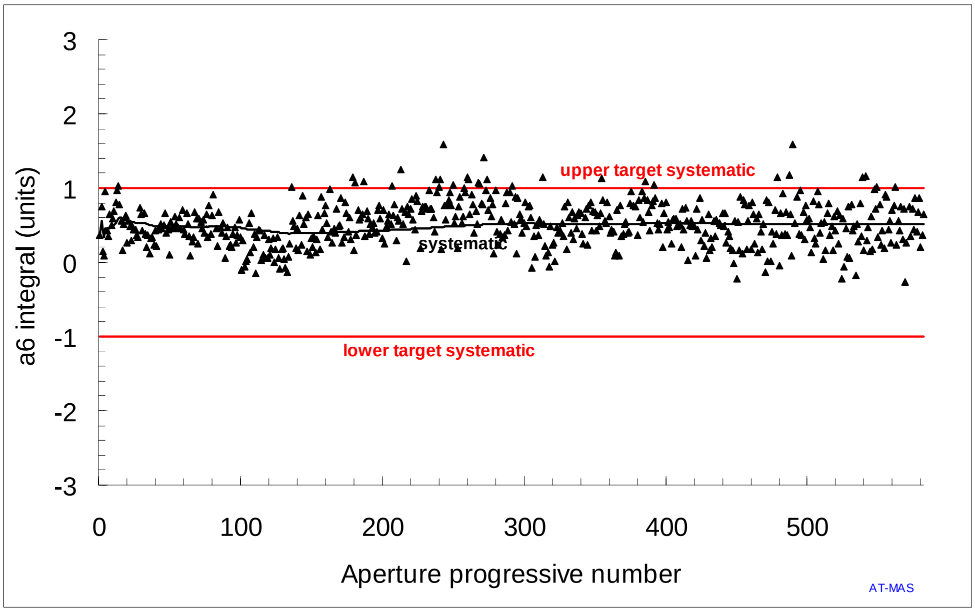


Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

3.4 Trends in correlations to measurements at 1.9 K

We give a trend plot for correlations for the two main critical values, namely the integrated field gradient and b6. Instead of giving the standard 'warm versus cold' plot, we give the measured offset, i.e. the difference between measurements at 1.9 K (at injection or high field), and at room temperature in the cold mass (at 12.5 A) versus the aperture progressive number. This gives an idea of the sampling that is being performed at 1.9 K (last aperture tested at 1.9 K is 314th, i.e. there is a delay of 130 quadrupoles between room temperature measurements of collared coil and test at 1.9 K[3], equivalent to 8 months of production), and allows to detecting trends in correlations along the production.

- Integrated field gradient: we present data of 16 measured quadrupoles (32 apertures). We plot the difference between the integrated gradient measured in the cold mass at room temperature and at high field at 1.9 K
  - The offset between cold masses (i.e., with iron yoke) at room temperature and quadrupoles at 1.9 K is shown in Fig. 21. In the right part, values are given in units relative to the nominal value of 58.5 T/kA. The average value of 0.15 T/kA.m (i.e., approximately 0.3%) is mainly due to the field increase due to the thermal contraction.
  - As observed in the previous report, two apertures, corresponding to magnet 004, have a rather low offset compared to the other ones. Indeed, the analysis of data at 1.9 K does not present any anomalies justifying a rejection of the measurement[4].
  - As observed in the previous report, magnet 120, corresponding to apertures 256th and 258th, have a lower offset (60 units less). These apertures had collars with high permeability, thus leading to a higher value of the focusing strength at room temperature (see Fig. 9). This effect disappears at 1.9 K, thus leading to a much lower offset for these apertures.
  - As observed in the previous report, magnet 114, corresponding to apertures 241st and 242nd, had normal values of b2, b6 and b10 at room temperature, and collar permeability within specifications. Nevertheless, the offset from warm to cold in the transfer function is around 30-50 units less than usual. The same anomaly is seen for the offset of b6 (see next page).
  - The new measurements of these two months are Magnet 117 and 151. They both have no anomalies due to collar permeability. Magnet 151 has a normal offset, but Magnet 117 has a lower offset of about 30 units, as 114.

