Report on field quality in the main LHC quadrupoles: February–March 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 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.

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The dashboard

- Available measurements: at room temperature we have 519 apertures (259.5 magnets) and 185 cold masses. At 1.9 K we have measurements of 17 quadrupoles.
- In these two months, 52 apertures (i.e., 26 equivalent quadrupoles) and 19 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:

- **Collar permeability:** The manufacturer has been obliged to use the batches of collars with high permeability due to the lack of 'good' collars. 20 apertures (520^{th} to 539^{th}) with very high permability 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. Recently, the stainless steel producer has managed to deliver melts within specifications and therefore the crisis should be over soon. Indeed, some material with high permeability is still to be used whilst waiting for the arrival of the collars punched from the new melt.
- **Spread of focusing strength:** due to the presence of 20 apertures with very high collar permeability, the spread of integrated field gradient has increased to around 15 units, i.e. 50% more than specified. Without these apertures, the spread is around 13 units.
- **Warm-cold correlations:** In these two months, one magnet has been measured at 1.9 K. Even though it 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. This worrying and unexplained result is under analysis.

Issues non-critical for beam dynamics:

- **Trends systematic b6:** the average b6 is increasing in the more recent production of about 0.5-1 units. The global average over cross-section 2 is well within targets, but this trend is pushing average b6 towards the upper target.
- **Outliers in not allowed multipoles:** Strong anomalies in the not-allowed harmonics observed in the previous two months are disappearing.

CONTENTS

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 52 new apertures (i.e. 26 equivalent quadrupoles) and 19 cold masses have been measured at room temperature (see Fig. 1).

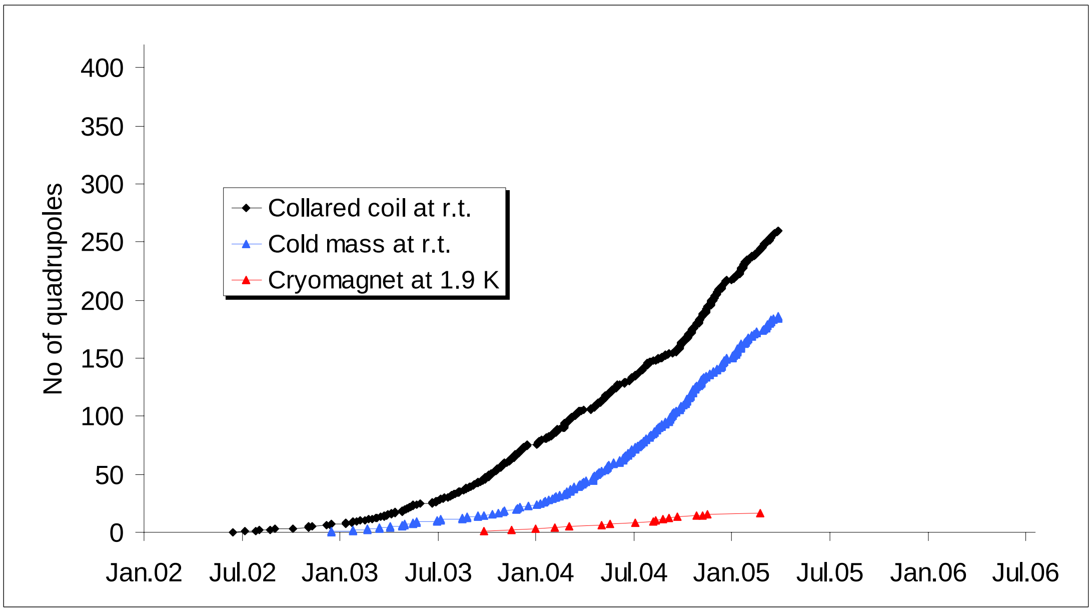


Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

- Cross-section: all apertures have X-section 2.
- Coil protection sheet[1]: all new apertures have a coil protection sheet of 0.87 mm.

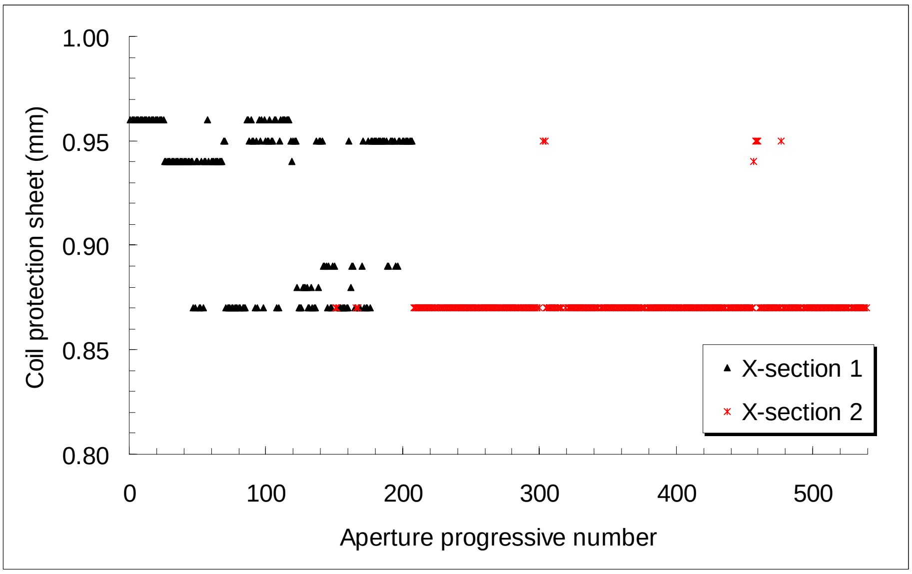
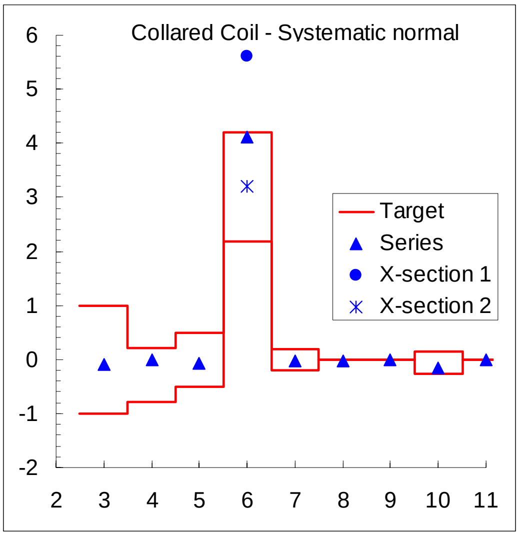


Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[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 319 with X-section 2: this gives a systematic b6 at the upper limit of 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).



