# Report on field quality in the main LHC quadrupoles: August-September 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 August-September 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.

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## The dashboard

- Available measurements: at room temperature we have 681 apertures (340.5 magnets) and 270 cold masses. At 1.9 K we have measurements of 22 quadrupoles.
- In these two months, 60 apertures (i.e., 30 equivalent quadrupoles) and 31 cold masses have been measured at room temperature. One new measurement is available at 1.9 K.

## What's new

**Issues critical for beam dynamics:**

- **More than 85%** of the production of quadrupole apertures (superconducting coils in the collars) has been completed.
- **Collar permeability:** Apertures are being produced with collar magnetic permeability within specifications. Magnetic measurements show no anomalies in b2, b6 and b10 as expected.
- **Spread of focusing strength:** The situation is stable.
- **Warm-cold correlations:** One magnet has been measured at 1.9 K in these two months. Its collar permeability has not been measured, but has been estimated as normal: no anomalies in correlations have been found, as expected. A method to estimate the permeability from field anomalies when no direct measurements are available has been developed. The phenomenology of data is consistent with the hypothesis that the permeability effect disappears in operational conditions.

## CONTENTS

# PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 60 new apertures (i.e. 30 equivalent quadrupoles) and 31 cold masses have been measured at room temperature (see Fig. 1).

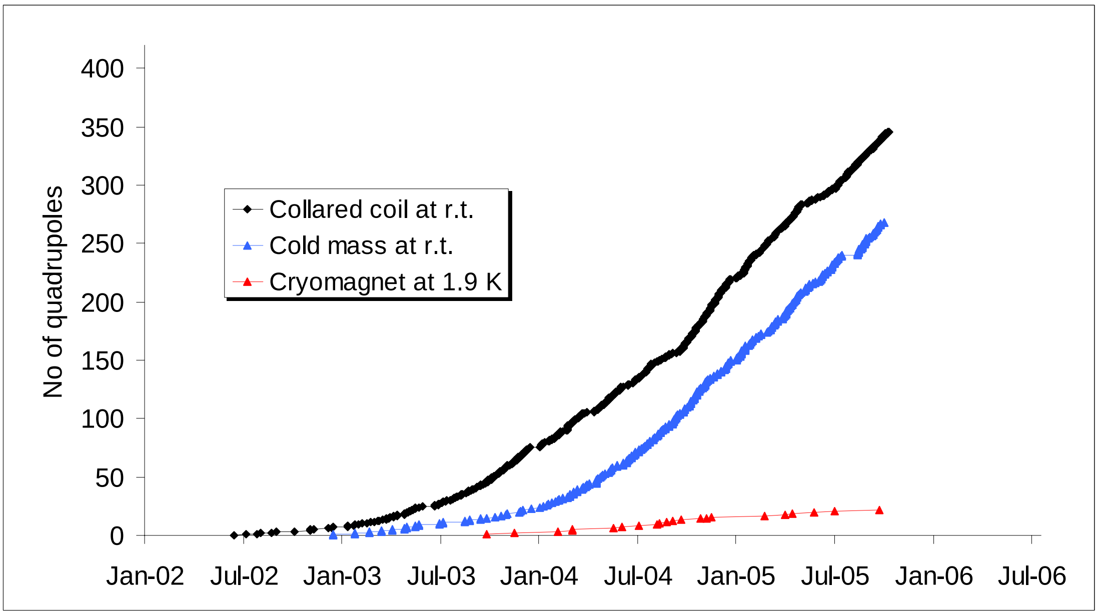


Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

- Coil protection sheet[1]: all new apertures have a coil protection sheet of 0.87 mm, with one exception.

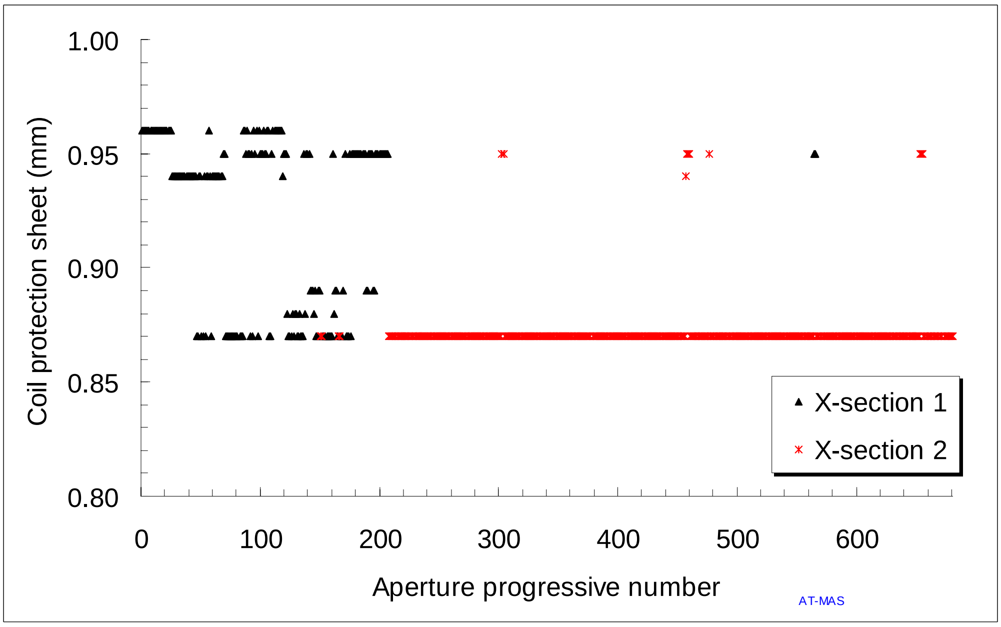


Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[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 481 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).

