Report on field quality in the main LHC quadrupole collared coils and cold masses: December 04 - January 05

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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 December 1 2004 – January 31 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 467 apertures (233.5 magnets) and 166 cold masses. At 1.9 K we have measurements of 16 quadrupoles.
- In these two months, 64 apertures (i.e., 32 equivalent quadrupoles) and 27 cold masses have been measured at room temperature. No new measurements are available at 1.9 K.

What's new

Issues critical for beam dynamics:

- **Spread of focusing strength:** the situation is stable, but still critical. The spread in the cold masses is 12 units, i.e. 20% more than target. Sorting is being carried out to minimize the effect on the beam dynamics.
- **Collar permeability:** only a few batches of collars with large magnetic permeability have been used, namely for two apertures. These apertures have a lower b6 and a higher b2, as expected.

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:** in the recent production, we had a few cases of magnets with strong anomalies in the values of a3, b5, a4, b5, b7. Since they are not critical for beam dynamics, all apertures have been accepted. Indeed, they indicate a deterioration of the quadrupole symmetry.

CONTENTS

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 64 new apertures (i.e. 32 equivalent quadrupoles) and 27 cold masses have been measured at room temperature (see Fig. 1).

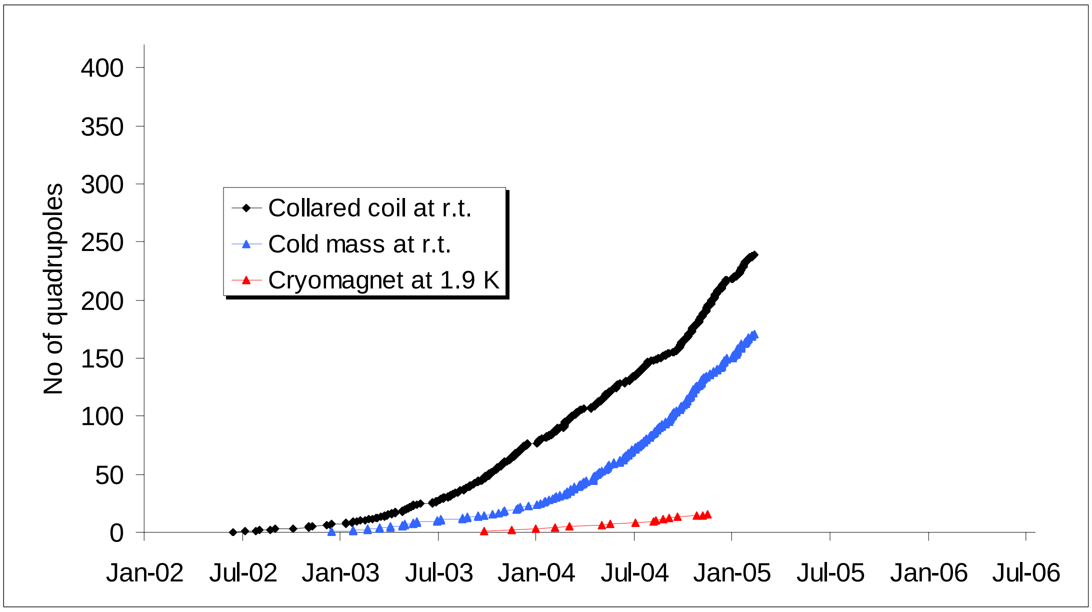

Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

- Cross-section: all apertures have X-section 2.
- Coil protection sheet[1]: all apertures have a coil protection sheet of 0.87 mm except 457th-460th, and 477th, where values of 0.94-0.95 mm had to be used to compensate a small coil size.