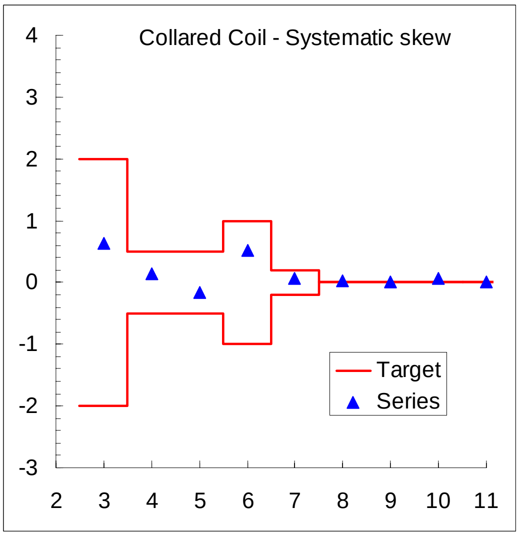
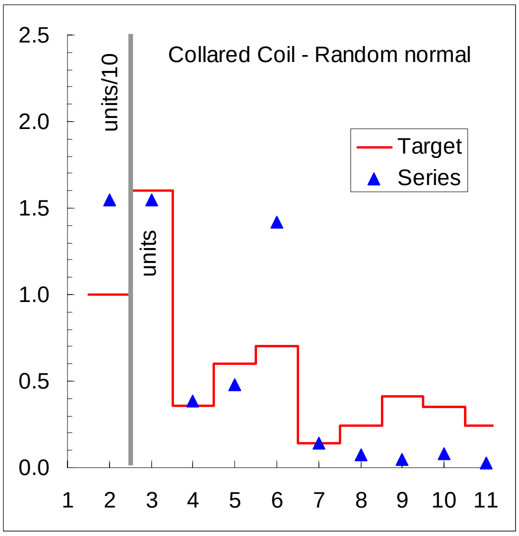


Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (solid lines).

- 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 15.4 units, i.e. 54% 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 13.0 units, confirmed by the measurements of cold masses. Indeed, 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).
- 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.



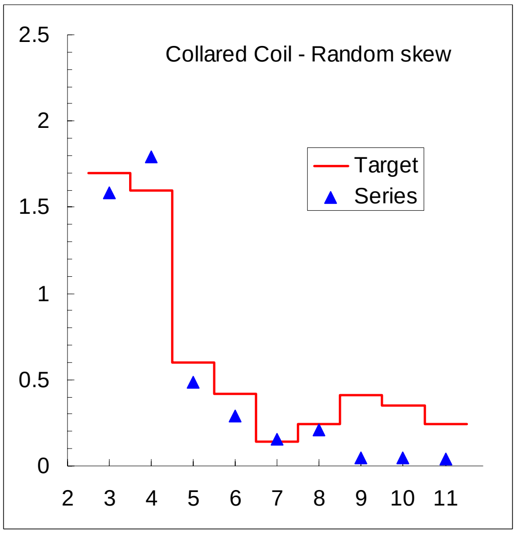


Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

PART III: TRENDS IN FIELD QUALITY

3.1 Trends in focusing strength

3.1.1 Trends in magnetic length

- Magnetic length of the apertures has a very low spread (2 units). Apertures 520th to 539th (see Fig. 5) have a magnetic length of around 5 units less than previous production. These apertures have been manufactured with a collar permeability out of tolerance, thus leading to higher field gradient, lower 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].

