

Report on field quality in the main LHC quadrupoles: October-November 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 October-November 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 742 apertures (371 magnets) and 301 cold masses. At 1.9 K we have measurements of 24 quadrupoles.
- In these two months, 59 apertures (i.e., 29.5 equivalent quadrupoles) and 31 cold masses have been measured at room temperature. Two new measurement is available at 1.9 K.

What's new

- **Around 95%** 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:** Two magnets have been measured at 1.9 K in these two months, one with high collar permeability and one with a low one. In both cases the collar permeability had been measured. Results confirm that the permeability effect disappears in operational conditions. For this reason, from this report on we will present room temperature data corrected to nominal permeability.

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PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 59 new apertures (i.e. 29.5 equivalent quadrupoles) and 31 cold masses have been measured at room temperature (see Fig. 1).

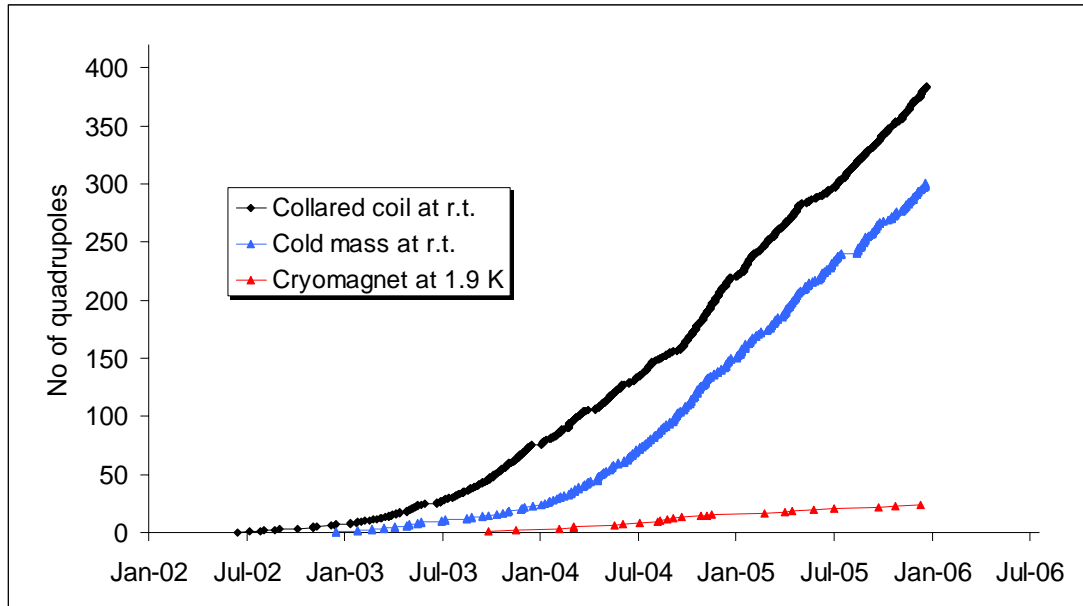


Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

- Coil protection sheet¹: all new apertures have a coil protection sheet of 0.87 mm.

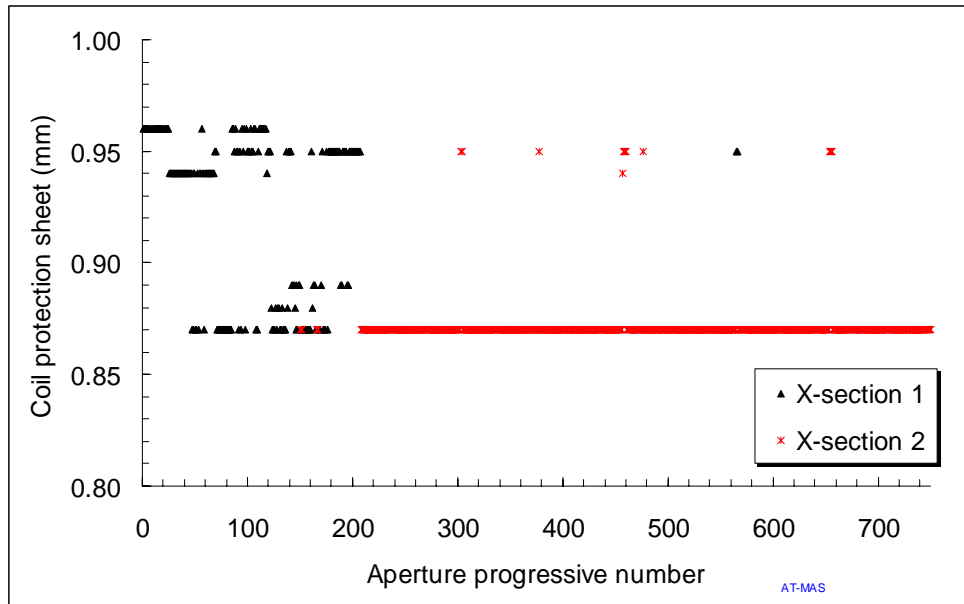


Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

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 b_6 , the average is carried out over 200 apertures with X-section 1 and 542 with X-section 2: this gives a systematic b_6 within the target. When the contribution of the different X-sections is separated, one finds that b_6 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.

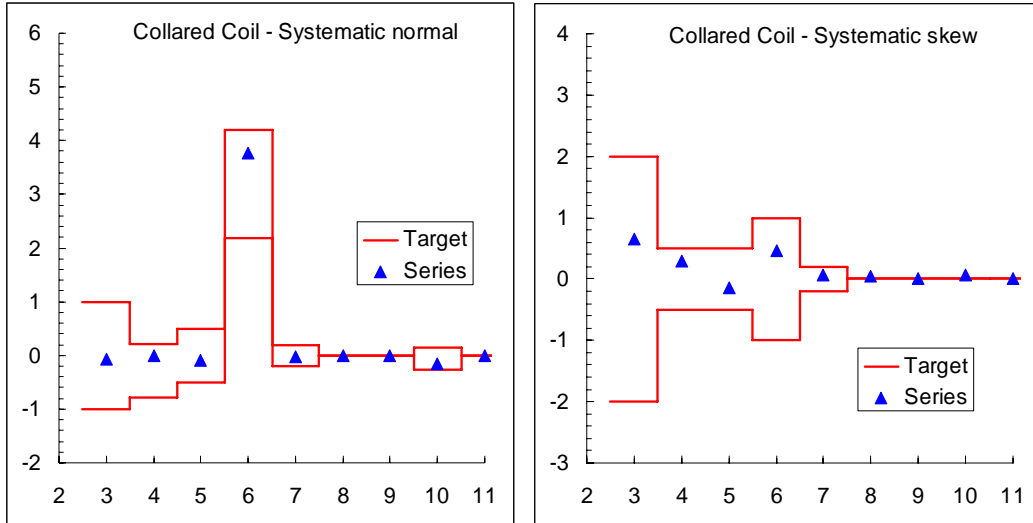


Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (solid lines).

