Report on field quality in the main LHC quadrupoles: June-July 2005

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This report gives data relative to field quality measured at room temperature in quadrupole collared coils and cold masses during the period June-July 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. **633852**

The dashboard

- Available measurements: at room temperature we have 621 apertures (310.5 magnets) and 239 cold masses. At 1.9 K we have measurements of 21 quadrupoles.
- In these two months, 51 apertures (i.e., 25.5 equivalent quadrupoles) and 23 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 crisis due to the use of collars with high permeability, inducing higher field gradient and lower b6 at room temperature, is over. A total of 39 apertures (19.5 magnets) have been produced. Now the permeability of collars is within specifications, and the stock of "bad" collars seems to be exhausted.
- **Spread of focusing strength:** With these apertures made up of collars with high permeability, we have a field gradient that can be up to 100 units more than average at room temperature. The spread in the main field is now 19 units, i.e. 50% more than the revised target of 13 units. Without these apertures, the spread is 13 units.
- **Warm-cold correlations:** A new calibration of the data has been performed. One aperture with high collar permeability has been measured at 1.9 K, showing that the effect disappears in operational conditions. Other anomalies in warm-cold correlations have been found, and part of them can be attributed to the collar permeability. More data should confirm this first encouraging result.

CONTENTS

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 51 new apertures (i.e. 25.5 equivalent quadrupoles) and 23 cold masses have been measured at room temperature (see Fig. 1).

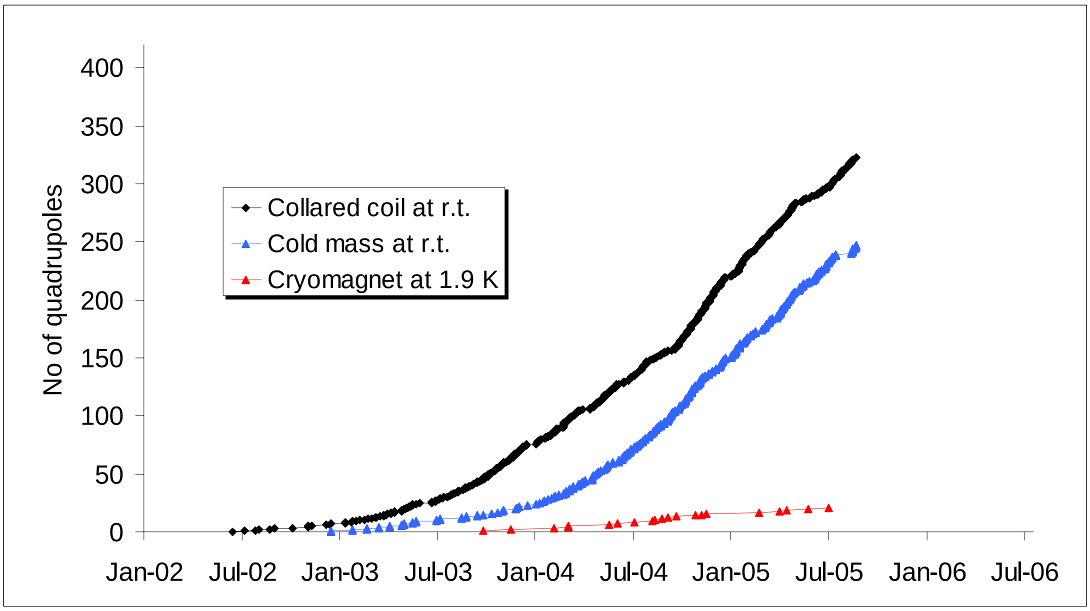

Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

- 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.

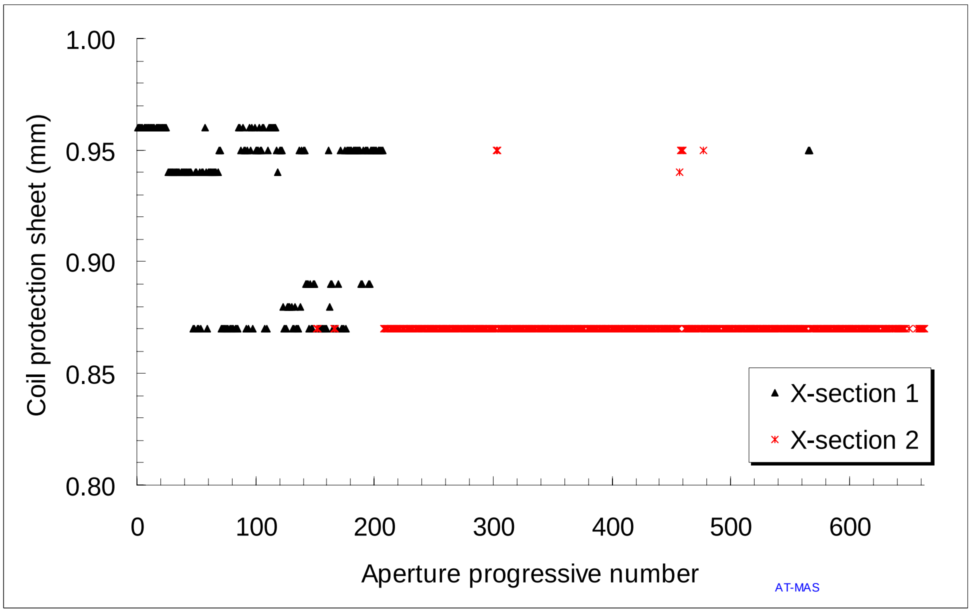

Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[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).