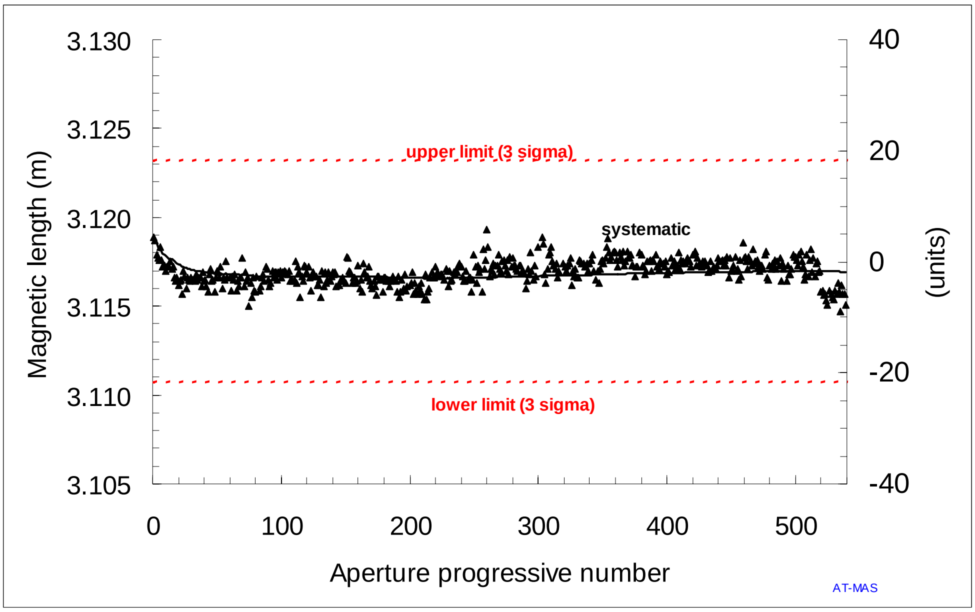


Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

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

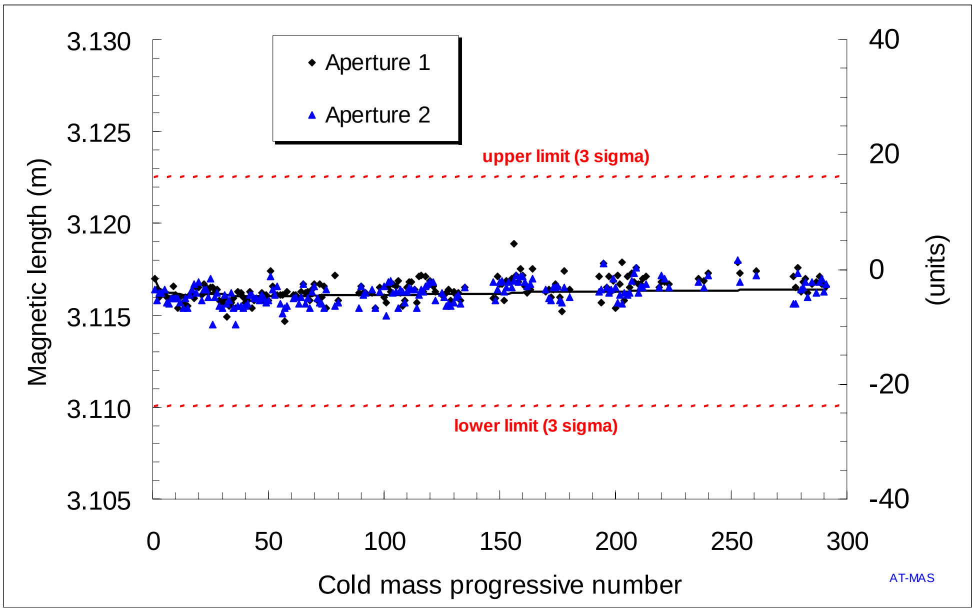


Fig. 6: Magnetic length of the measured **cold masses** and running average (solid line).

[2] F. Simon, private communication

3.1.2 Trends in field gradient

- Apertures 520th to 539th (see Fig. 7) have a field gradient of around 50 units more than previous production. These apertures have been manufactured with a collar permeability out of tolerance, but the effect on the field gradient is much stronger with respect to previous cases. These data would be compatible with a permeability variation of 0.015, or of only 0.01 if it is assumed that the apertures have a higher gradient of 20 units than average for other reasons, as part of the recent production.
- The spread of the field gradient excluding apertures 520th-539th is 13.3 units, and it becomes 16.1 units if these apertures are included in the statistics..

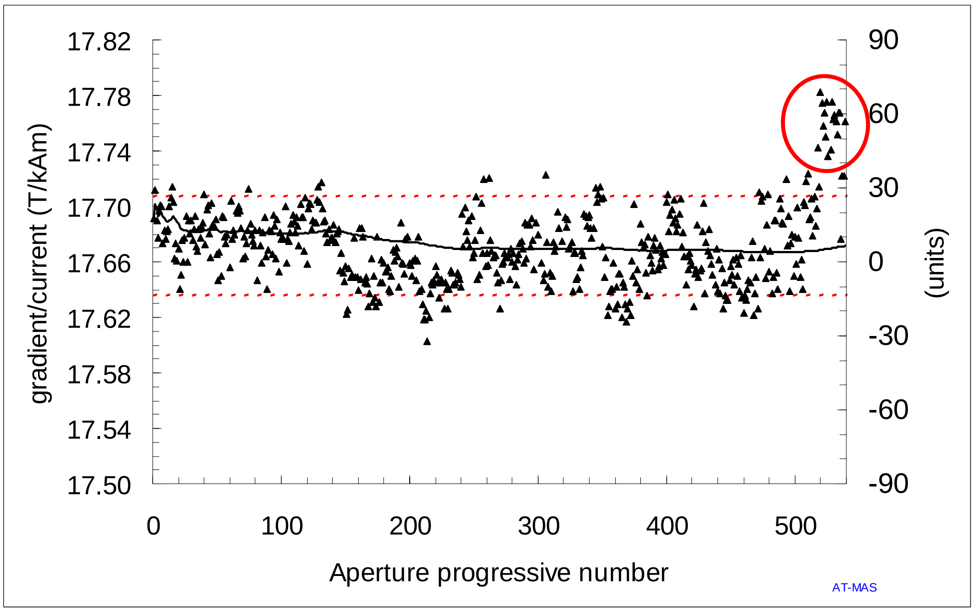


Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines). Recent apertures manufactured with high permeability collars are marked by a circle.

- The large spread observed in apertures (13.3 units) is confirmed by **cold mass** data, where it is 13.2 units (see Fig. 8). No one of the apertures 520th-539th has been assembled in a cold mass for the moment.

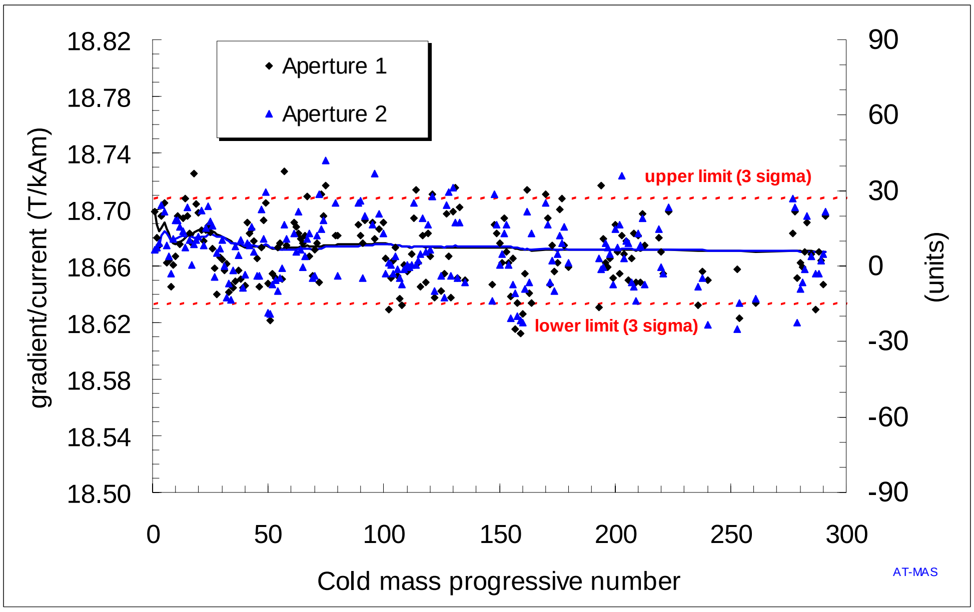


Fig. 8: Field gradient of the measured **cold masses** and running averages (solid line).