- Best estimates of the random components are given in Fig. 4. All values are within targets with the exception of b_6 and a_4 . Data for b_2 , corrected to nominal permeability, are within targets.
- The spread of b_6 over all apertures (1.5 units) is due to the mixing of the two different X-sections. Indeed, the target for beam dynamics on random b_6 is not a hard limit. The spread of a_4 is 10% larger than target; also in this case, this is not considered to be critical.

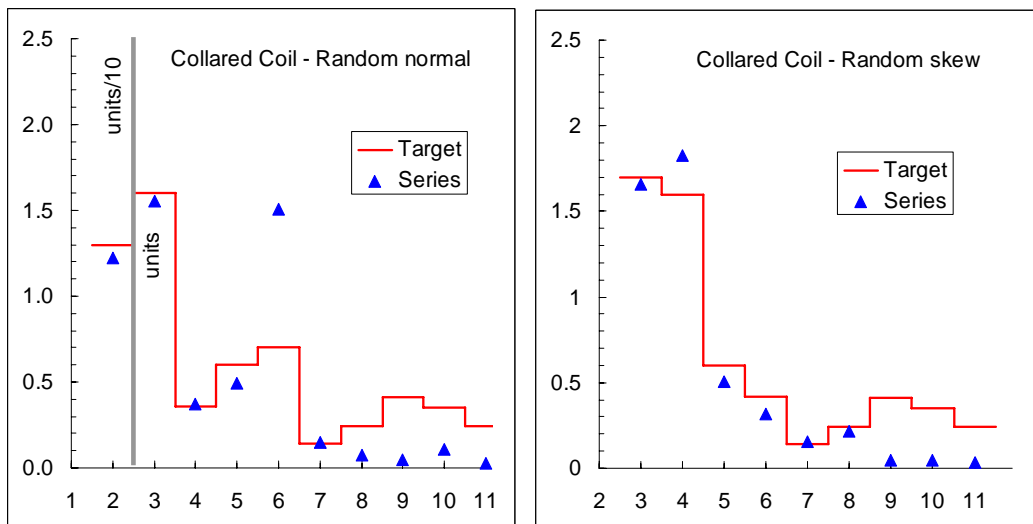


Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

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 (2.2 units).

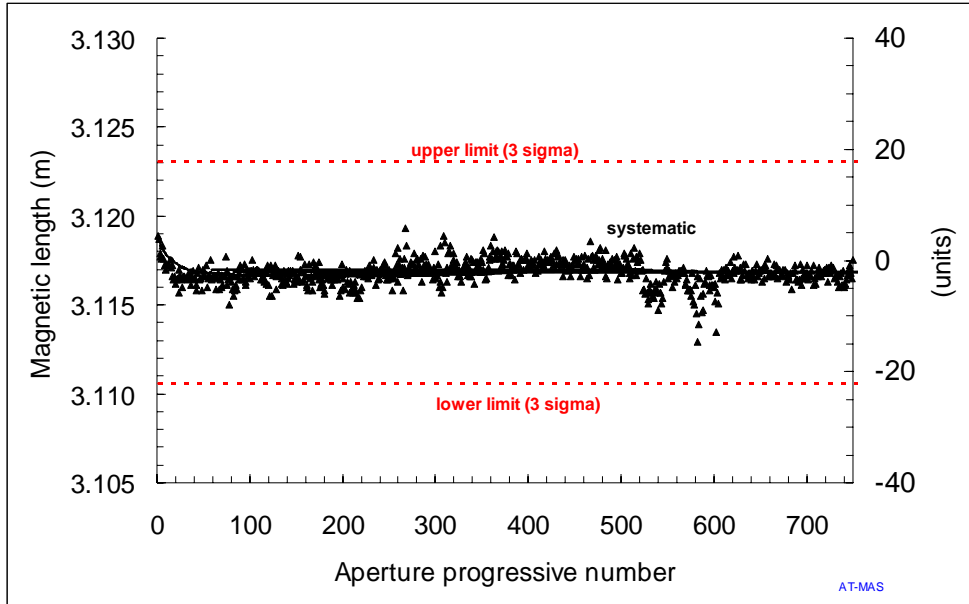


Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

- Standard deviation of magnetic length of **cold masses** is 2.3 units.

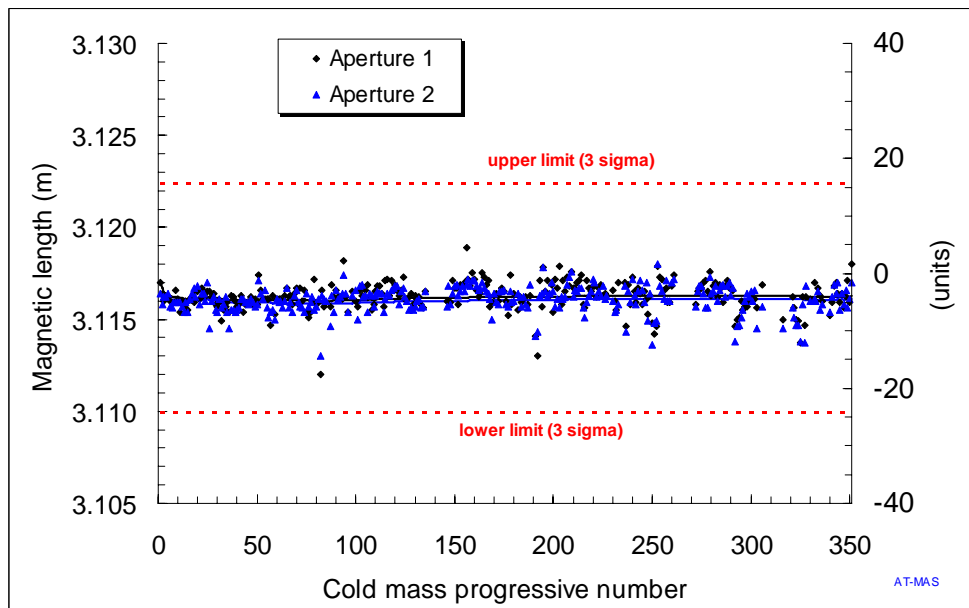


Fig. 6: Magnetic length of the measured cold masses (dots) and running average (solid line).