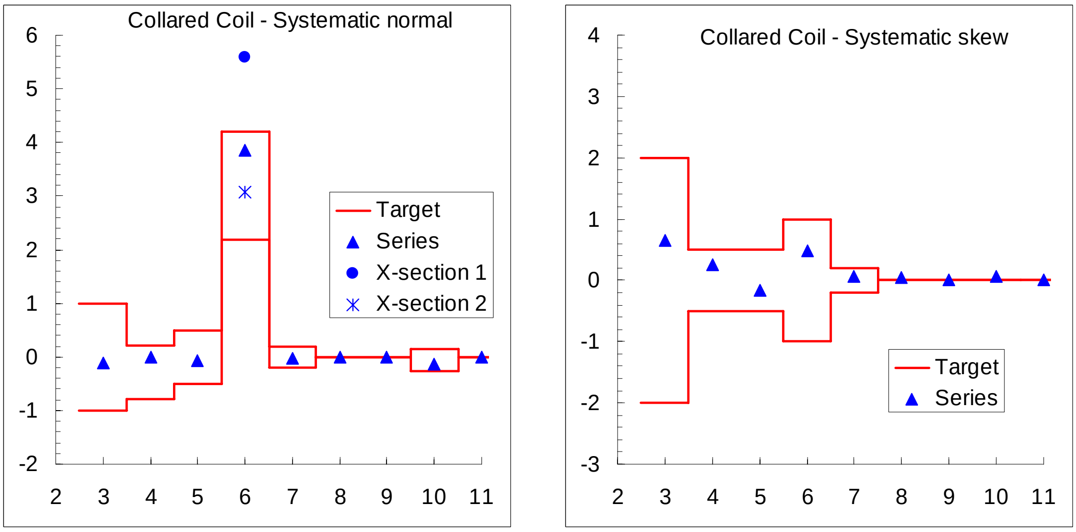


Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (solid lines).

- 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 18.3 units, i.e. 83% 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.

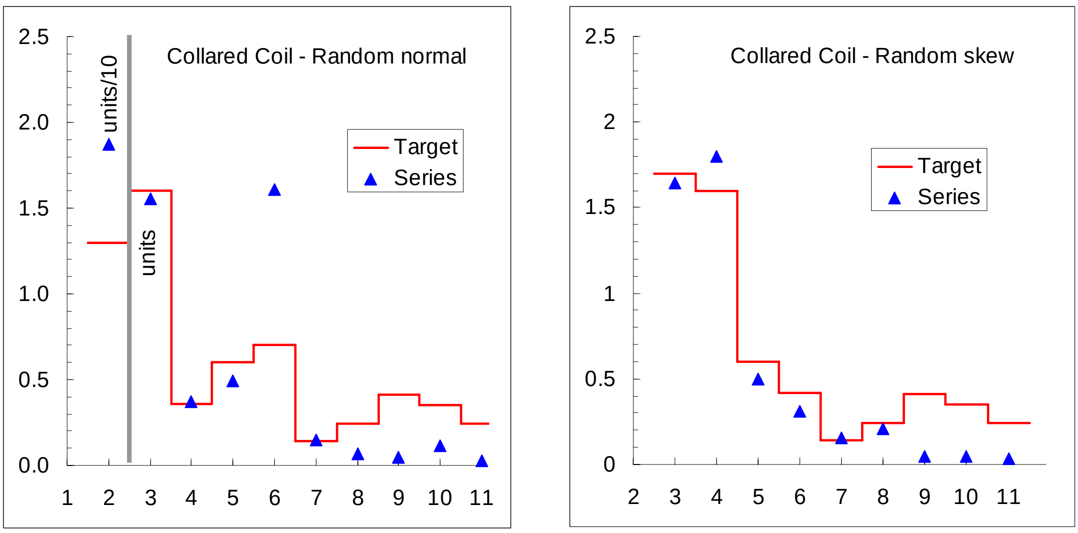


Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

# 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). No anomalies due to high collar permeability have been found in the last two months.