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 13.0 units (15.4 units including the apertures 520th-539th), and for the cold masses is 12.9 units.

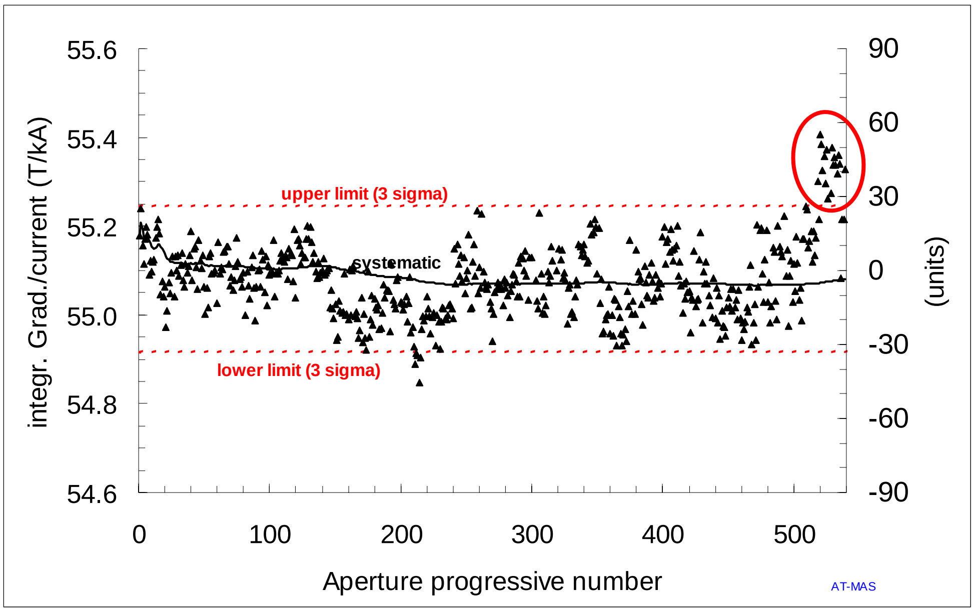


Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid line). Recent apertures manufactured with high permeability collars are marked by a circle.

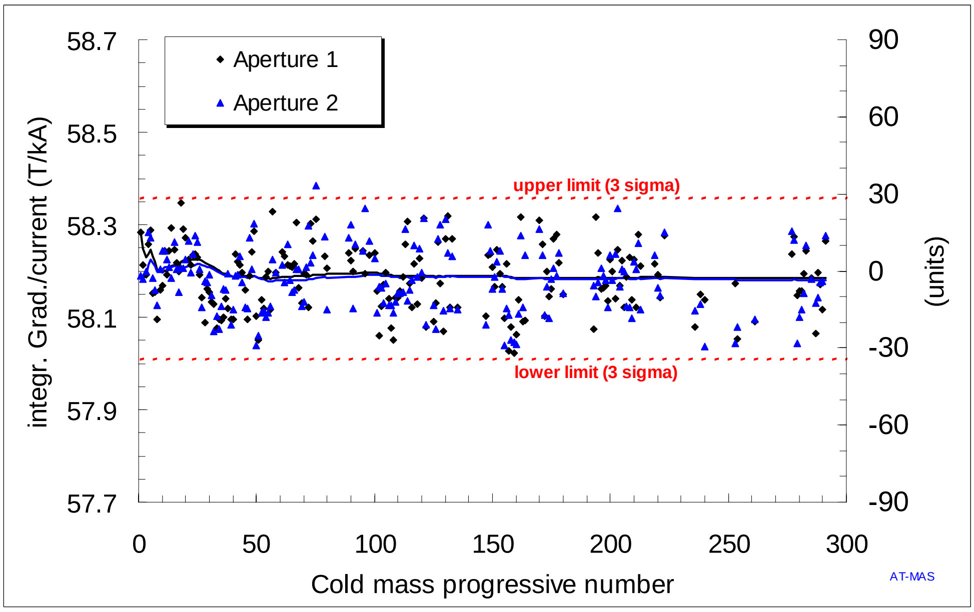


Fig. 10: Integrated field gradient of the measured **cold masses** and running averages (solid line).

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-539th, that have been manufactured with high collar permeability (solid circle in Fig. 11) have a very low b6, as in similar cases observed between 250th and 400th. These apertures have a b6 of 2.5 units lower than the recent production, corresponding to a permeability variation of 0.01.

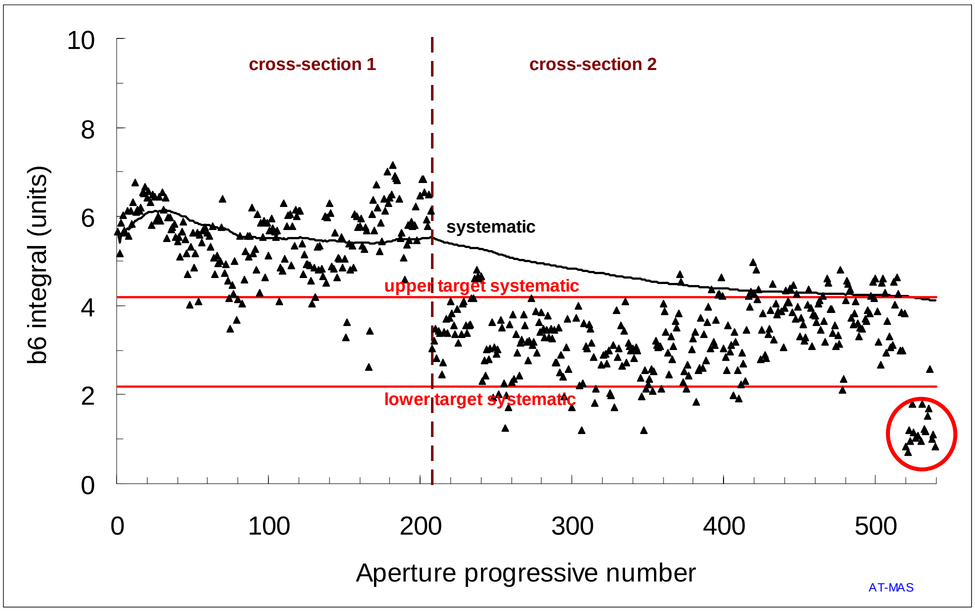


Fig. 11: Integral b6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations measured at 1.9 K on 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a circle.