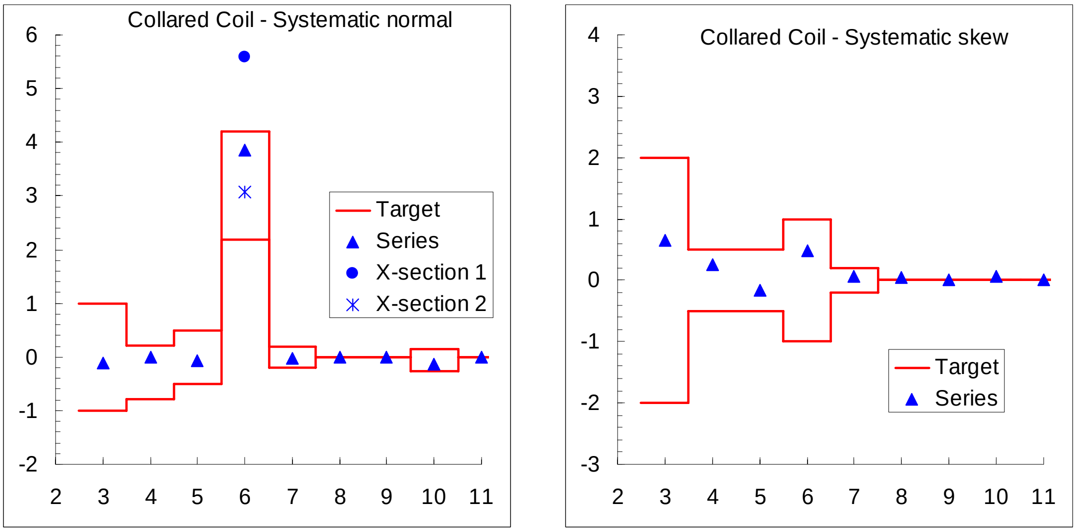

Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (solid lines).

- 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 18.7 units, i.e. 87% 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 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 of the integrated field gradient.
- The spread of b6 over all apertures (1.6 units) is mainly due to the mixing of the two different X-sections and partly to the high permeability collars. Indeed, the target for beam dynamics on random b6 is not a hard limit.

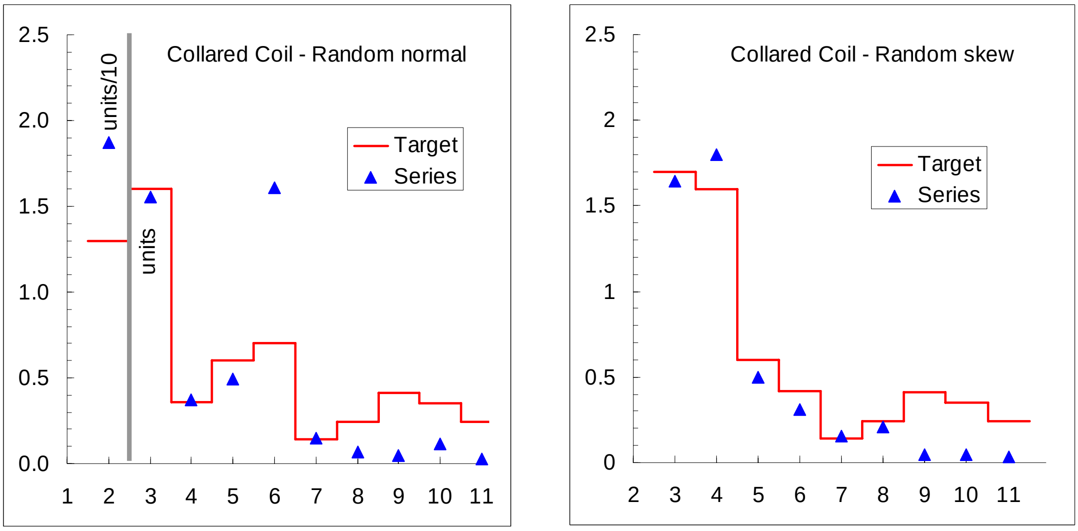

Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

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 17 apertures between 567th and 600th (see Fig. 5) have a magnetic length of around 5 to 15 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].