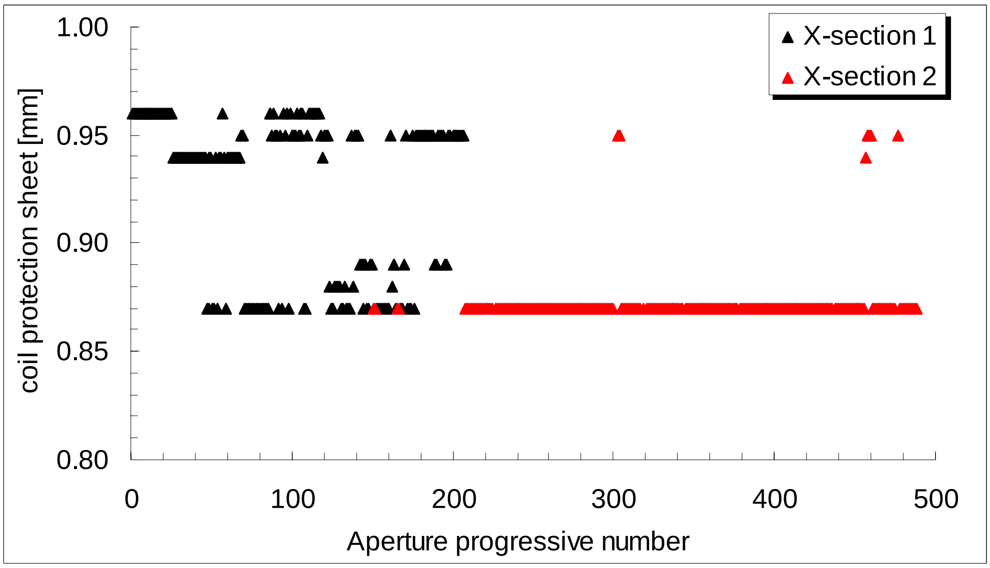

Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[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 276 apertures with X-section 1 and 191 of 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).

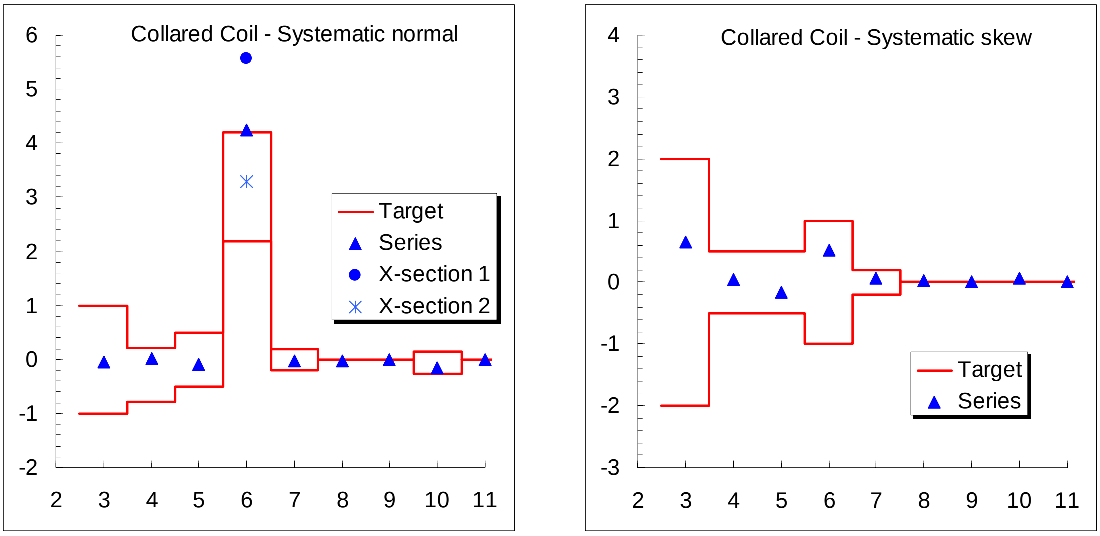

Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (red line).

- Best estimates of the random components are given in Fig. 4. All values are within targets with the exception of b2 and b6 and, for the first time, a4. This out of target random a4 is due to two large values measured in apertures 389th and 445th (see fig 18. pg 10).
- The standard deviation of b2 (integrated field gradient) is 12.7 units, i.e. 27% more than the upper limit of 10 units. In the cold masses, the spread is 12.0 units. The target is a hard limit, which is established on the budget allocated for beta beating. The large measured spread is not given by the mixing of the two different cross-sections. The situation for X-section 1 was at the limit of the specification, the spread being of 11.3 units. The situation is worse for X-section 2, where the spread is of 13.3 units.
- 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.