- Systematic b10 is well within targets (see Fig. 12). Apertures 520th-539th, that have been manufactured with high collar permeability (solid circle in Fig. 12) have a very high b10, even more than in similar cases observed between 250th and 400th. These apertures have a b10 of 0.25 units higher than the recent production, corresponding to a permeability variation of 0.01.

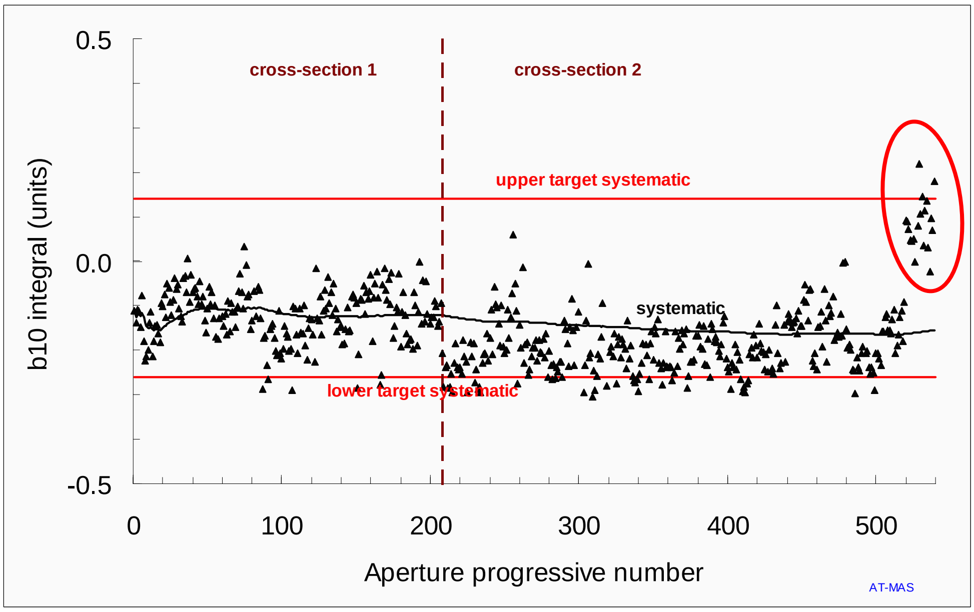


Fig. 12: Integral b10 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines) based on correlations with 17 quadrupoles. Recent apertures manufactured with high permeability collars are marked by a red circle.

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.

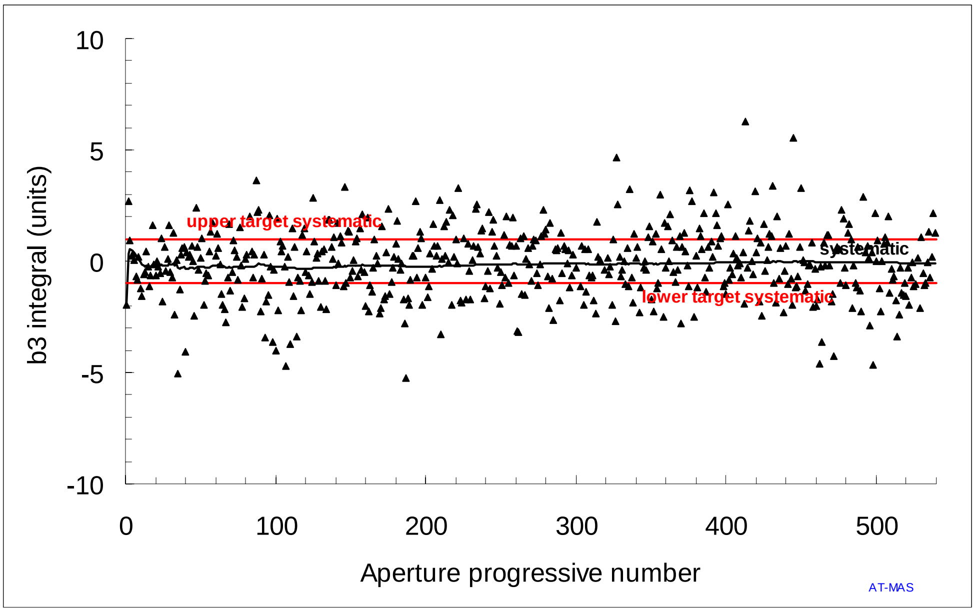


Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

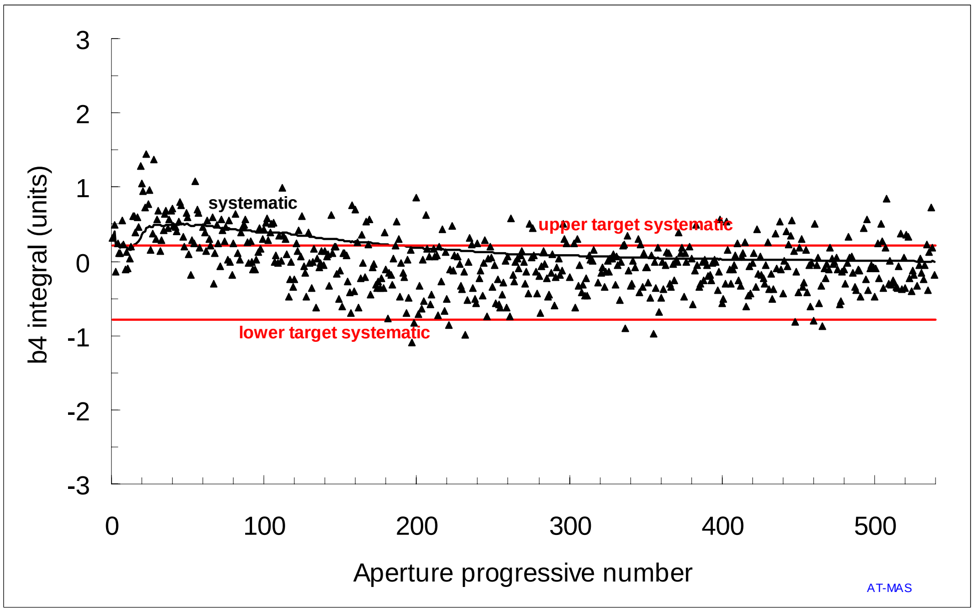


Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

- 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.