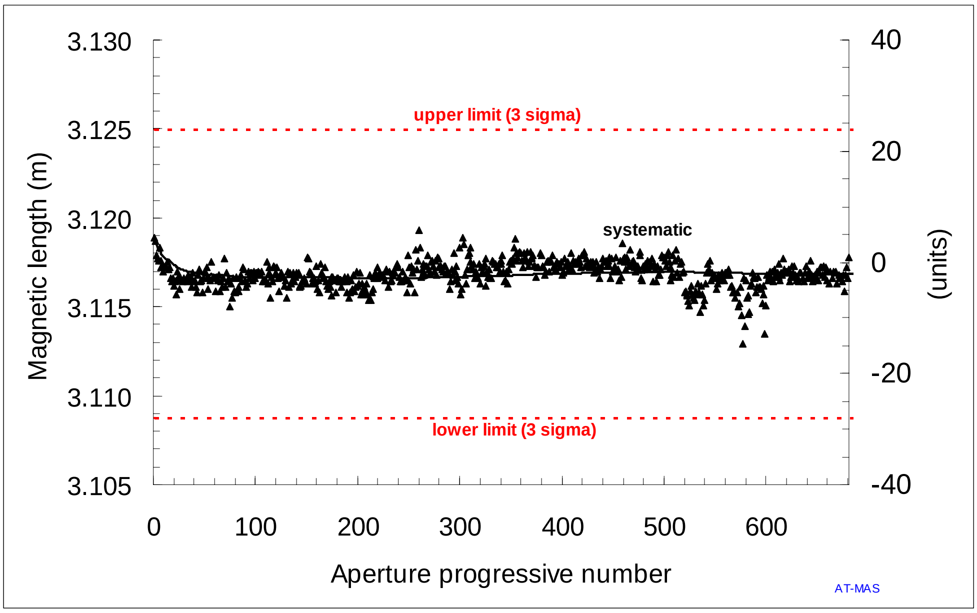


Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

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

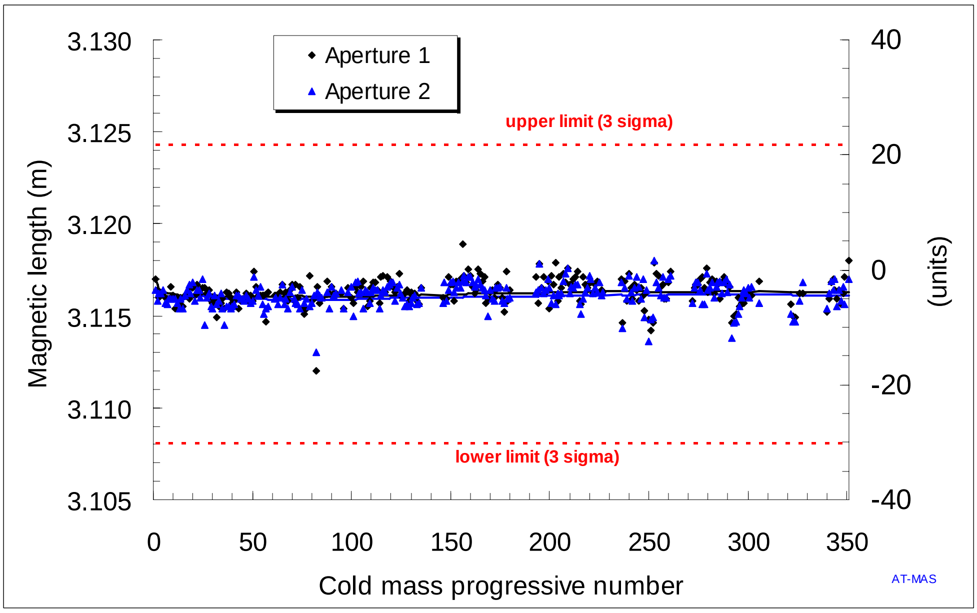


Fig. 6: Magnetic length of the measured **cold masses (black dots, aperture1 and blue dots, aperture 2)** and running average (solid line).

### 3.1.2 Trends in field gradient

- The apertures manufactured in these two months (620th to 681st) have a field gradient within targets. These apertures have collars with permeability within specifications.
- The spread of the field gradient excluding apertures 520th-541st and 567th-600th (high permeability collars) is 13.5 units, and it becomes 19.2 units if these apertures are included in the statistics.

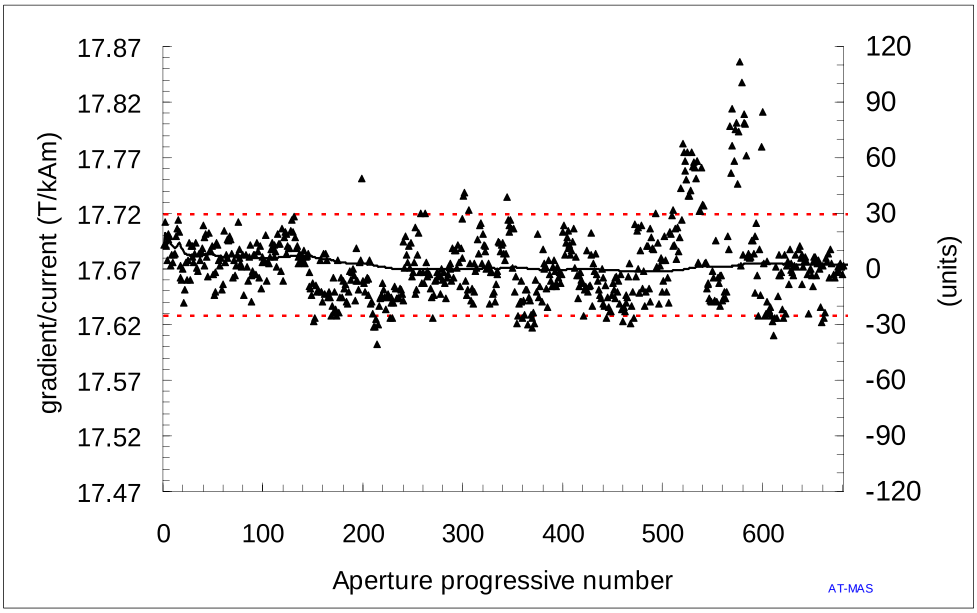


Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines).

- The spread observed in apertures is confirmed by **cold mass** data. Eight more apertures manufactured with high permeability collars (527th, 539th, 567th, 568th, 570th, 577th, 579th and 583rd) 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).

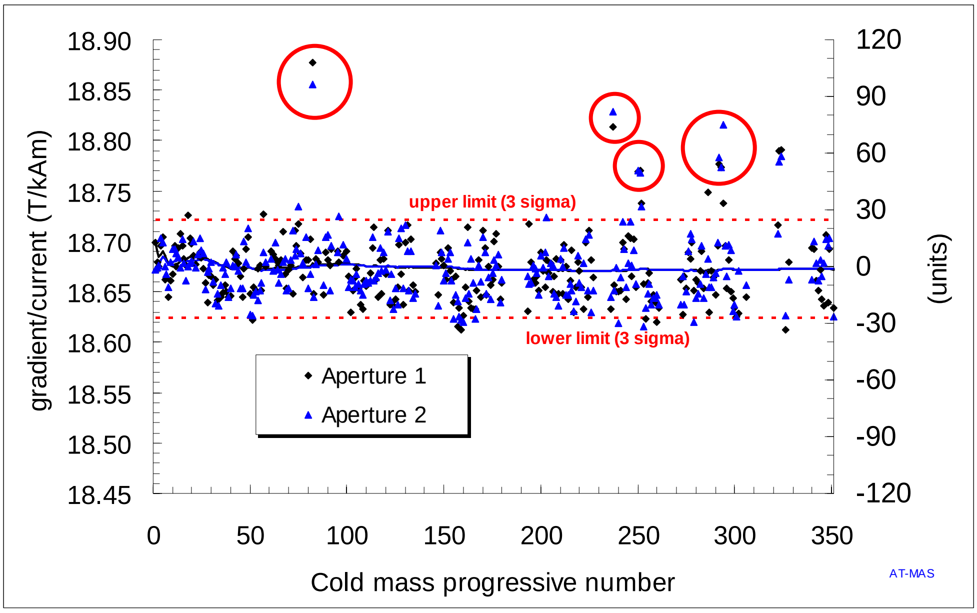


Fig. 8: Field gradient of the measured **cold masses (black dots, aperture1 and blue dots, aperture 2)** and running averages (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

### 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 13.3 units (18.3 units including the apertures 520th-541st and 567th-600th), and for the cold masses is 16.7 units (high permeability apertures included).