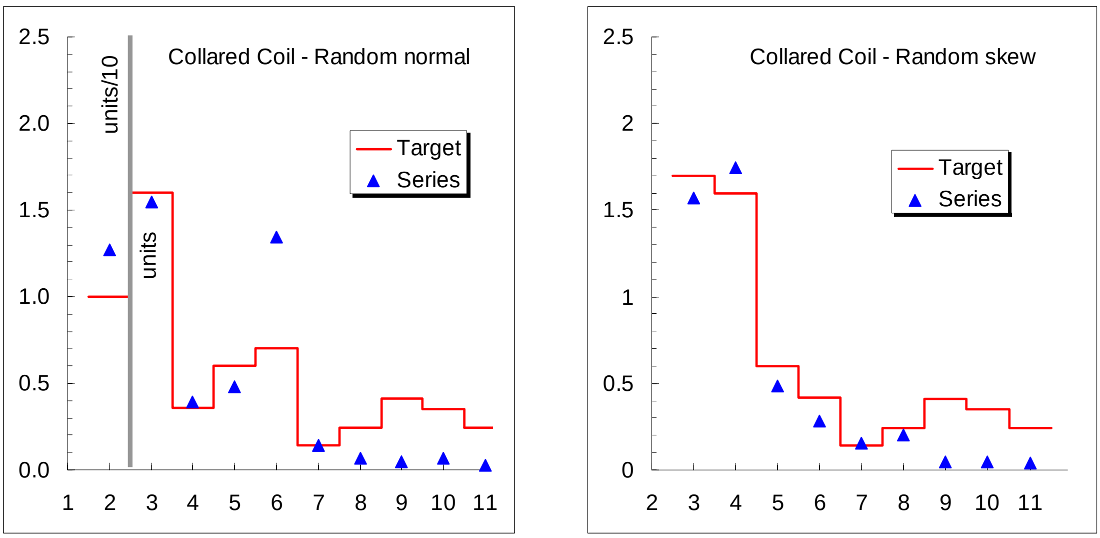

Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

PART III: TRENDS IN FIELD QUALITY

3.1 Trends in focusing strength

3.1.1 Trends in magnetic length

- Magnetic length of the aperture is extremely stable (within ±5 units). The standard deviation over all apertures is very small (2 units).

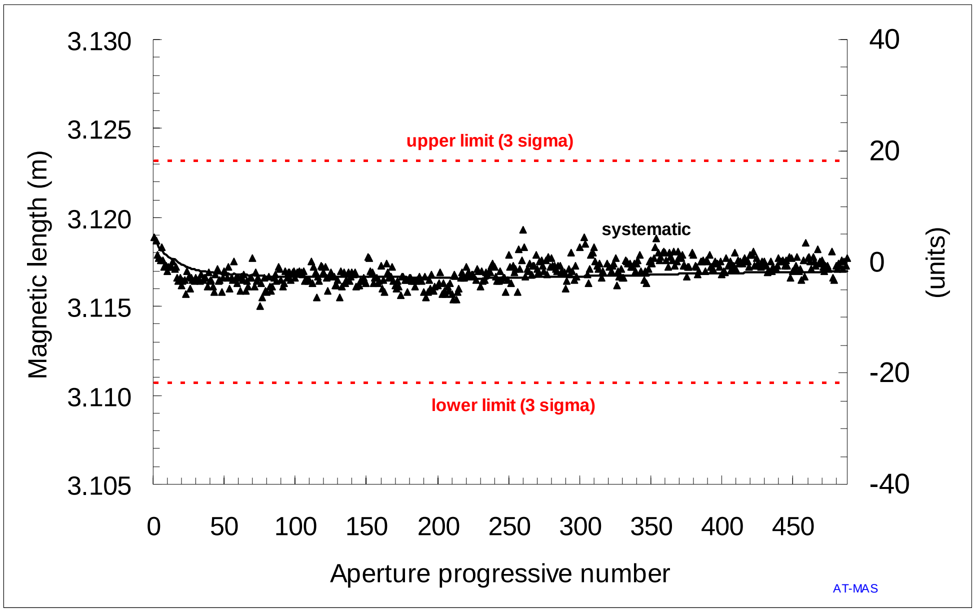

Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

- Magnetic length of **cold masses** is also extremely stable (see Fig. 6)[2]. The standard deviation over all cold masses is 1.8 units.