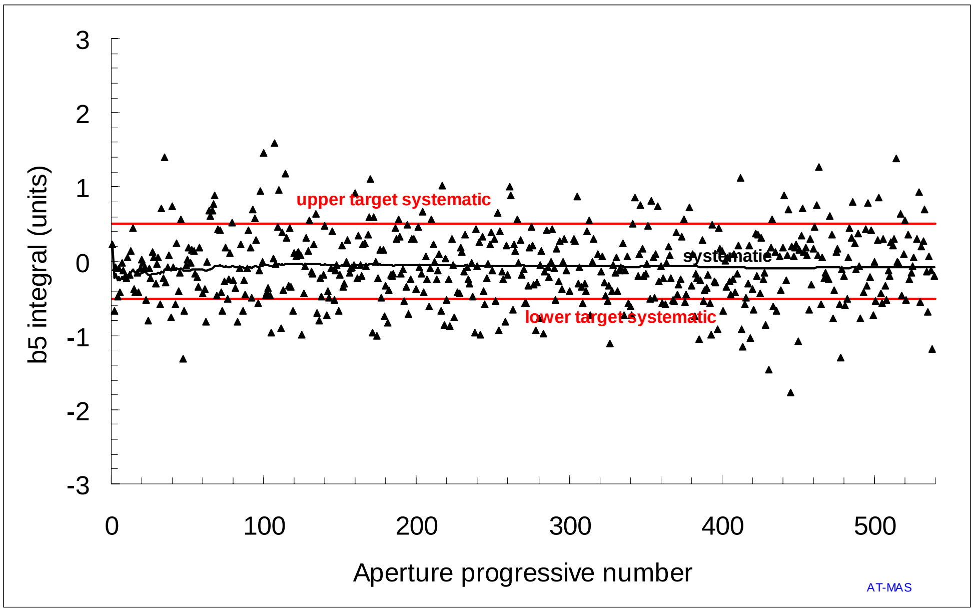


Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

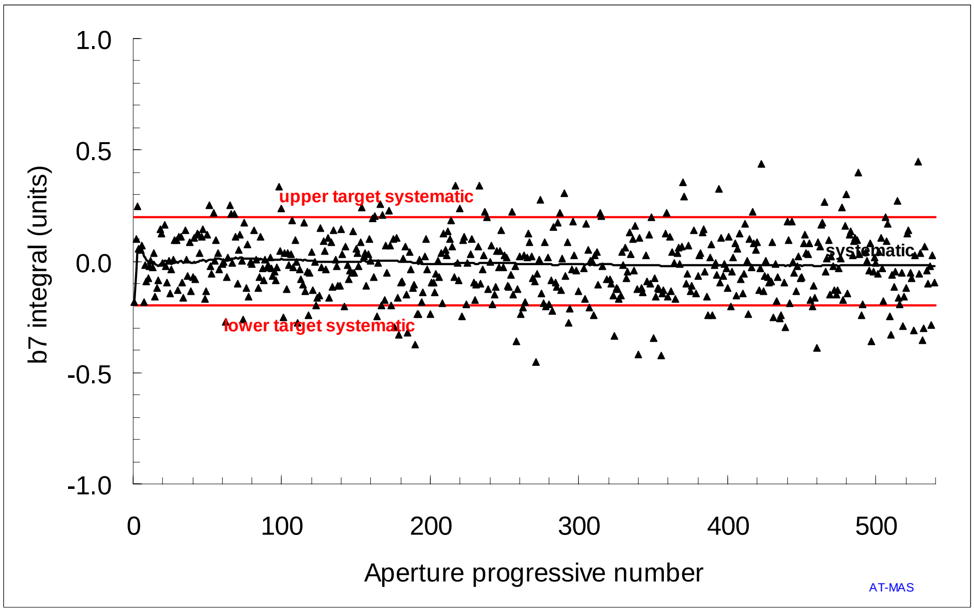


Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

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 has trends along the production, is not critical for beam dynamics since it is within targets.
- We still have rather large values of a3 and a4 in a few magnets of the recent production, but the situation is improving with respect to the previous period (see Figs. 17 and 18).