3.1.2 Trends in field gradient

We present data reduced to the nominal permeability, since measurements at 1.9 K show that the effect of permeability disappears in operational conditions.

- The apertures manufactured in these two months (682nd to 740th) have a field gradient within targets. These apertures have collars with permeability within specifications.
- The spread of the field gradient is 12.7 units.

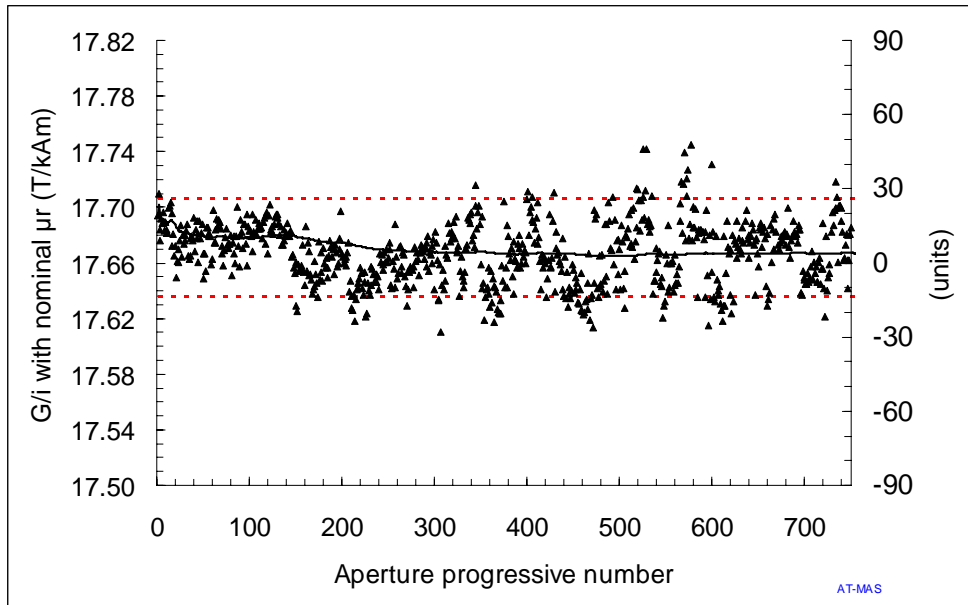


Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines). Data reduced to nominal permeability.

- The spread observed in apertures is confirmed by **cold mass** data (12.8 units).

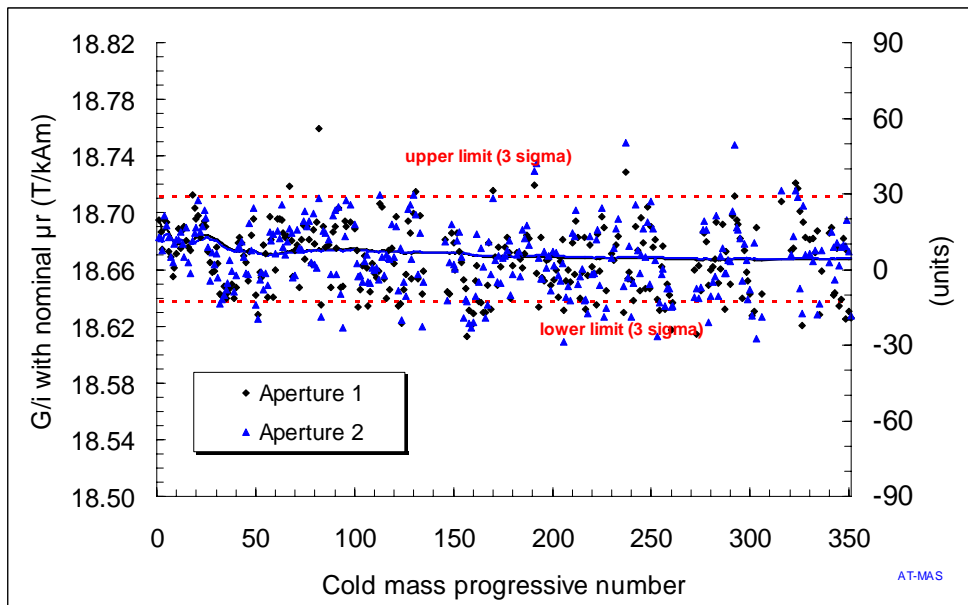


Fig. 8: Field gradient of the measured **cold masses** (dots) and running averages (solid line). Data reduced to nominal permeability.

3.1.3 Trends in integrated field gradient

We present data reduced to the nominal permeability, since measurements at 1.9 K show that the effect of permeability disappears in operational conditions.

- 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 12.2 units, and for the cold masses is 12.0 units.