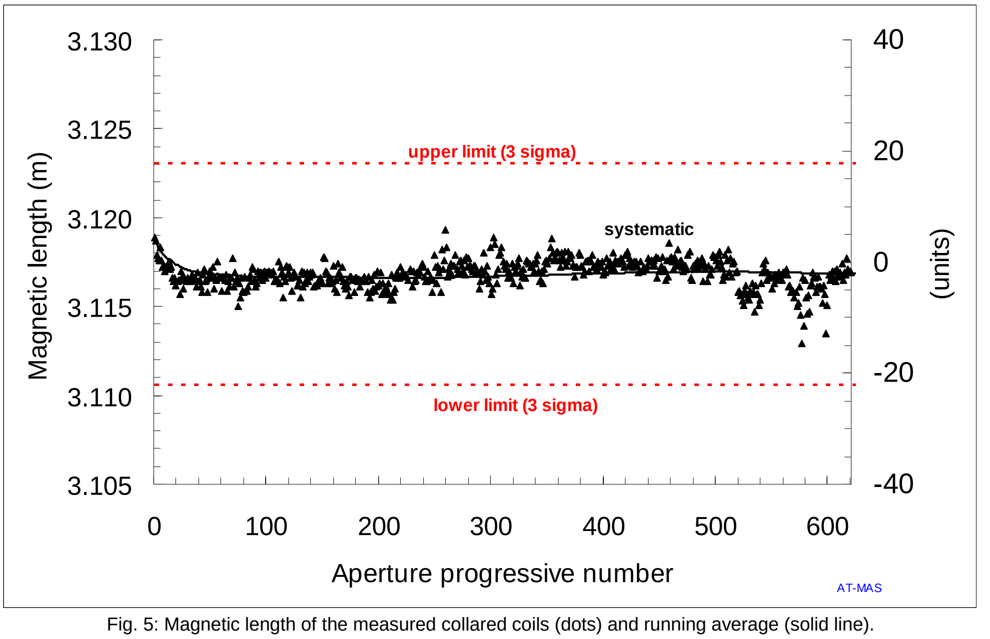

Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

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

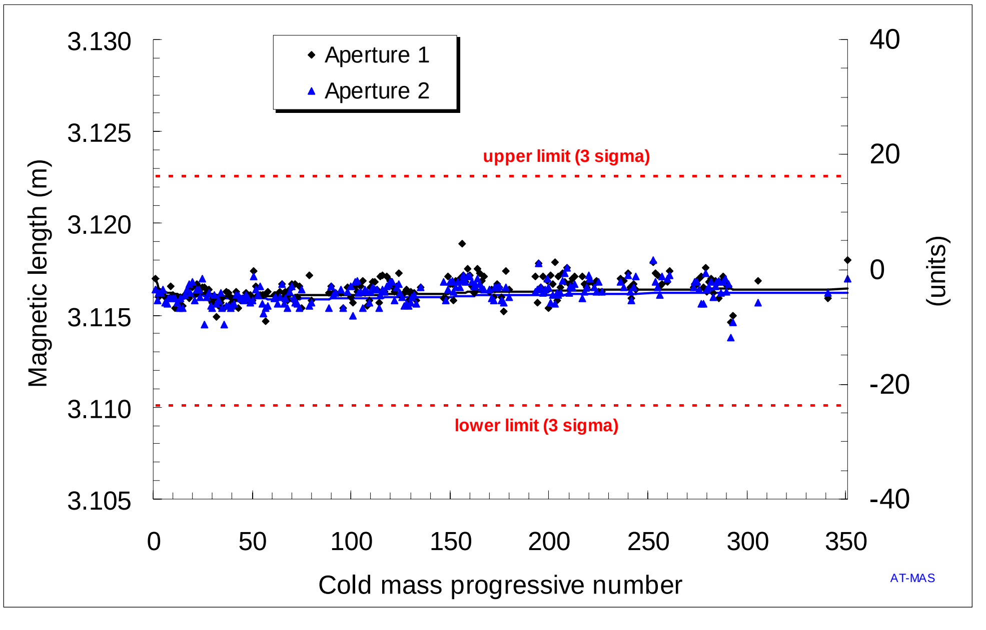

Fig. 6: Magnetic length of the measured **cold masses** and running average (solid line).

[2] F. Simon, private communication

3.1.2 Trends in field gradient

- 22 apertures between 520th and 541st and 17 apertures between 567th and 600th (see Fig. 7, circles) 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 17 of 40 to 100 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-600th is 13.7 units, and it becomes 19.8 units if these apertures are included in the statistics.

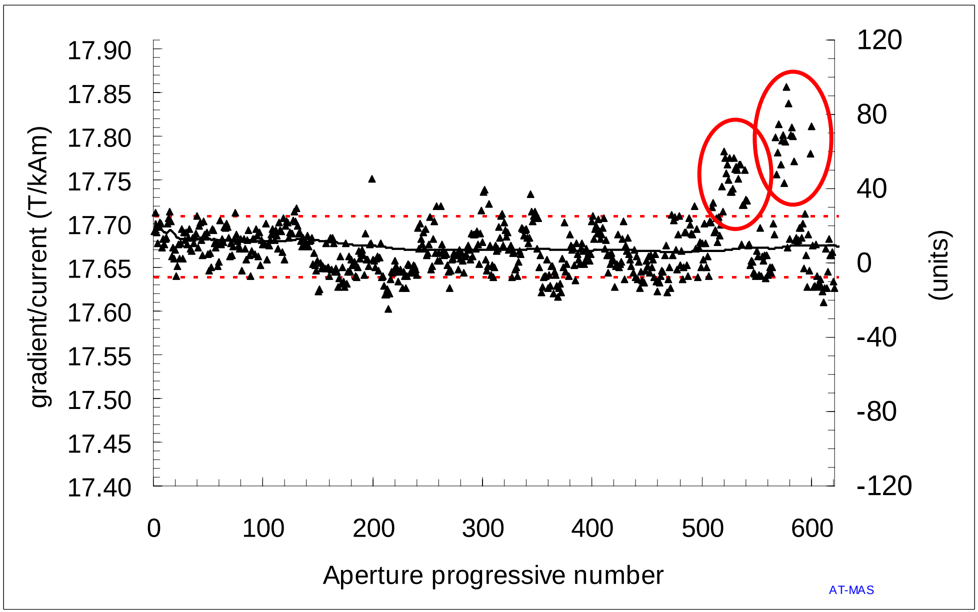

Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines). Recent apertures manufactured with high permeability collars are marked by a circle.

- The spread observed in apertures is confirmed by **cold mass** data. Eight apertures manufactured with high permeability collars (523rd, 525th, 531st, 534th, 527th, 583rd, 567th and 570th) 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, circles).

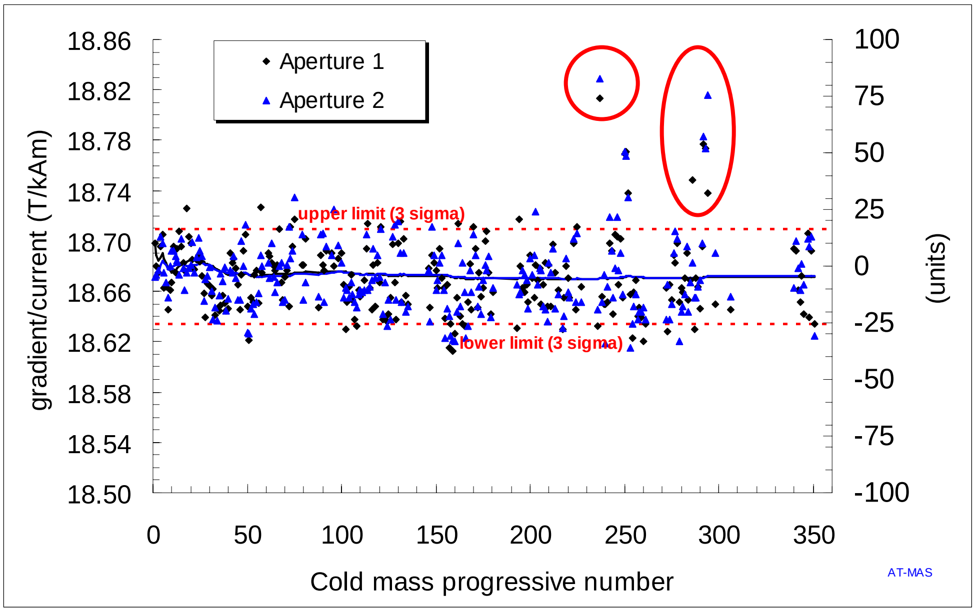

Fig. 8: Field gradient of the measured **cold masses** and running averages (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

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 13.5 units (18.7 units including the apertures 520th-541st and 567th-582nd), and for the cold masses is 16 units (high permeability apertures included).