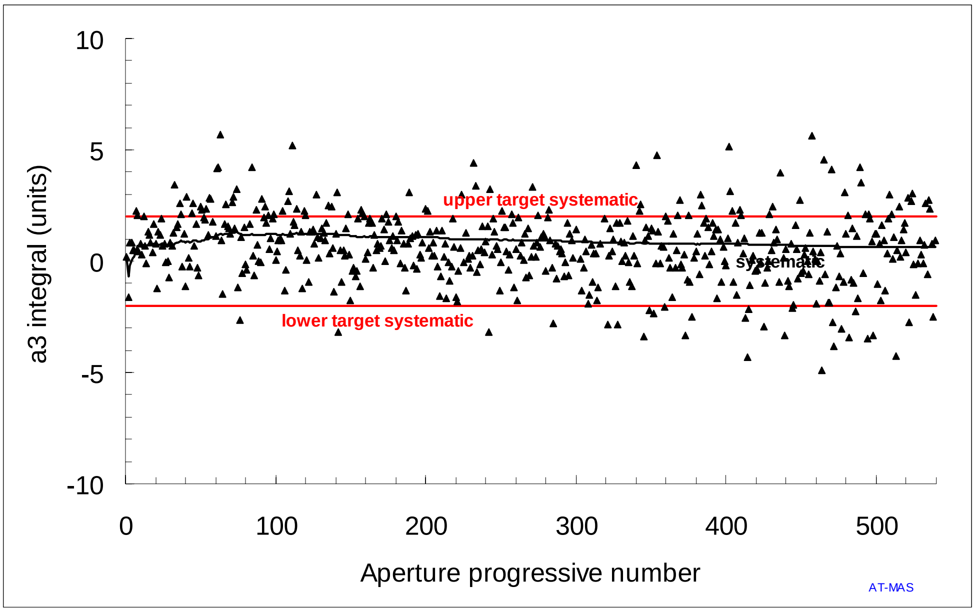


Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

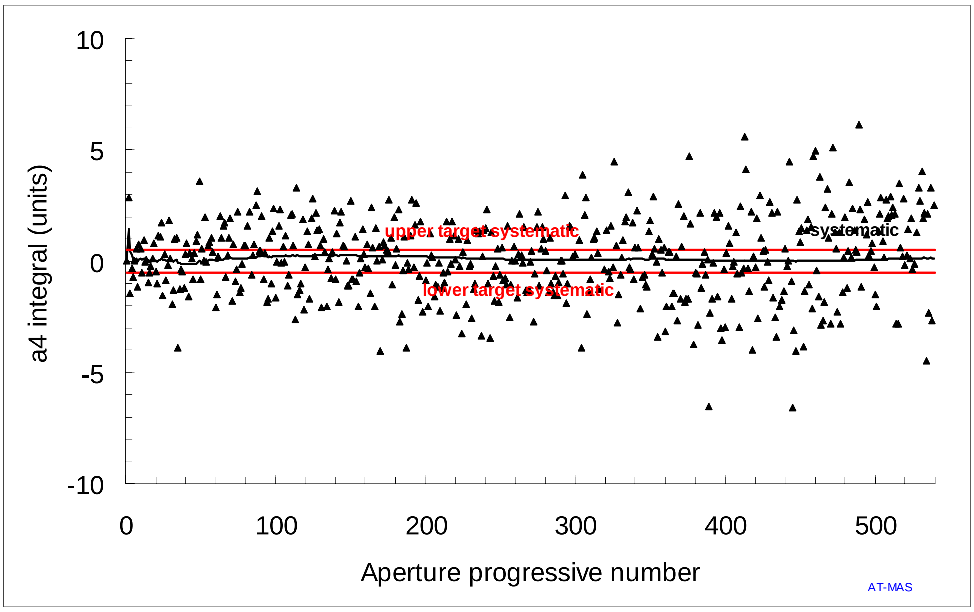


Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

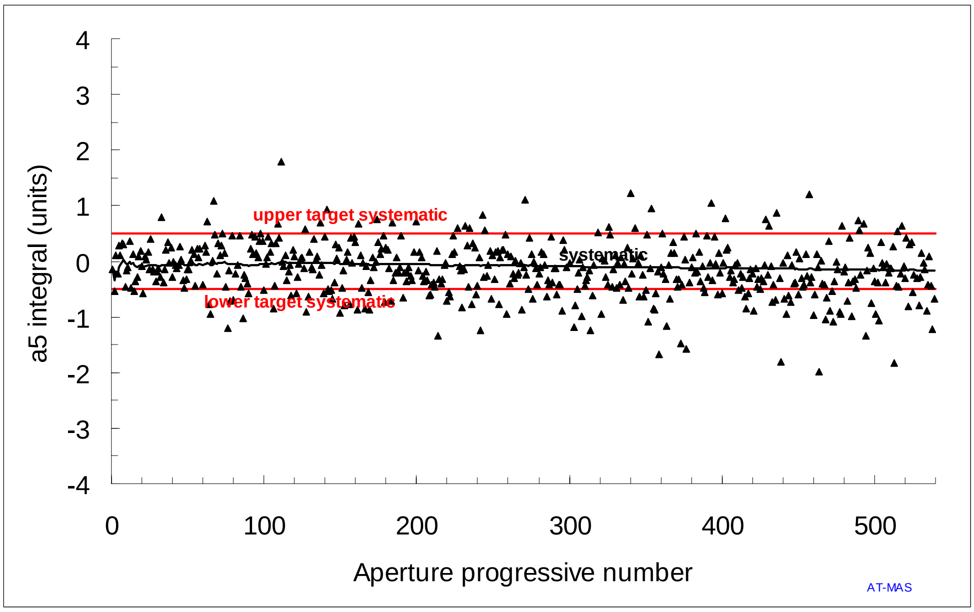


Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

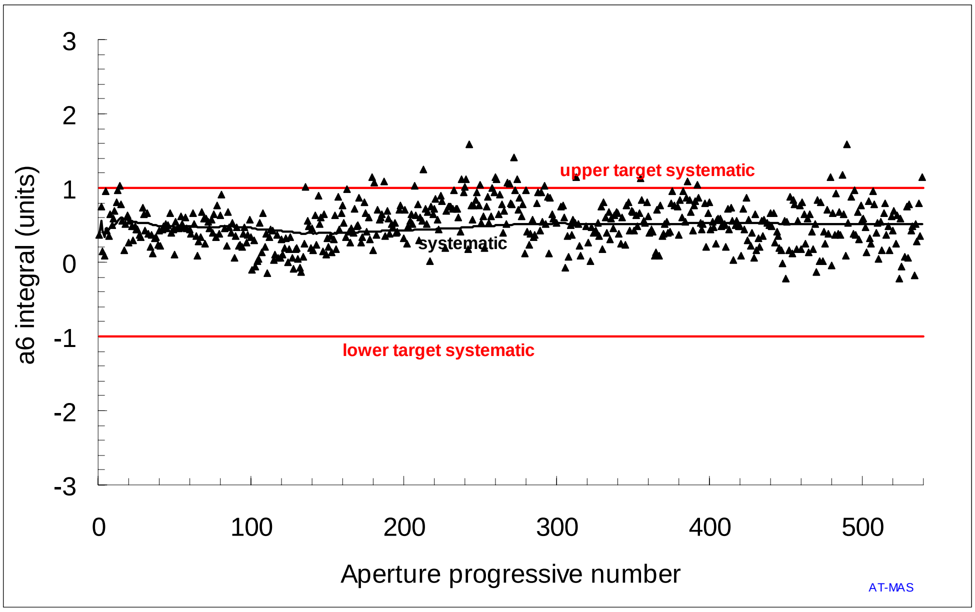


Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (solid straight lines).

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 258th, 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 4 months of production), and allows to detecting trends in correlations along the production.

- Integrated field gradient: we present data of 13.5 measured quadrupoles (27 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.
  - The new measurement carried out in these two months is magnet 114, corresponding to apertures 241st and 242nd. This magnet had normal values of b2, b6 and b10 at room temperature, and a 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).