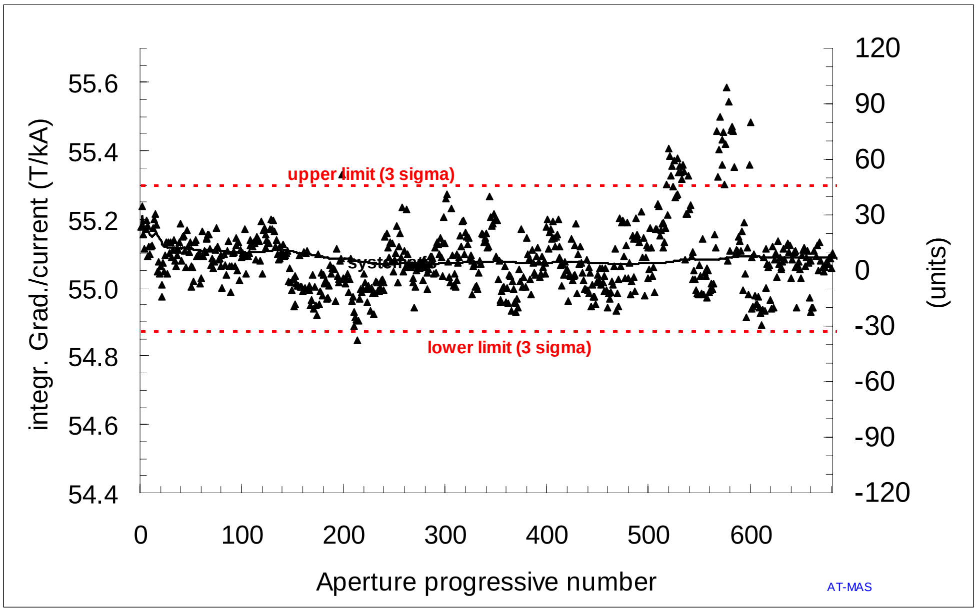


Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid line).

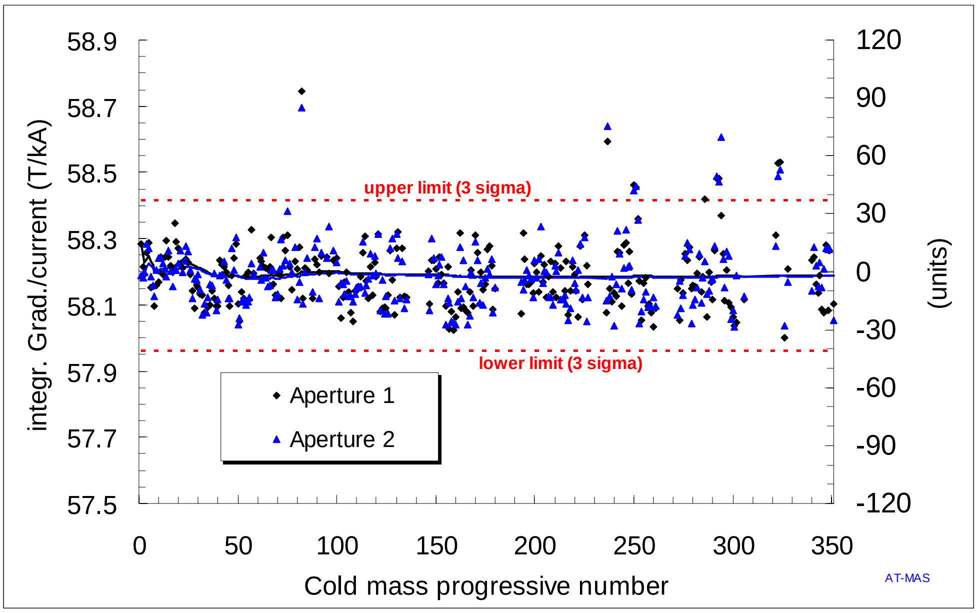


Fig. 10: Integrated field gradient of the measured **cold masses (black dots, aperture1 and blue dots, aperture 2)** and running averages (solid line).

## 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).
- The permeability being within specifications, measured values of b6 and b10 in the last two months are within targets (see Fig. 11 and 12).

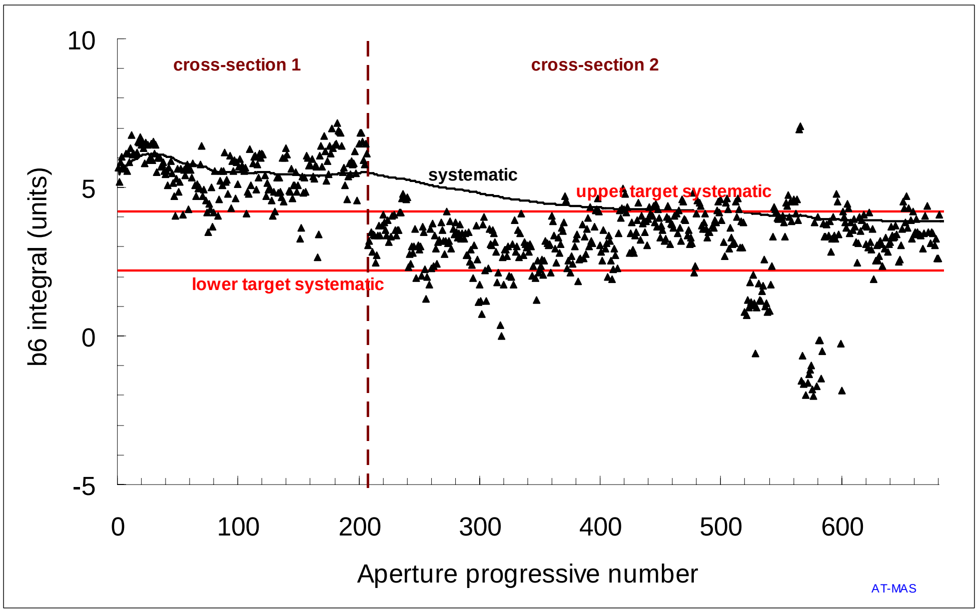


Fig. 11: Integral b6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations measured at 1.9 K on 17 quadrupoles.