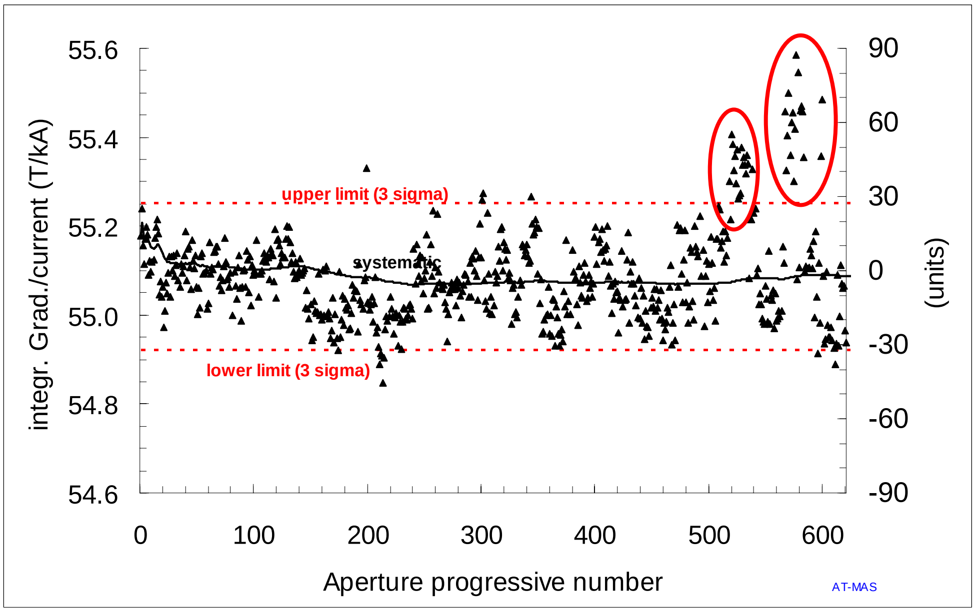

Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

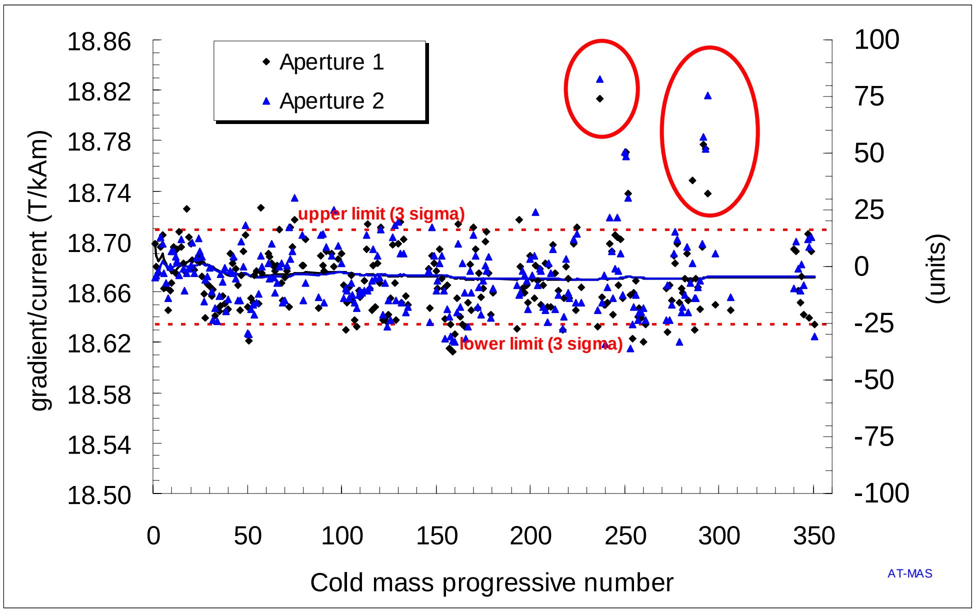

Fig. 10: Integrated field gradient of the measured **cold masses** and running averages (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

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 17 apertures between 567th and 600th have manufactured with high permeability collars (circles in Fig. 11). These apertures have a b6 of 2 to 8 units lower than the recent production, corresponding to a higher permeability of 0.01 to 0.03.

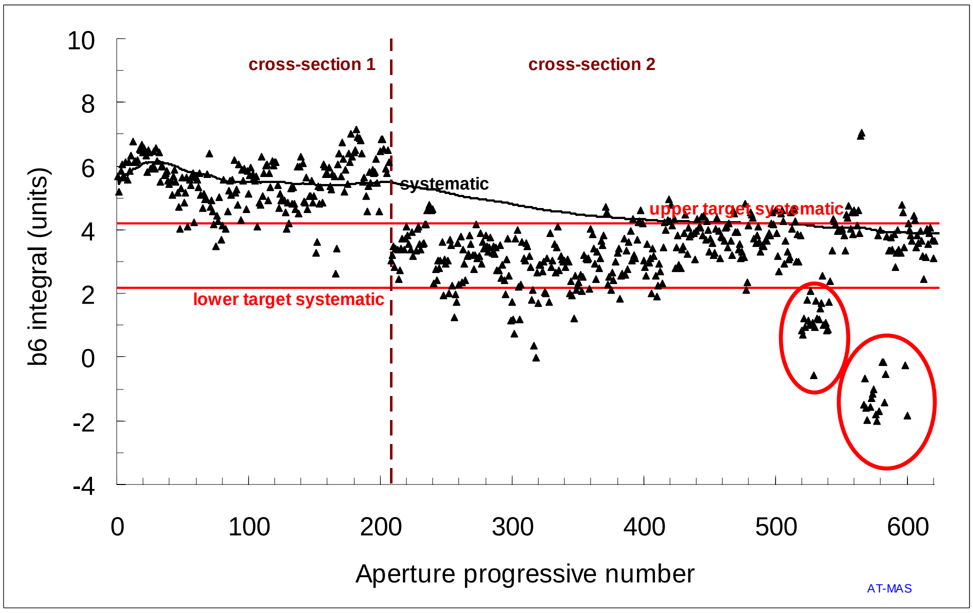

Fig. 11: Integral b6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations measured at 1.9 K on 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a circle.

- Systematic b10 is well within targets (see Fig. 12). Apertures 520th-541st and 17 apertures between 567th and 600th have manufactured with high permeability collars (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.