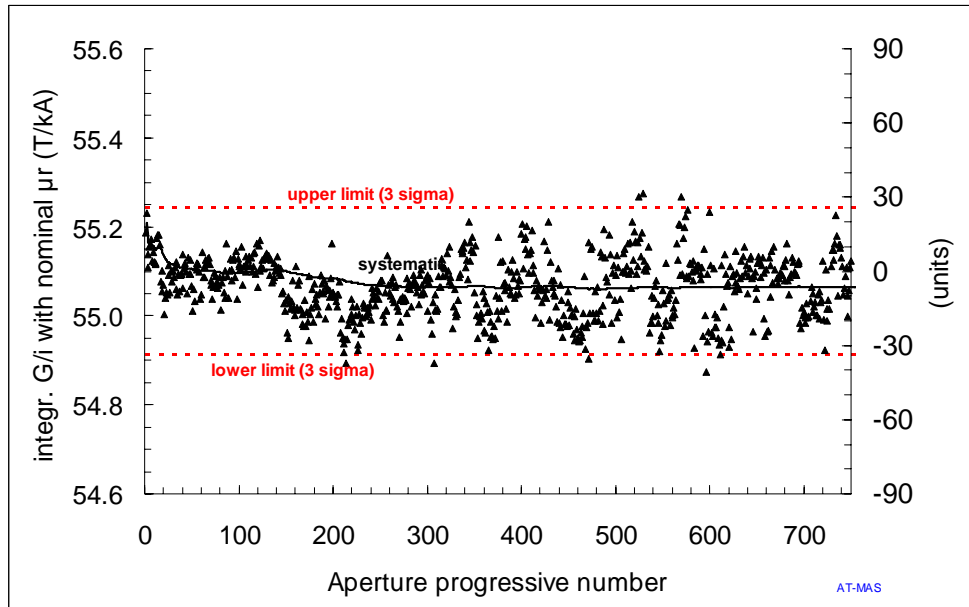


Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid line). Data reduced to nominal permeability.

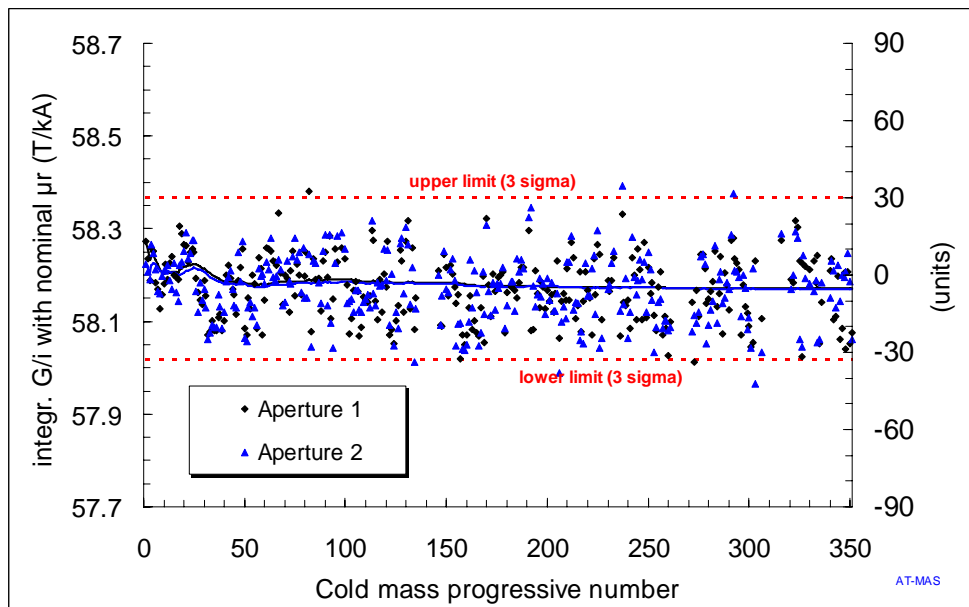


Fig. 10: Integrated field gradient of the measured **cold masses** (dots) and running averages (solid line). Data reduced to nominal permeability.

3.2 Trends in allowed multipoles

We present data reduced to the nominal permeability, since it is becoming more and more evident that the effect of permeability disappears in operational conditions.

- The systematic value of b6 and b10 on cross-section 2 are within targets. Systematic b6 has dropped from 5.5 units to about 3 units with the introduction of cross-section 2 (see Fig. 11).
- A negative trend is being observed for b6, which is approaching the low part of the band in the recent production (see Fig. 11).

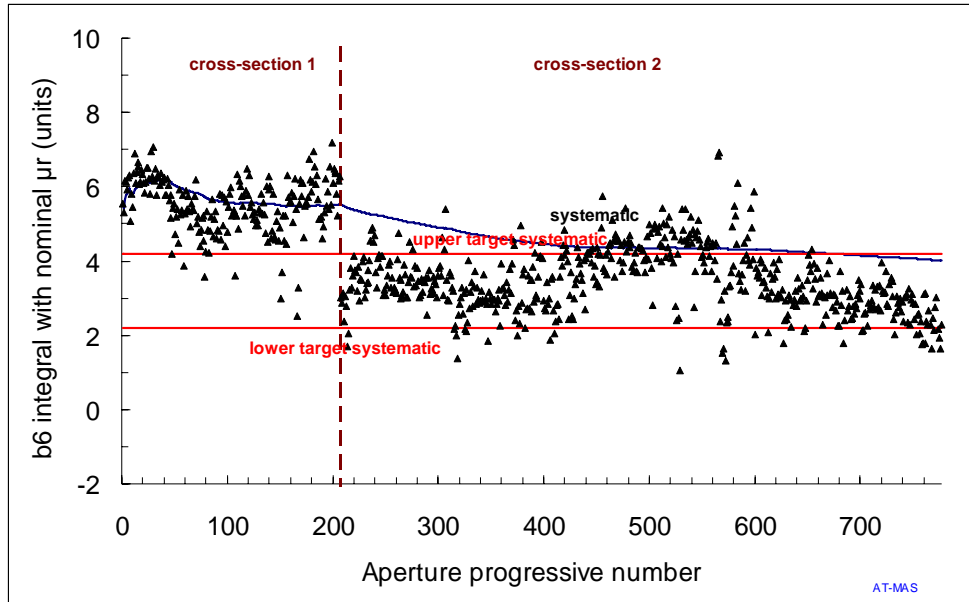


Fig. 11: Integral b6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations measured at 1.9 K on 24 quadrupoles. Data reduced to nominal permeability.