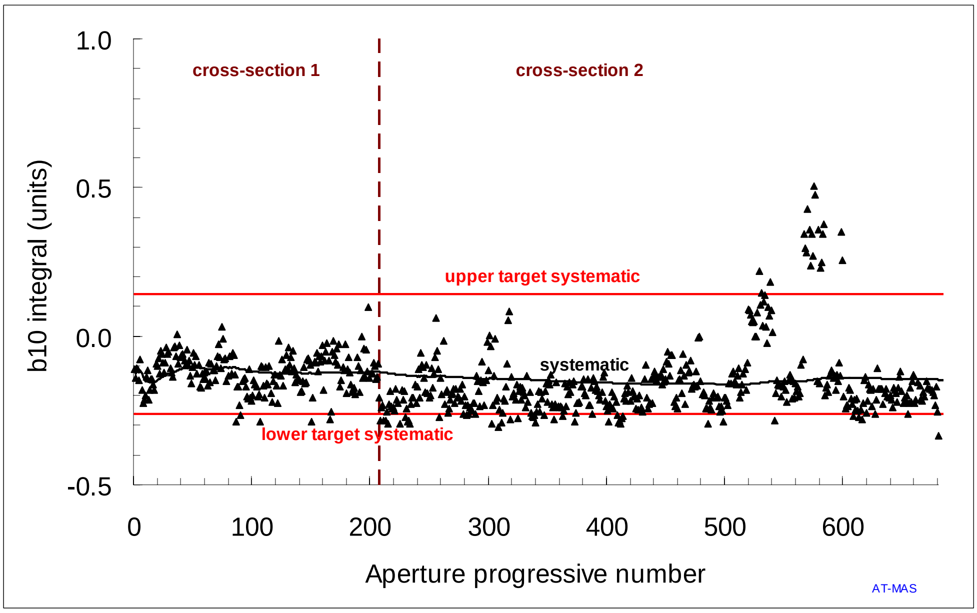


Fig. 12: Integral b10 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations with 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a red circle.