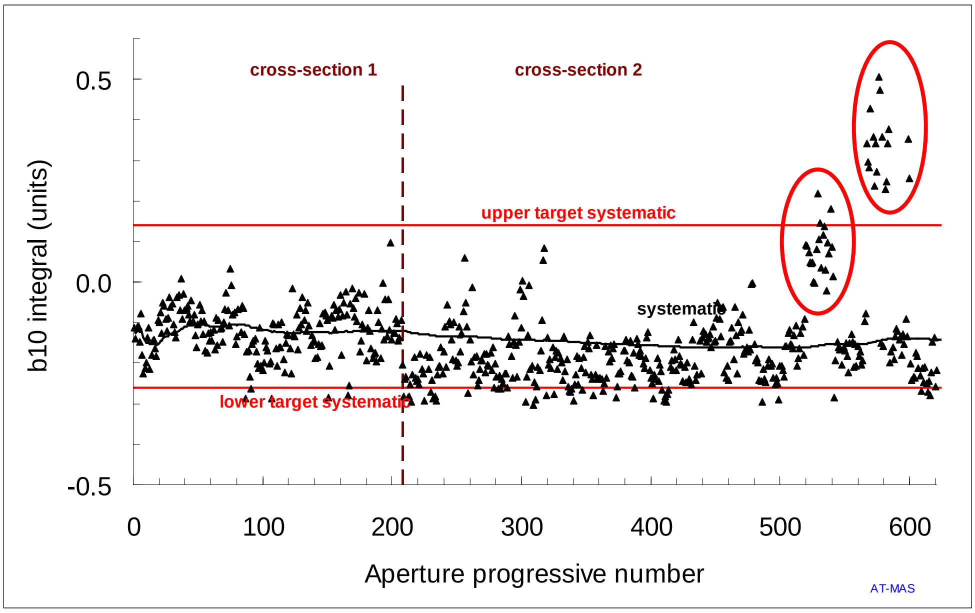

Fig. 12: Integral b10 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations with 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a red circle.

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.