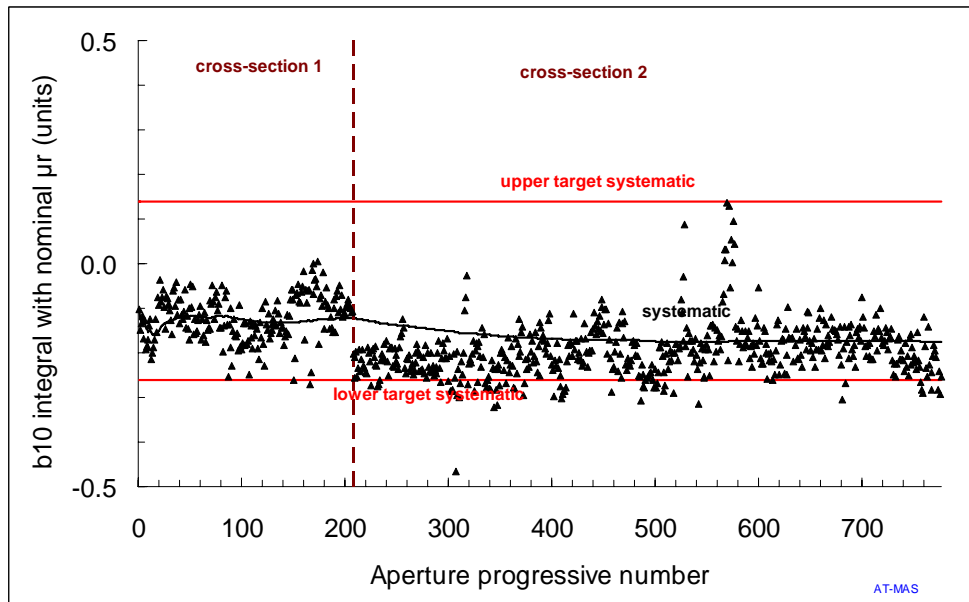


Fig. 12: Integral b10 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations with 24 quadrupoles. Data reduced to nominal permeability.

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.