## 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.

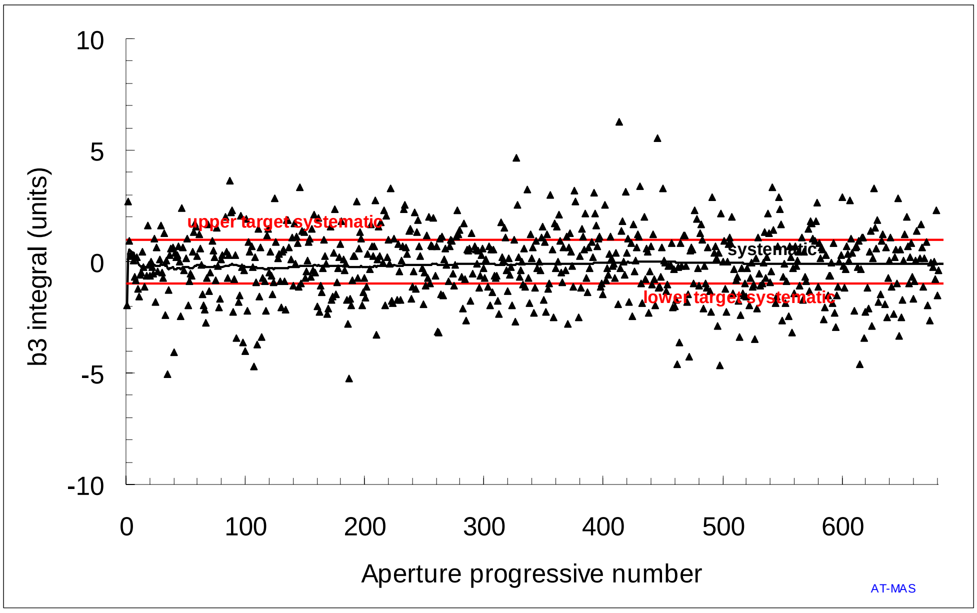


Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

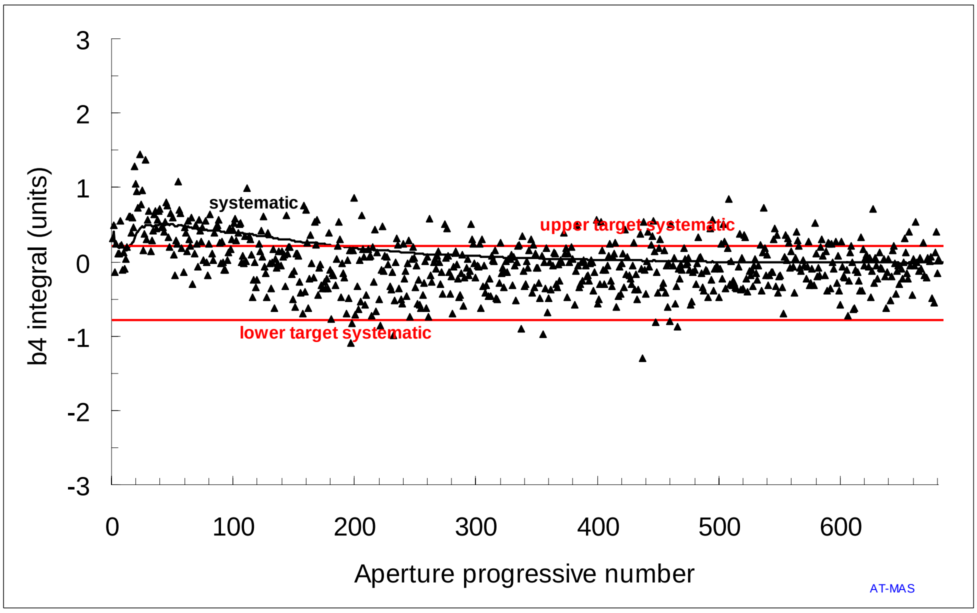


Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

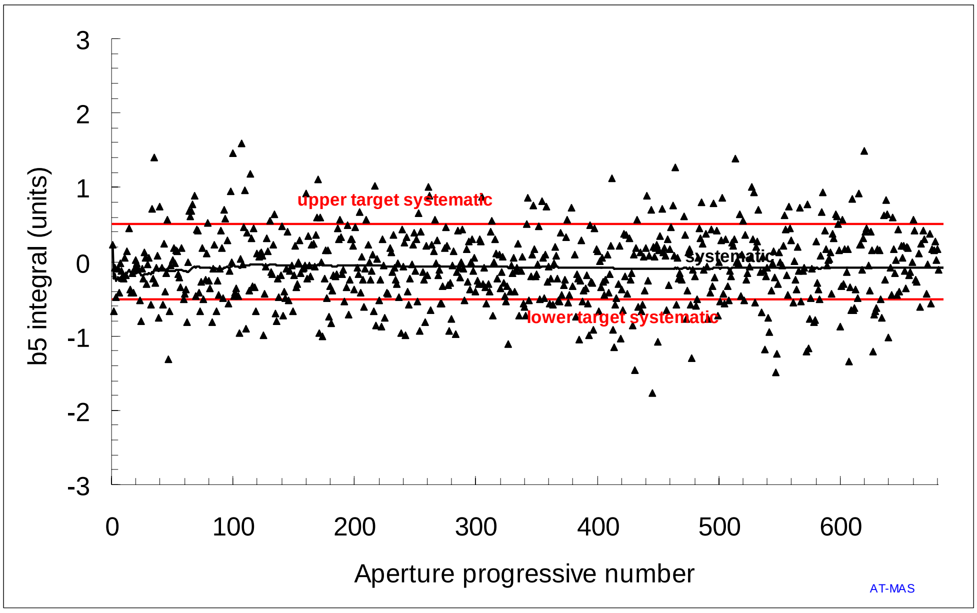


Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

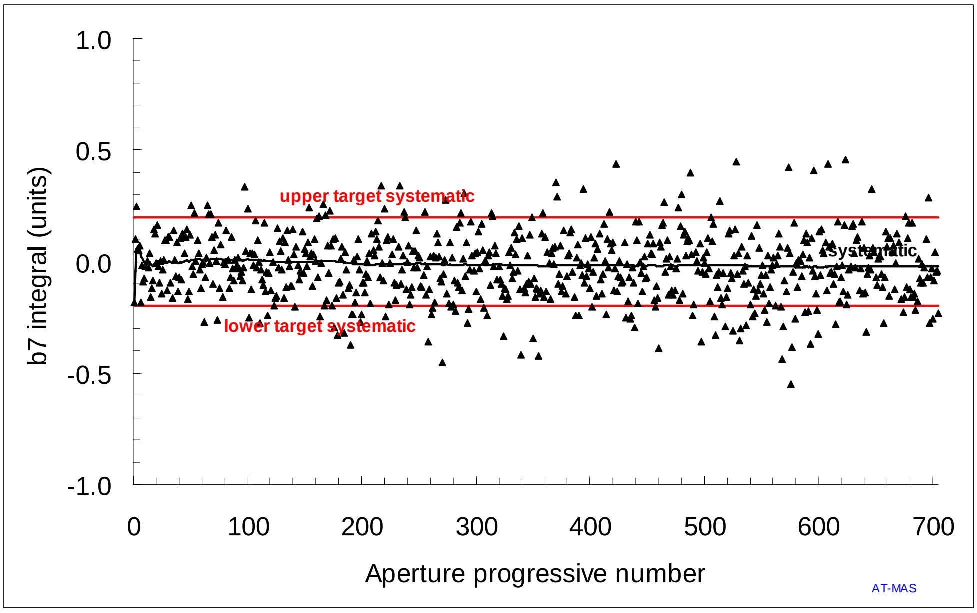


Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

## 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.

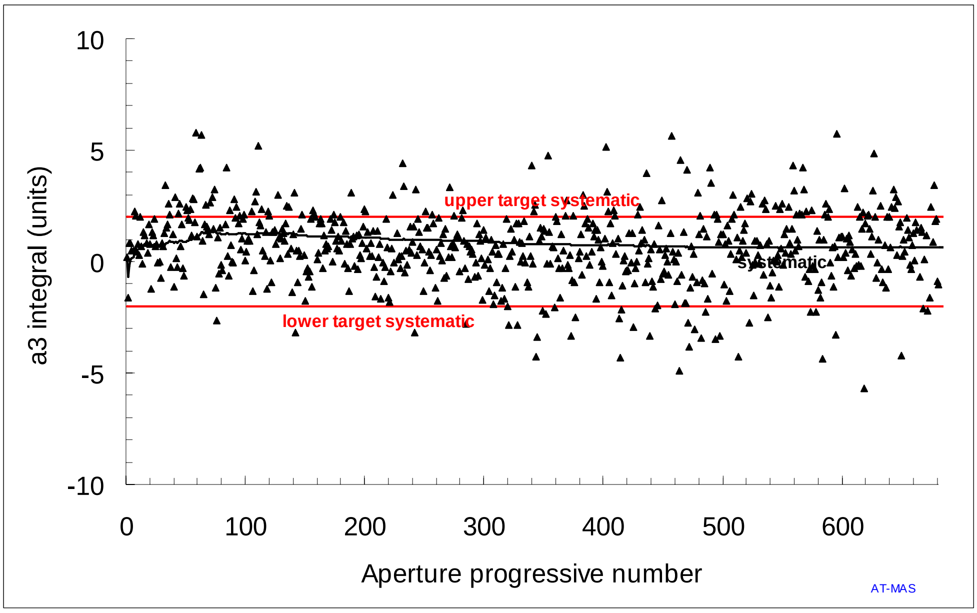


Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

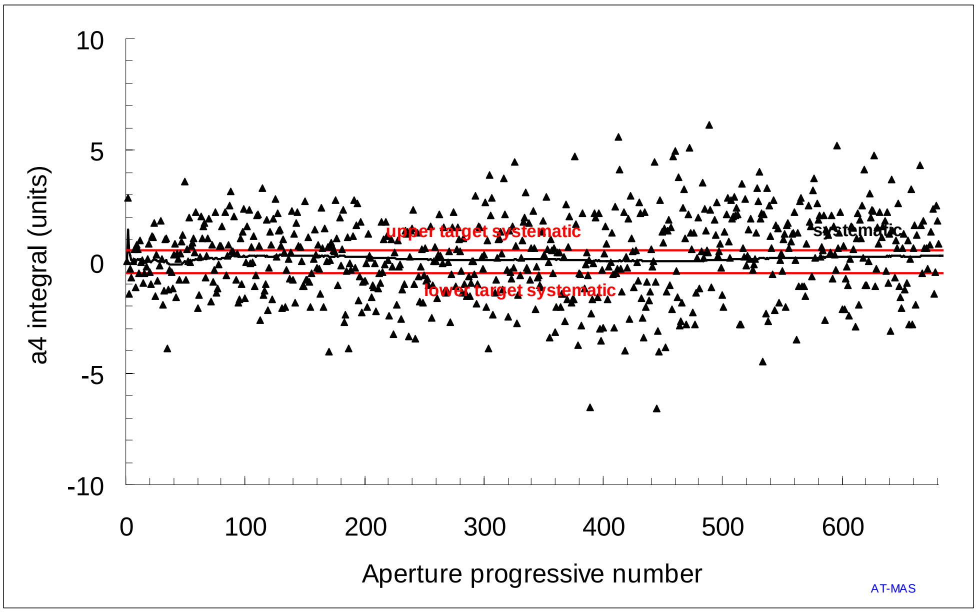


Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

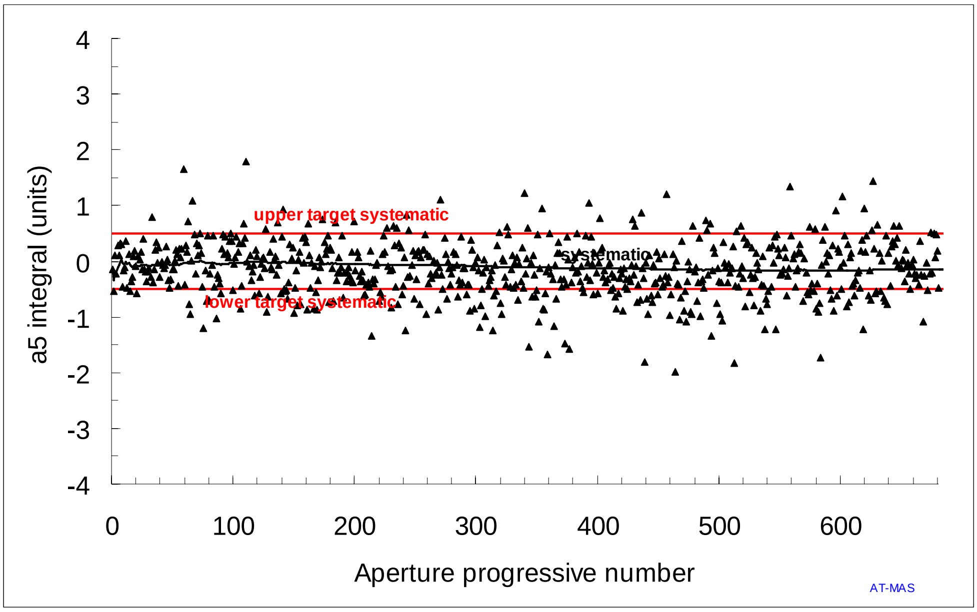


Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

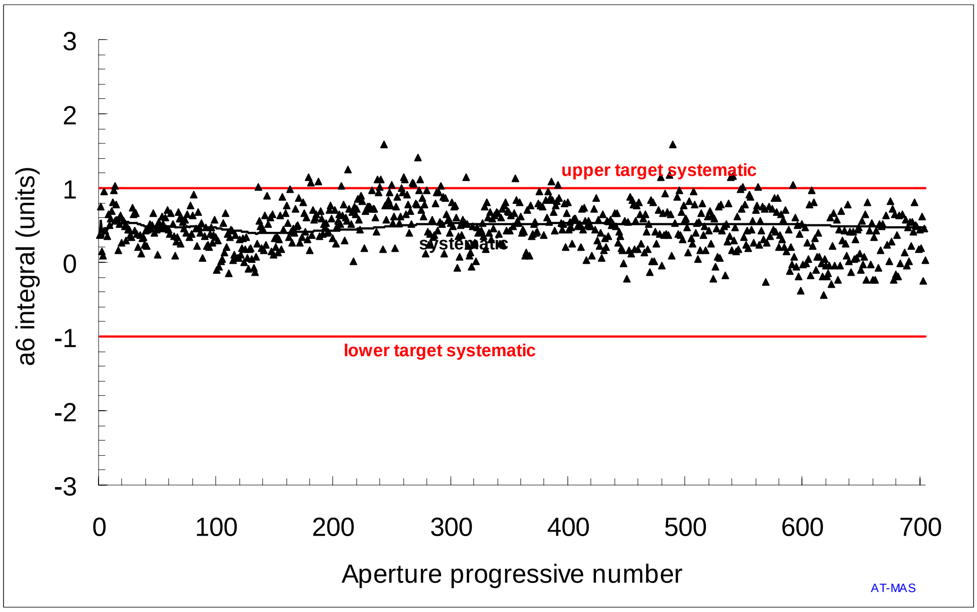


Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

## 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 160 quadrupoles between room temperature measurements of collared coil and test at 1.9 K[2], equivalent to 11 months of production), and allows to detecting trends in correlations along the production.

- Integrated field gradient: we present data of 18 measured quadrupoles (36 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. With respect to the previous report, we worked out an estimate of the permeability for the cases in which no measurement of the collars is available. This estimate is based on the magnetic measurements[3], namely considering the anomalies of the focusing gradient, b6 and b10 as due to a higher collar permeability. The whole set of magnets for which correlations are available is split in low permeability (<1.008, measured or guessed) and high permeability (>1.008, measured or guessed).The following remarks can be done
    - o Magnets with high collar permeability show anomalies in correlations, i.e. a much lower offset (20 to 50 units less), corresponding to the vanishing of the permeability impact on focusing strength at 1.9 K. One has the well-known exception of one magnet at the very early stage of the production (MQ004) that shows anomalies in correlations that are not explained.
    - o The new measurement that has been performed in these two months (red circle) is relative to a magnet with a non measured permeability, which has been estimated as normal (no anomalies observed on focusing strength, b6 and b10). The offset is consistent with what has been measured before.