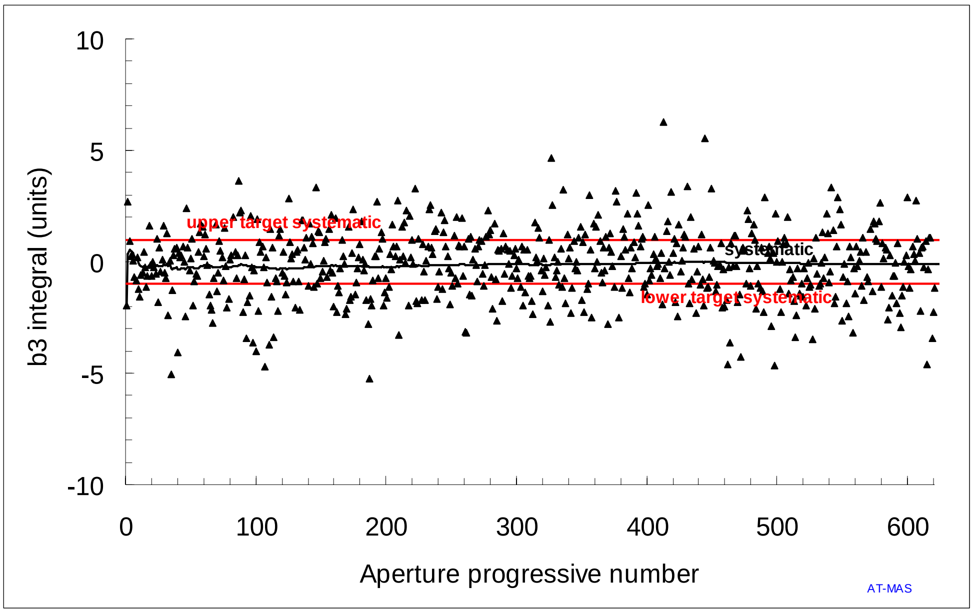

Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

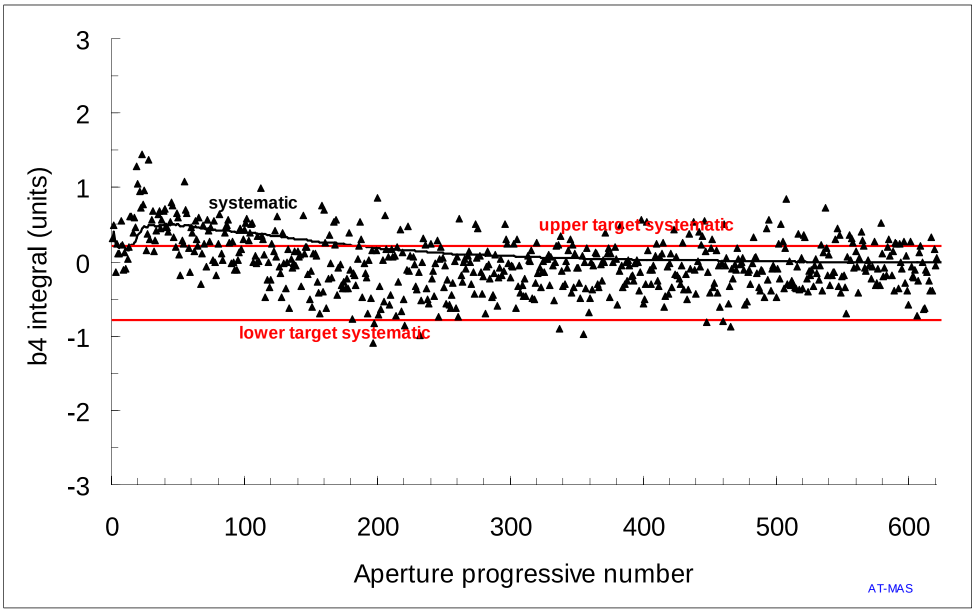

Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

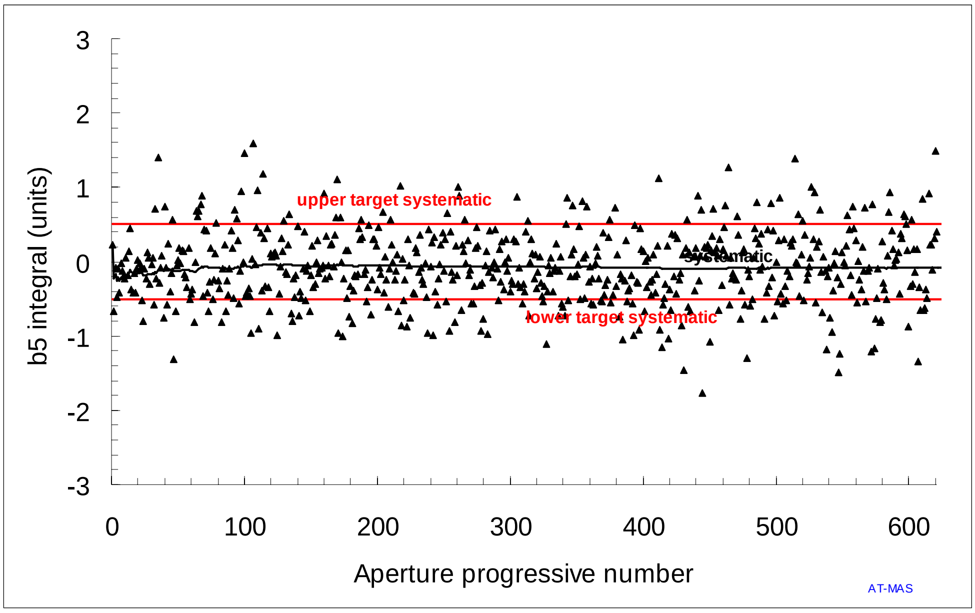

Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

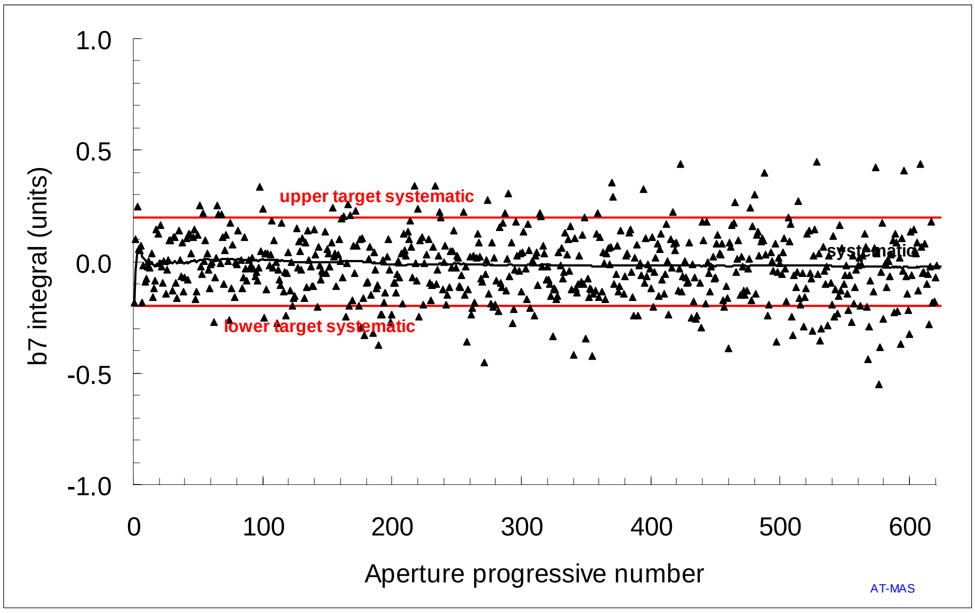

Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

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 is not critical for beam dynamics since it is within targets.