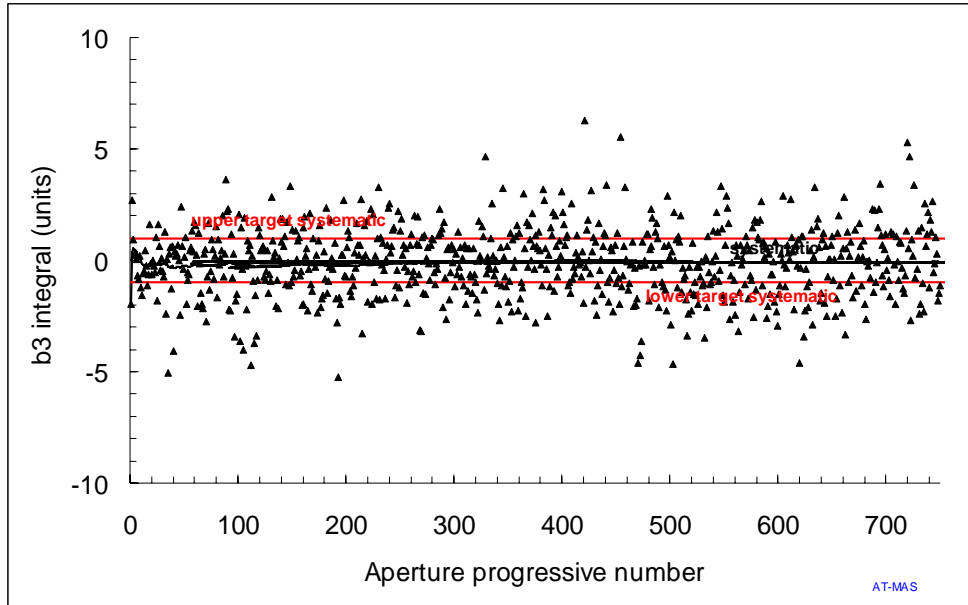


Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

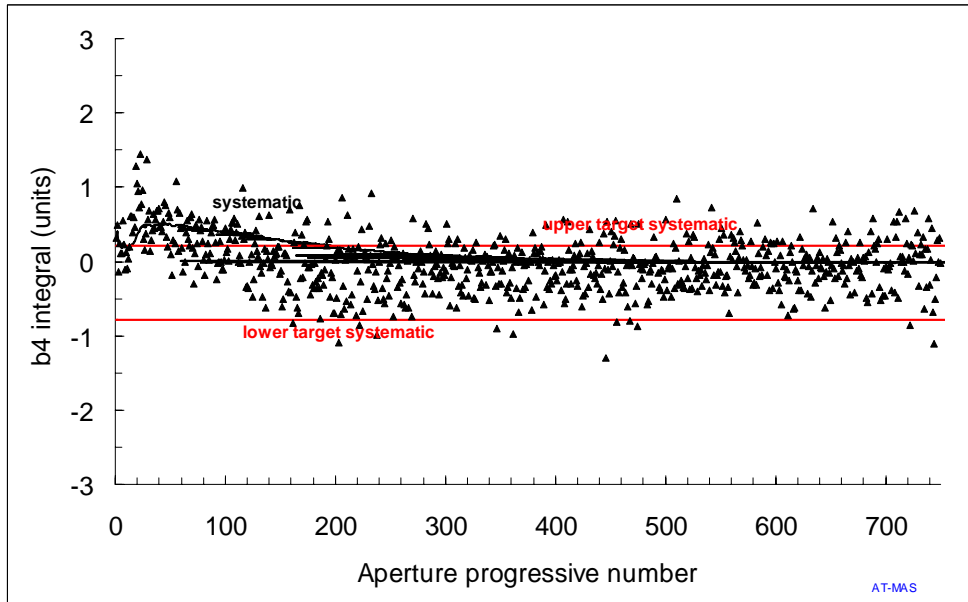


Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

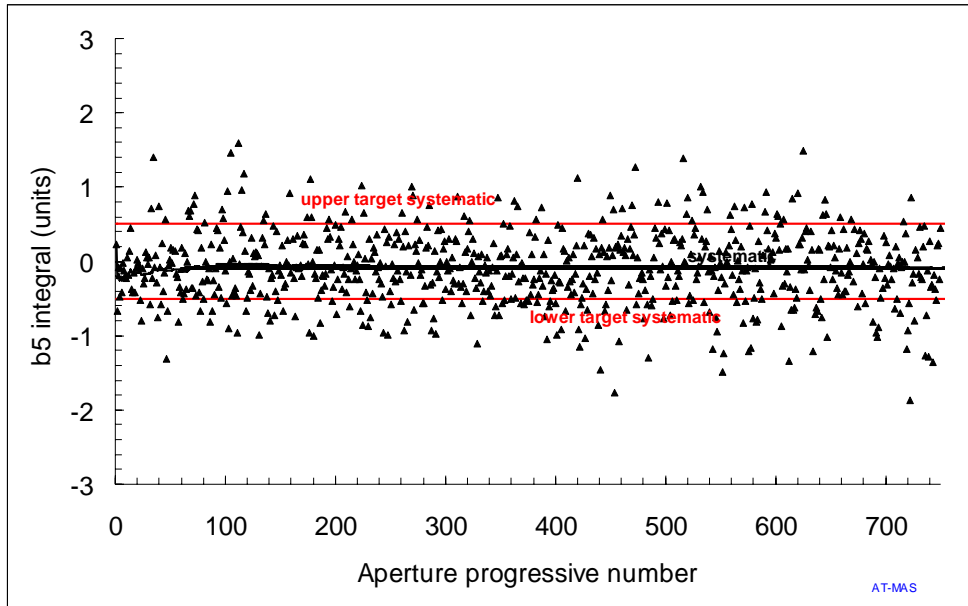


Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

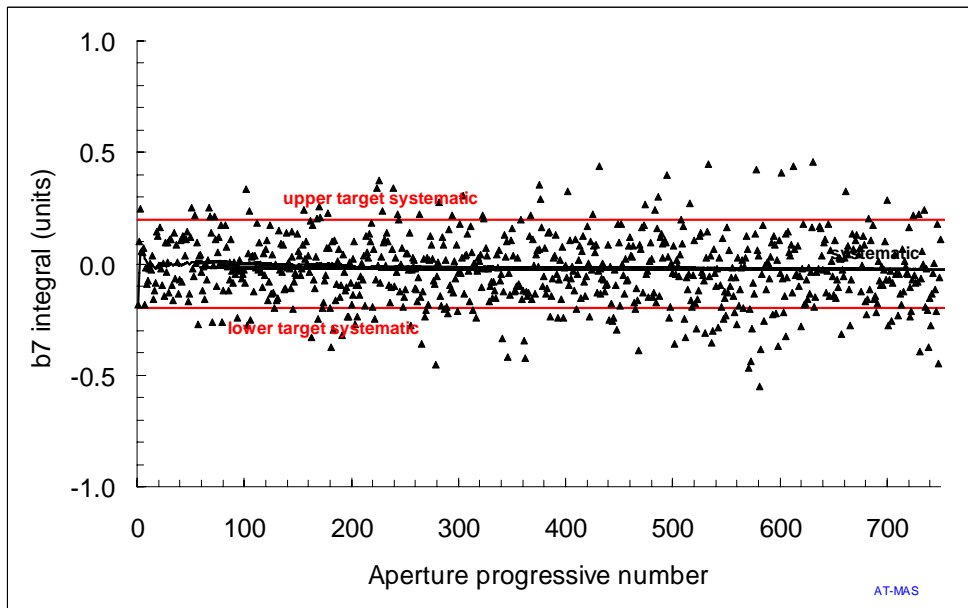


Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

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.