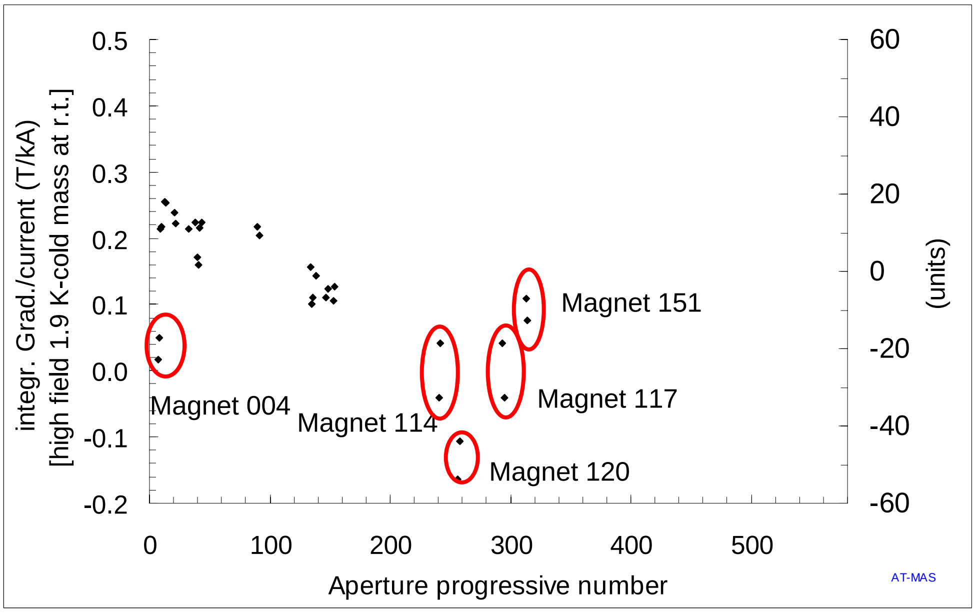


Fig. 21: Difference in focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

---

[3] Please note that measurements of cold masses at block4 are not included in this analysis.
[4] S. Sanfilippo, private communication

- Allowed multipole b6: over the 19 available measurements (36 apertures), we see a difference between injection field at 1.9 K and cold masses at room temperature of -1.5 to –4.5 units.
    - As observed in the previous report, the measurements relative to apertures 256^{th} and 258^{th} (that were assembled in magnet 120) show a different offset from the previous ones (-1.5 units). These apertures had collars with very high permeability, thus leading to a lower b6 at room temperature (see Fig. 11). According to the cold measurements, this effect disappears at 1.9 K.
    - Magnet 114, 117 and 151, which has been measured in the last four months, also have an anomaly in the b6 correlation, the difference between cold and warm measurements being 1 to 2 units larger than usual. This would suggest that they belong to the family of high permeability collars, but as already observed in the previous paragraph this is not the case: both the measurements of the collar permeability and the values of b2 b6 and b10 measured at room temperature show no anomaly. The situation is not yet understood.
    - The correlation between room temperature measurements and high field at 1.9 K gives additional relevant information. Contrary to the previous case, in this offset the contribution of persistent current is not present and therefore one can exclude an effect of the cable magnetization. The observed pattern (see Fig. 23) is rather similar to the offsets at injection. Indeed, for 114 and 117 there is a rather large difference between the apertures. Anomalies in the offsets between high field at 1.9 K and room temperature are observed for Magnet 120, for one aperture of 114 and for one aperture of 117. The other data are consistent with an offset close to zero, as expected.