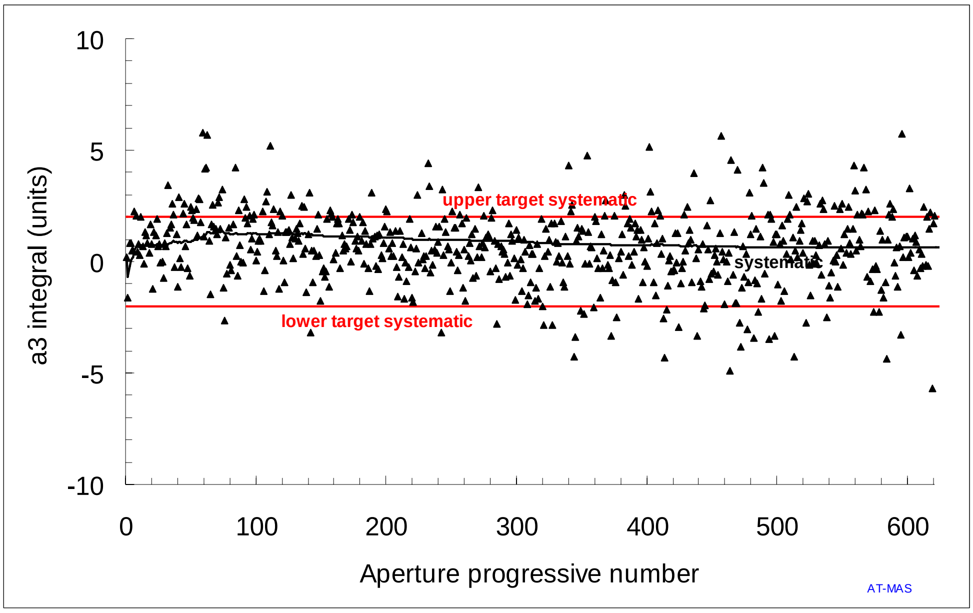

Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

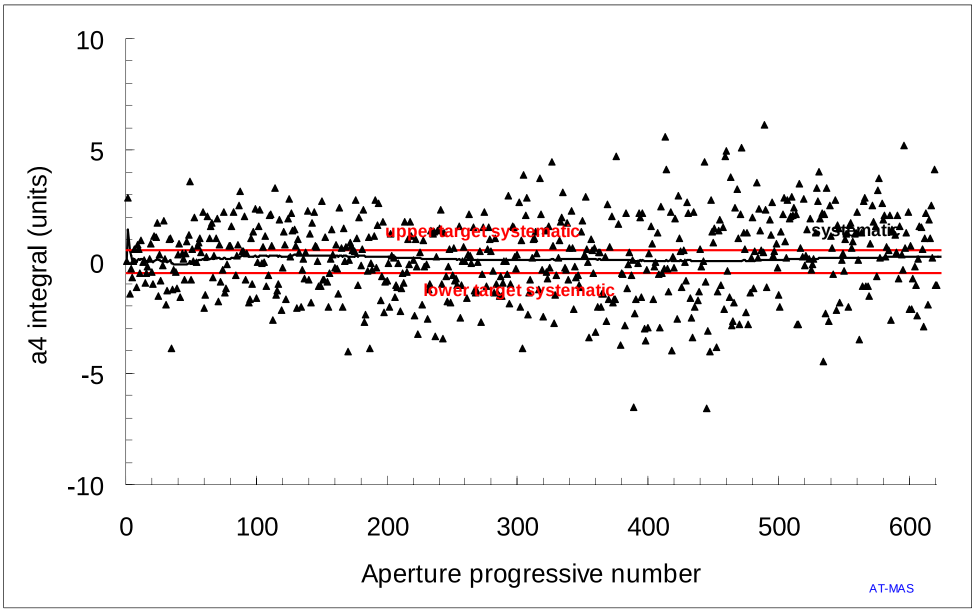

Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

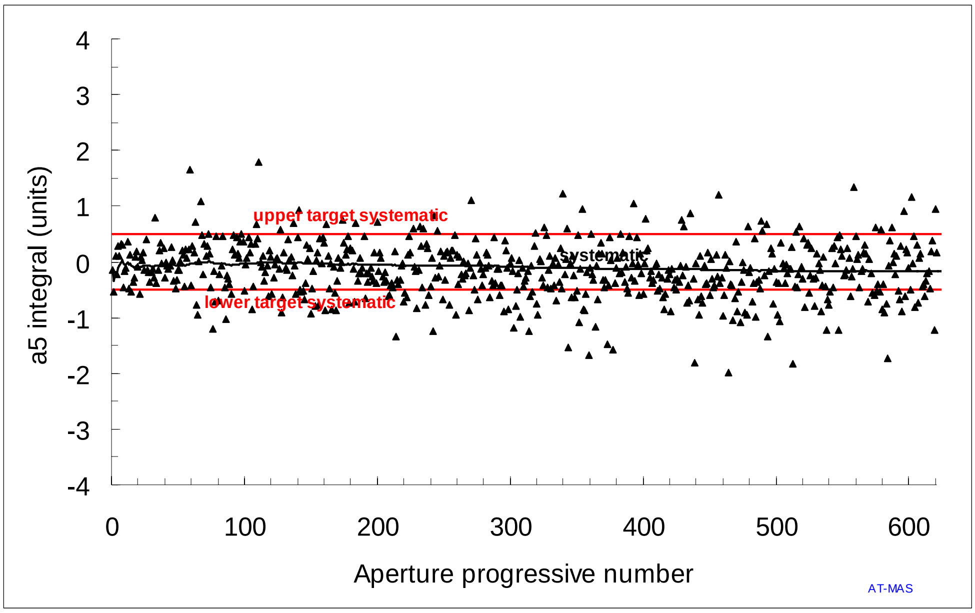

Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

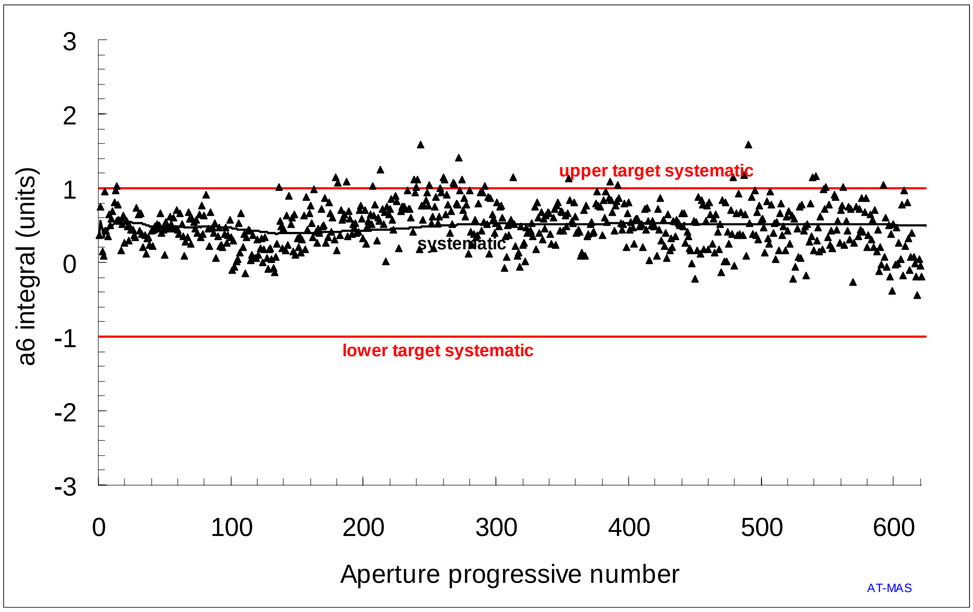

Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

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 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 364th, 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 17 measured quadrupoles (34 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 following remarks can be done
    - The plot does not agree with the plot of the previous report, since an update of data at 1.9 K has been done. Since a systematic offset was observed between measurements with single stretched wire and mole, data relative to the mole measurement have been shifted to cancel out the offset.
    - In Fig. 21, we distinguish between magnets for which no permeability measurement is available, and magnets whose permeability is normal (≤1.008) and large (more than 1.008).
        - The 2 apertures with measured high permeability have an anomalous correlation, corresponding to a vanishing effect at 1.9 K.
        - The 4 apertures with measured normal permeability have normal correlation.
        - For the data without permeability measurement, 6 apertures have anomalies in correlation: two at a very early stage of the production, which cannot be attributed to an error in permeability since the correlation for b6 is normal (see next section). Four of them (between aperture 200th and 400th) correspond to apertures whose field gradient is 17.69 to 17.72, i.e. in the upper part of the range (see Fig. 7). The same magnets also have high offset for the b6, and therefore they are compatible with the hypothesis of a high permeability. Indeed, these tested apertures have a field gradient at room temperature of 20 to 30 units higher than average, i.e. we are still very far from the strongest anomalies that have been produced (up to 100 units).