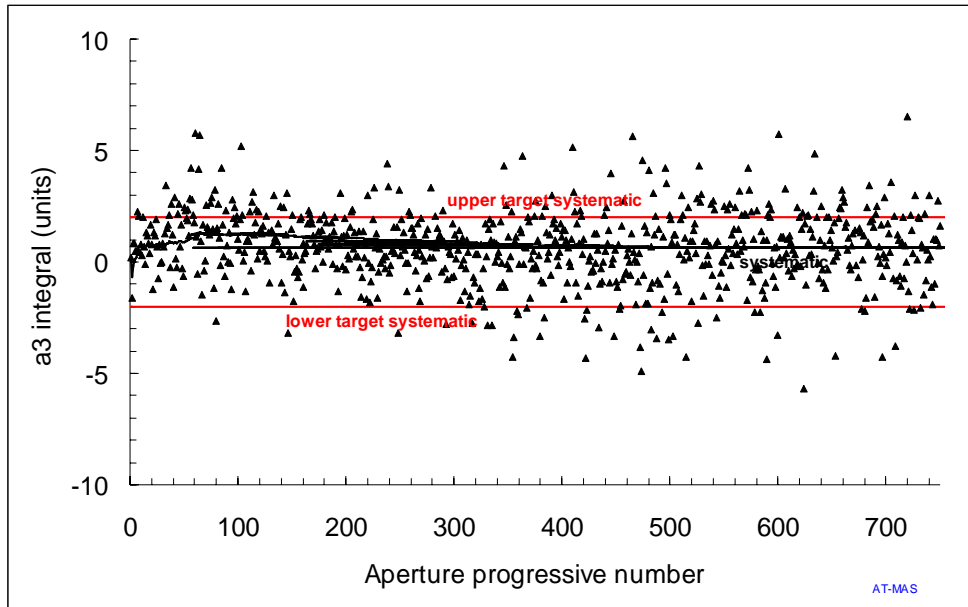


Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

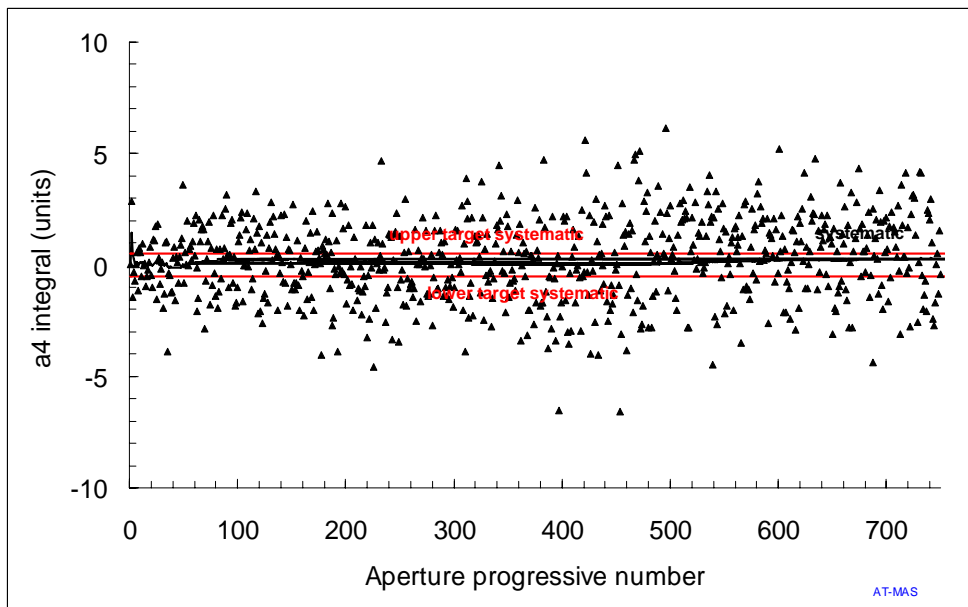


Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

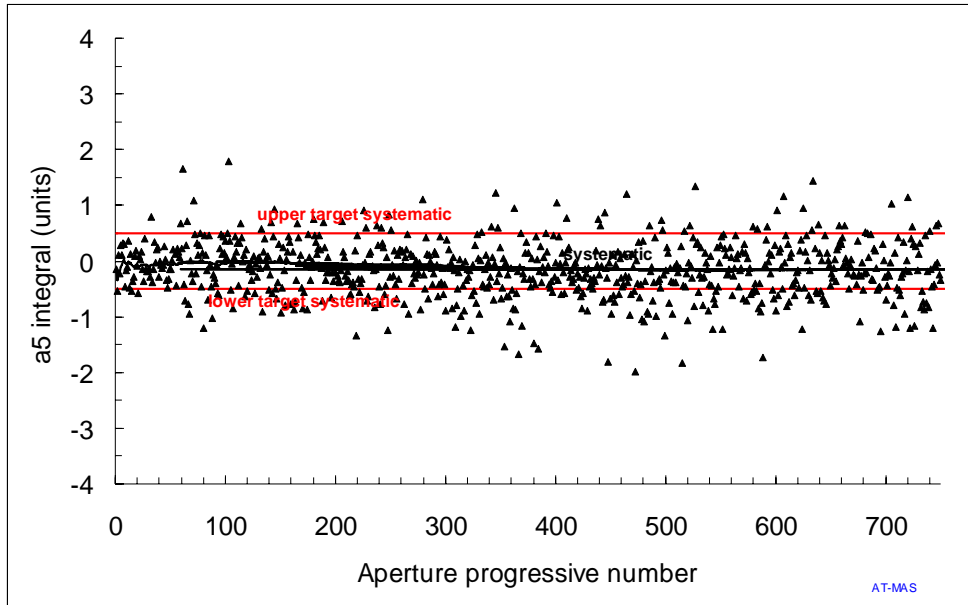


Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

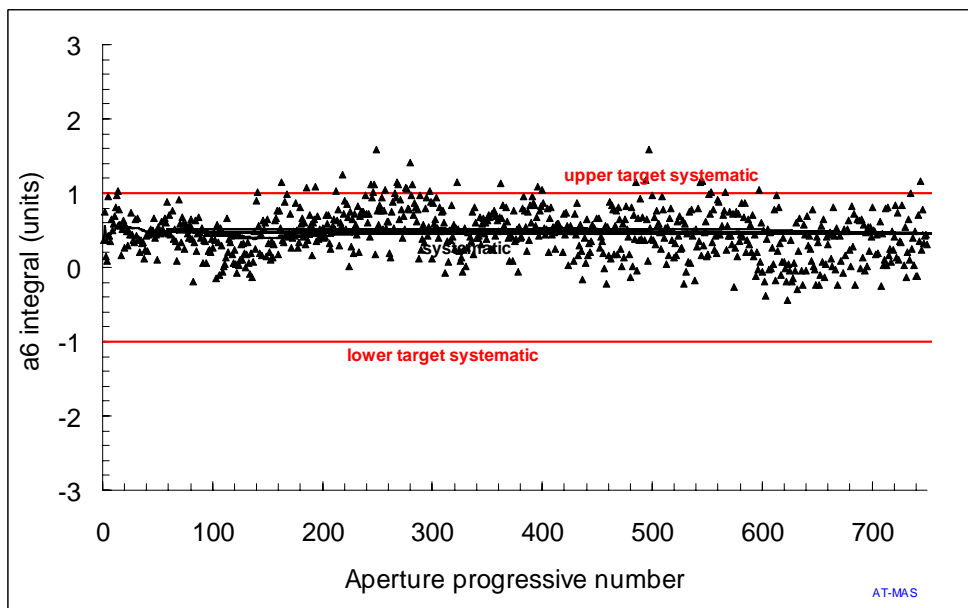


Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

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 525th, i.e. there is a delay of 110 quadrupoles between room temperature measurements of collared coil and test at 1.9 K², equivalent to 7 months of production), and allows to detecting trends in correlations along the production.

- Integrated field gradient: we present data of 20 measured quadrupoles (40 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. As in 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 measurements³, 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
 - 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.
 - The new measurements that have been performed in these two months (solid circle in Fig. 21) are relative to two magnets, one with a high permeability and one with a low one. The offsets are consistent with what has been measured before: no anomalies for normal permeability and strong negative anomalies for high permeability.