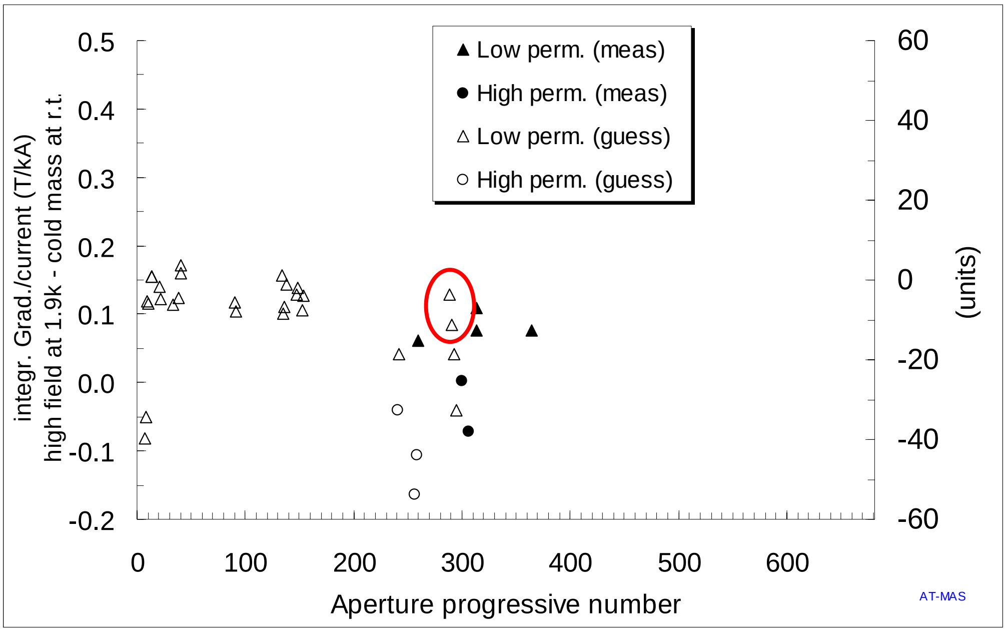


Fig. 21: Difference in focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number. The new measurement (two apertures) carried out in these two months is marked by a red circle.

[2] Please note that measurements of cold masses at block4 are not included in this analysis.
[3] P. Hagen, E. Todesco, LHC Project Note in preparation.

- Allowed multipole b6: over the 22 available measurements (44 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 198th) 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 measured 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. The estimated permeability, based on the anomalies on focusing strength, b6 and b10 is high (>1.008).
    - The measurements of the two apertures carried out in the last two months show a normal offset, and the estimated permeability is low. This is consistent with what observed for the focusing strength.

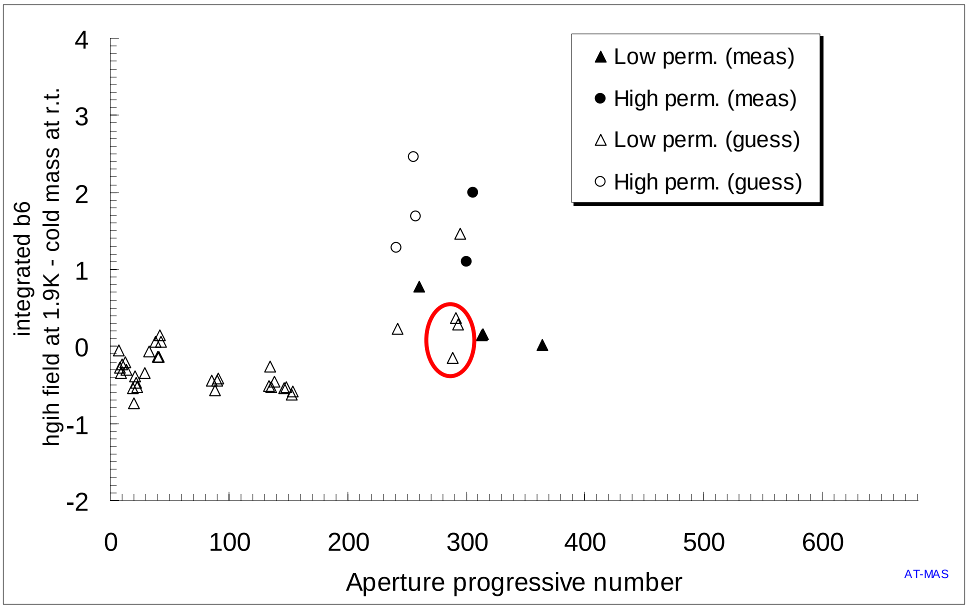


Fig. 22: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number. The new measurement (two apertures) carried out in these two months is marked by a red circle.

Based on these results, is appears more and more evident that the influence of the high collar permeability on field quality at room temperature is likely to disappear in operational conditions. To reconstruct a reliable estimate of the field quality in operational conditions for the magnets that will not be measured at 1.9 K, the following strategy is being implemented:

- Data at room temperature will be post-processed to subtract the effect of the collar permeability according to sensitivity tables based on simulations.
- The warm-cold offsets used to extrapolate warm measurements to operational conditions will be computed either on all post-processed data or on raw data relative to magnets with normal permeability.

## 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).

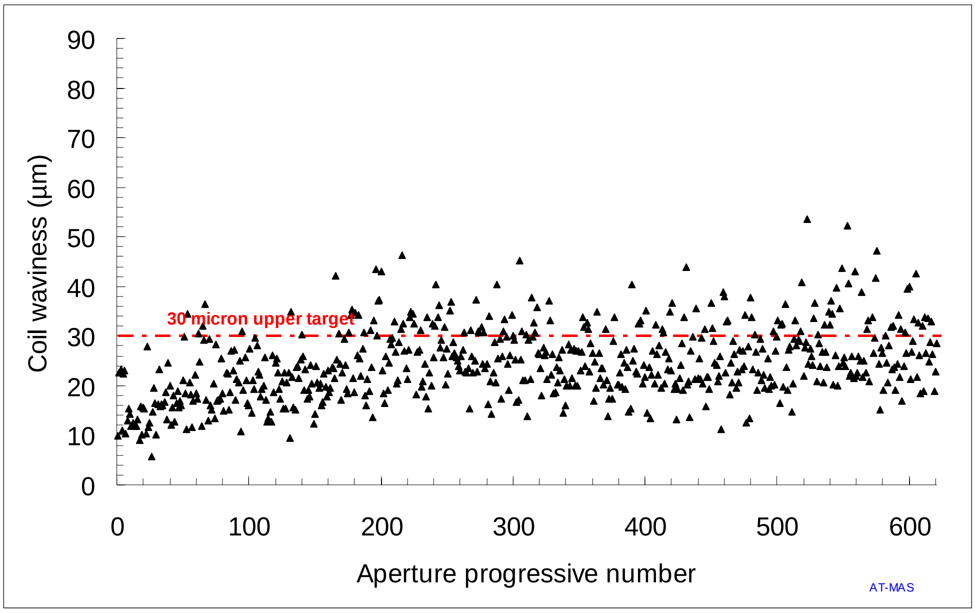


Fig. 24: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).


## Acknowledgements

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