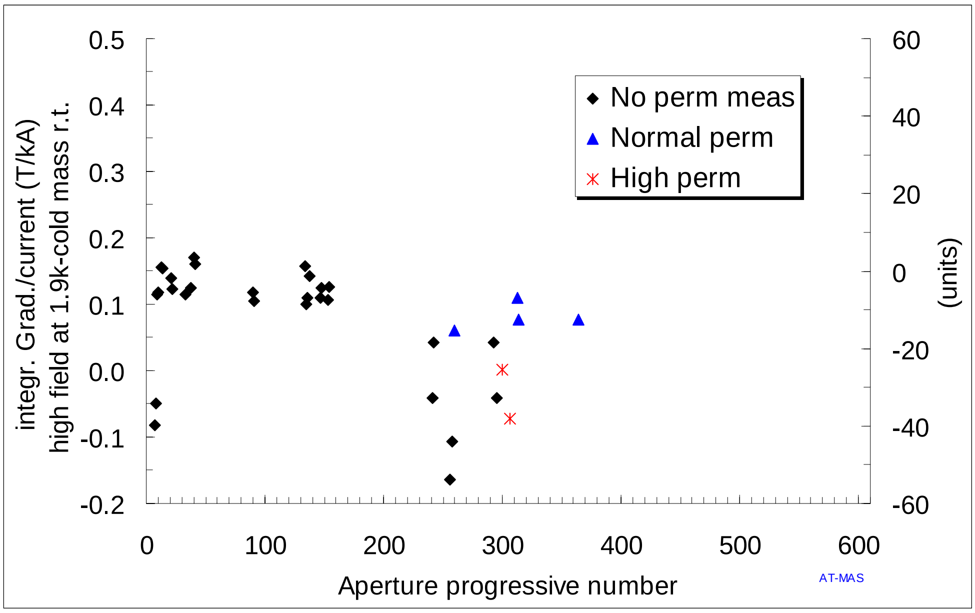

Fig. 21: Difference in focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

[3] Please note that measurements of cold masses at block4 are not included in this analysis.

- Allowed multipole b6: over the 21 available measurements (42 apertures), we see a difference between high field at 1.9 K and cold masses at room temperature of -1 to 2.5 units.
    - Measurements in the early phase of the production (up to aperture 200th) are coherent with an offset close to zero, and a spread of 0.2-0.3 units (one sigma). Contrary to the case of the field gradient we have no anomalies in correlations for this part of the production.
    - Measurements of two apertures with high permeability show a strong anomaly in the correlation, corresponding to a vanishing effect of the permeability at 1.9 K.
    - Measurements of four apertures with normal permeability show an offset from 0 to 0.8 units, which is close to what observed in the previous production (-0.8 to 0.15 units), but not exactly the same.
    - Strong anomalies are found in four apertures (241st, 256th, 258th, 295th) for which no permeability measurements are available, with offsets from 1.3 to 2.5 units. All these apertures have b6 at room temperature between 1.2 and 2.3 units, i.e. rather low values, suggesting an anomaly in the permeability.

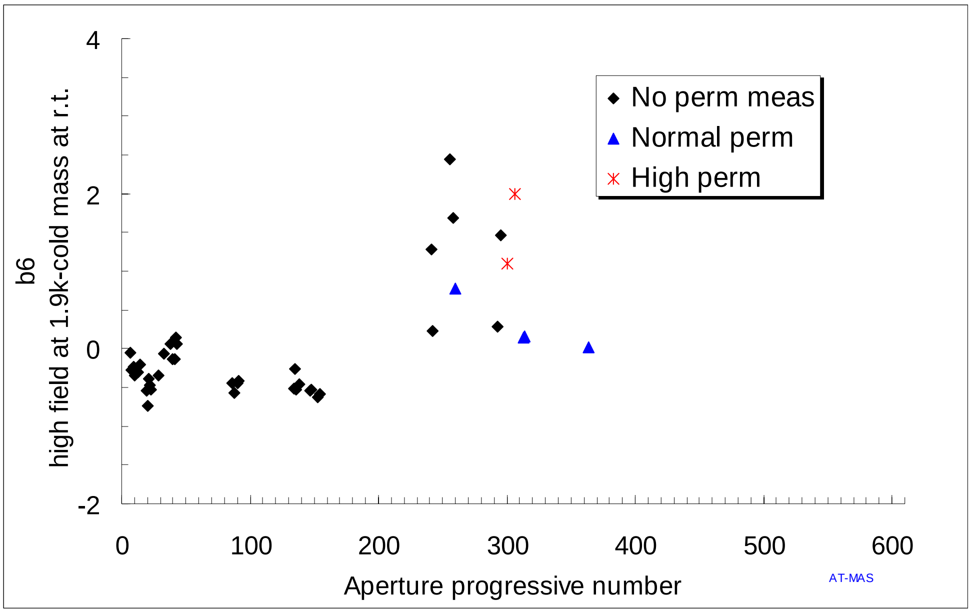

Fig. 22: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

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 improving in the production of the last two months (see Fig. 23).

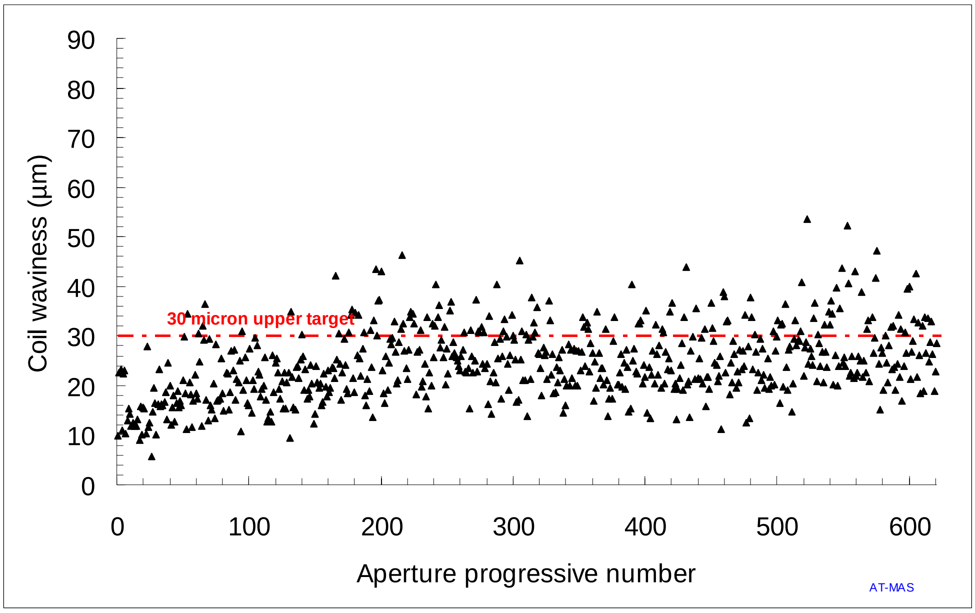

Fig. 24: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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.