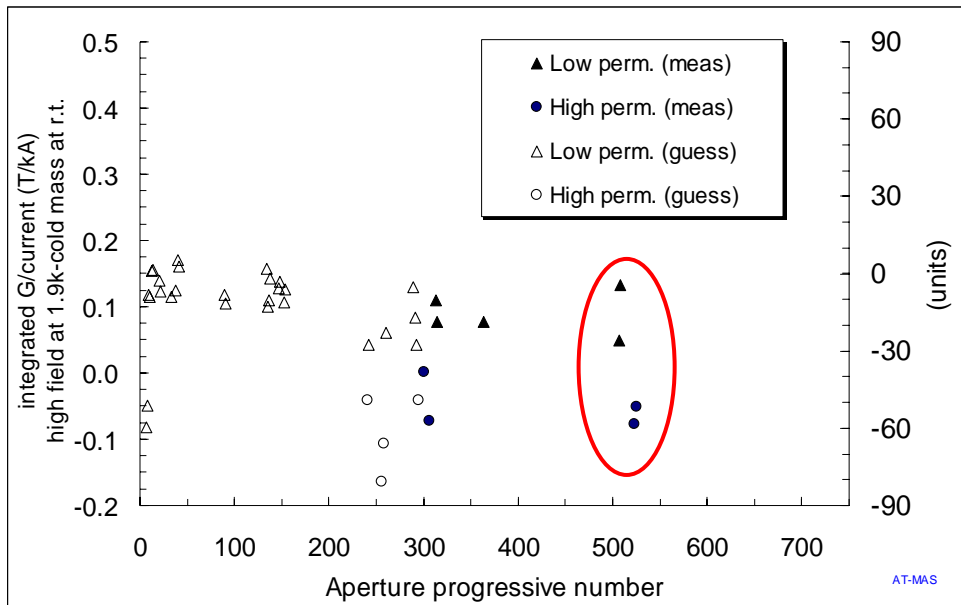


Fig. 21: Difference in focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number. The new measurement (four apertures) carried out in these two months is marked by a solid circle.

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 24 available measurements (48 apertures), we see a difference between high field at 1.9 K and cold masses at room temperature of -1 to 2.5 units.
 - Magnets with high collar permeability show anomalies in correlations, i.e. a much higher offset (1 to 2.5 units), corresponding to the vanishing of the permeability impact on b6 at 1.9 K. The magnet MQ004, that had anomalies in correlations for the integrated field gradient, has a normal correlation for the b6.
 - The new measurements that have been performed in these two months (solid circle) are relative to two magnets, one with a high permeability and one with low permeability. The offsets are consistent with what has been measured before: no anomalies for normal permeability and strong negative anomalies for high permeability, as for the focusing strength.

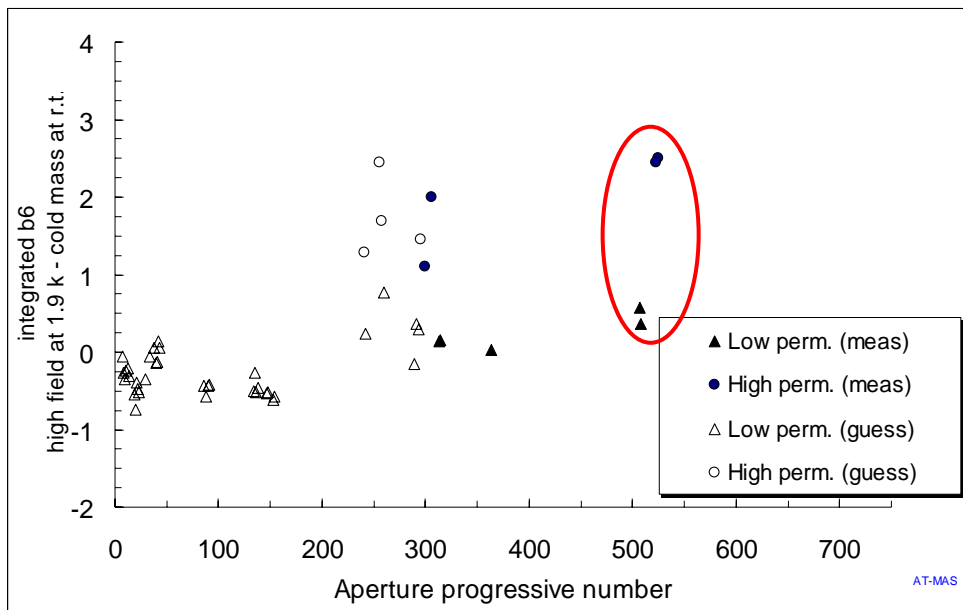


Fig. 22: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number. The new measurement (four apertures) carried out in these two months is marked by a solid circle.

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. A few more high waviness apertures have been manufactured in the last two months (see Fig. 23).

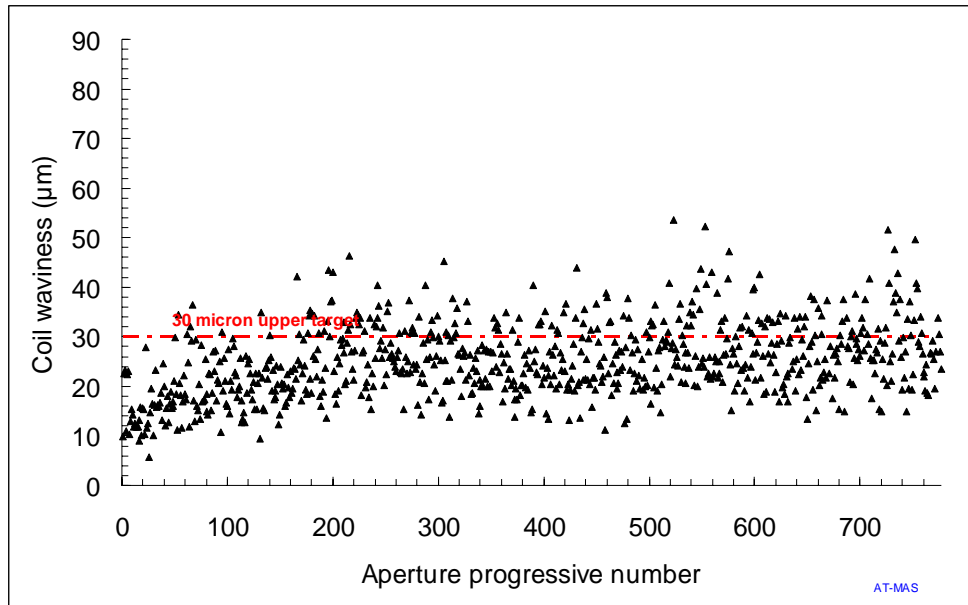


Fig. 24: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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.