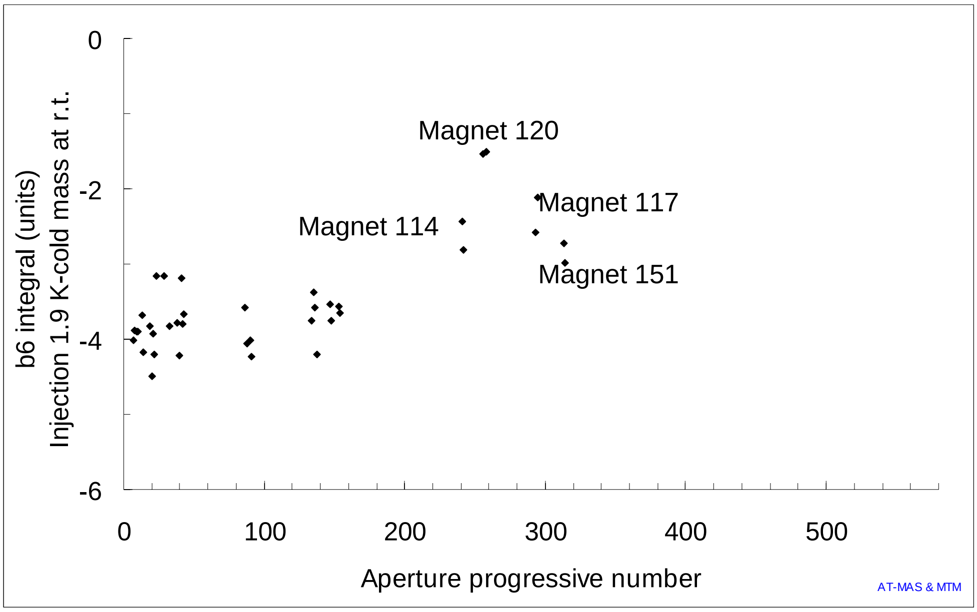


Fig. 22: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

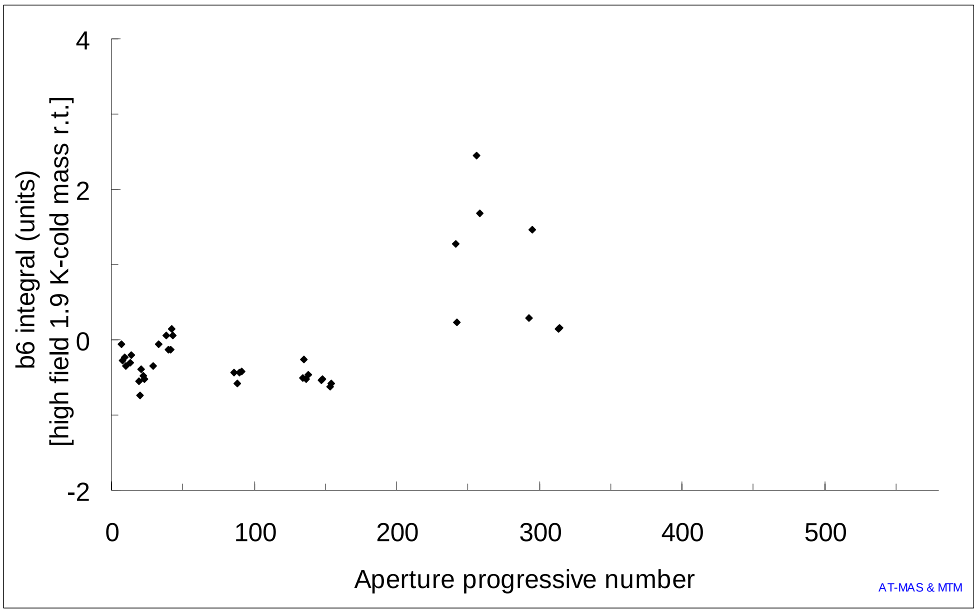


Fig. 23: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

3.5 Trends in coil waviness

- The coil waviness estimated from the variation of the multipoles along the axis has drifted from initial values of 10 to 30 micron to 15 to 45 micron in the more recent production. The situation is getting worse in the last 50 aperture manufactured in April-May (see Fig. 23).

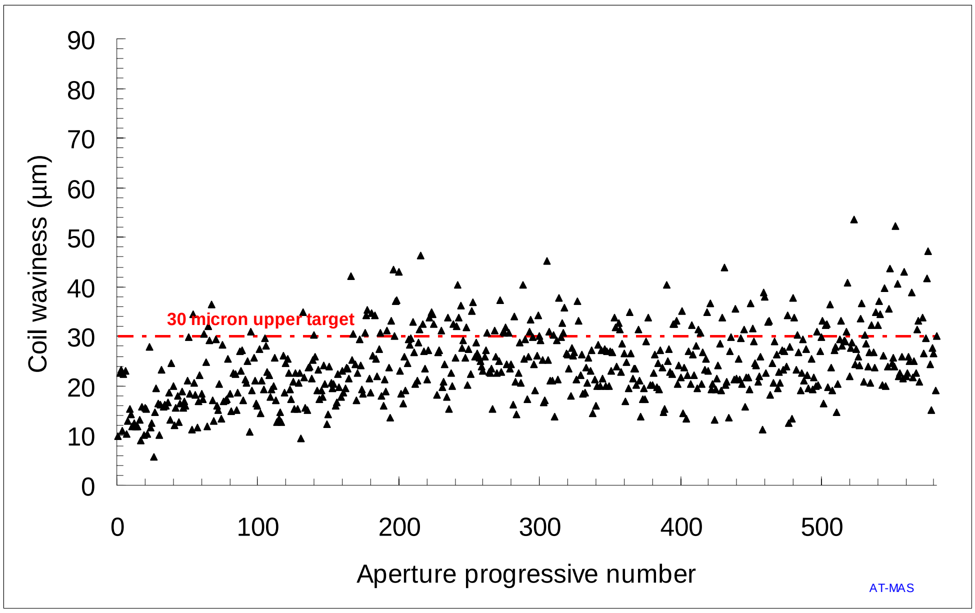


Fig. 24: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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 for data validation, storage, and analysis. We acknowledge F. Simon for comments and discussions.