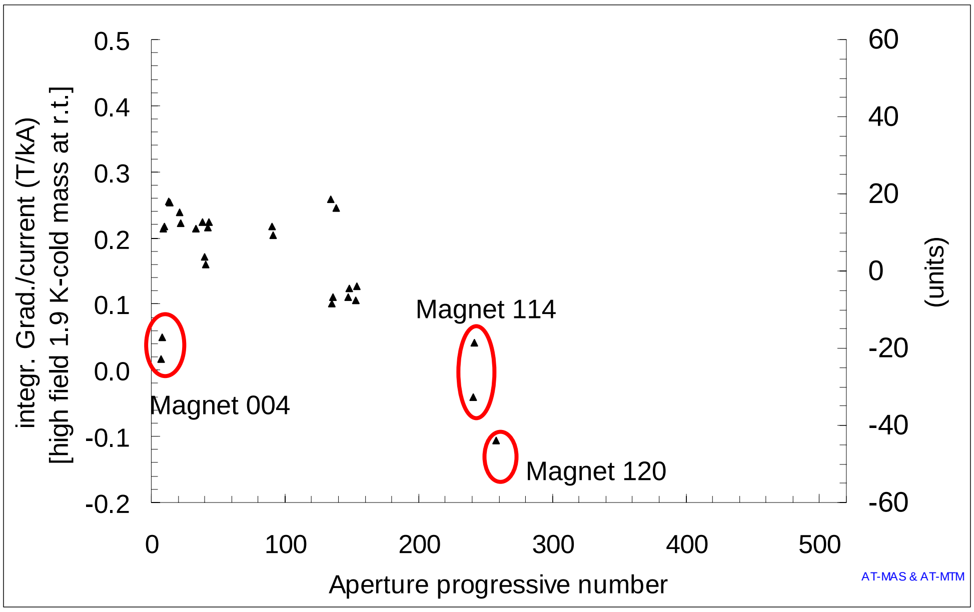


Fig. 21: Difference in focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

[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 17 available measurements (34 apertures), we see a difference between injection field at 1.9 K and cold masses at room temperature of -3.0 to –4.5 units.
    - o As observed in the previous report, the measurements relative to apertures 256th and 258th (that were assembled in magnet 120) show a different offset (-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.
    - o Magnet 114, which has been measured in these two months, also has a anomaly in the b6 correlation, the difference between cold and warm being 1 unit larger than usual. This would suggest that it belongs 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.

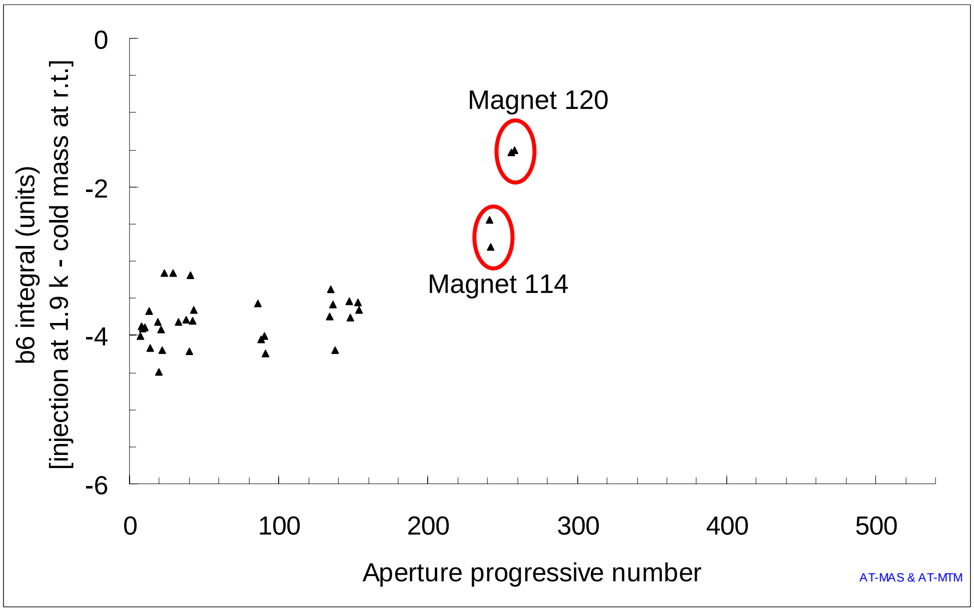


Fig. 22: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

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 stable in the last 200 apertures (see Fig. 23); a very large waviness has been found in aperture 523.

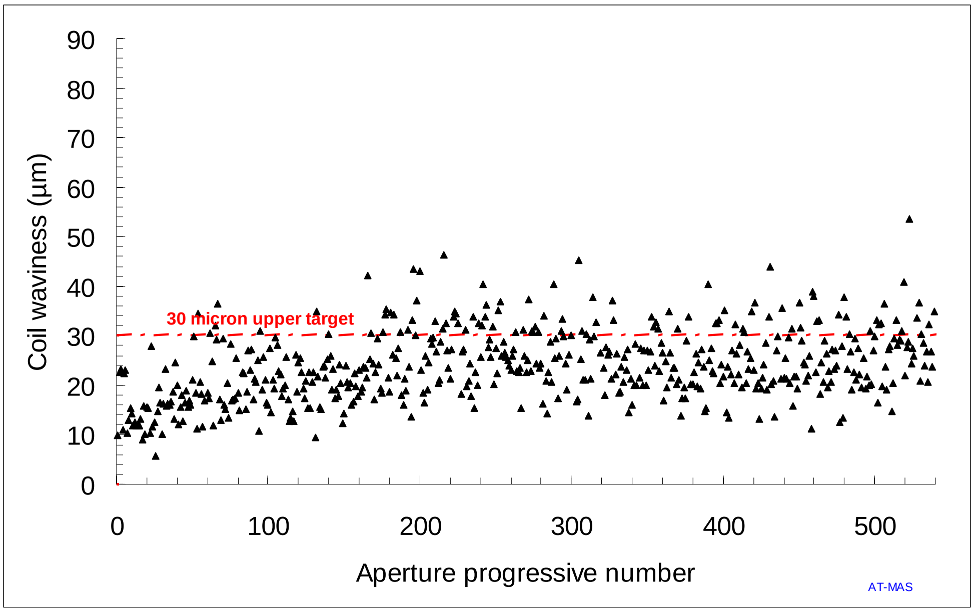


Fig. 23: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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, analysis, and careful reading of this manuscript. We acknowledge F. Simon for several comments, suggestions and discussions about the MQ production steering.