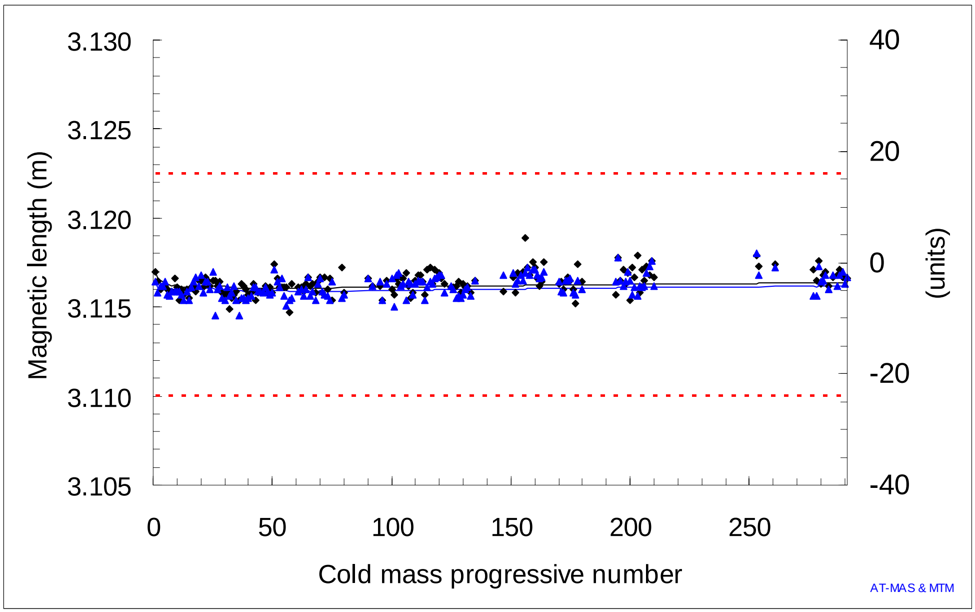

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Fig. 6: Magnetic length of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

[2] Please note that the ordering of the apertures is not the same of the ordering of the cold masses. Therefore, the trends in plots of Figs. 5-6, 7-8 and 9-10 are not directly comparable. The two apertures that compose a cold mass are chosen according to a matching criteria developed by CEA.

3.1.2 Trends in field gradient

- The spread of the field gradient in the straight part of the magnet is still large (12.9 units in the apertures), but stable in the recent production (see Fig. 7).

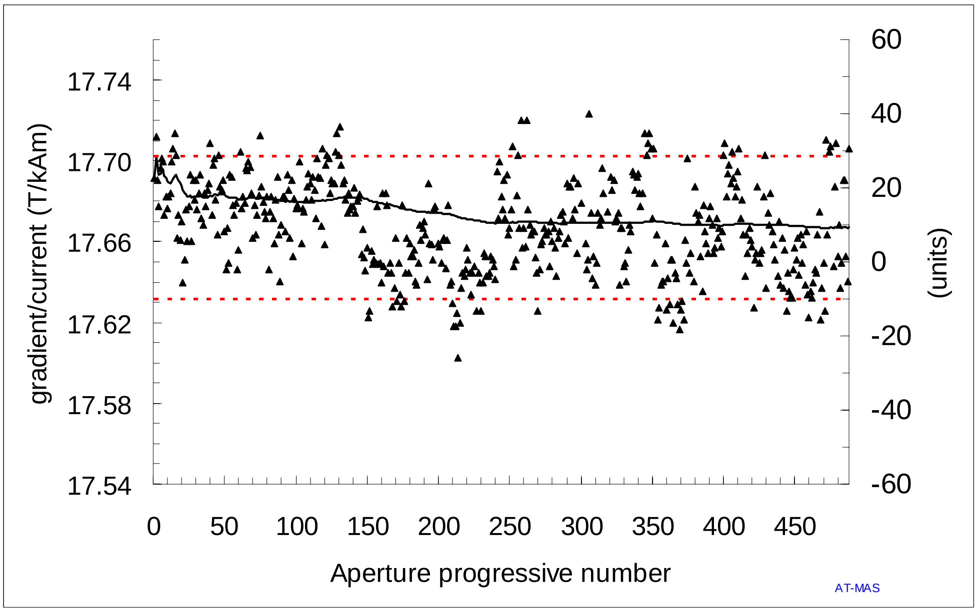

Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines, separated according to different cross-sections).

- The large spread observed in apertures (12.9 units) is confirmed by **cold mass** data, where it is 12.5 units (see Fig. 8).

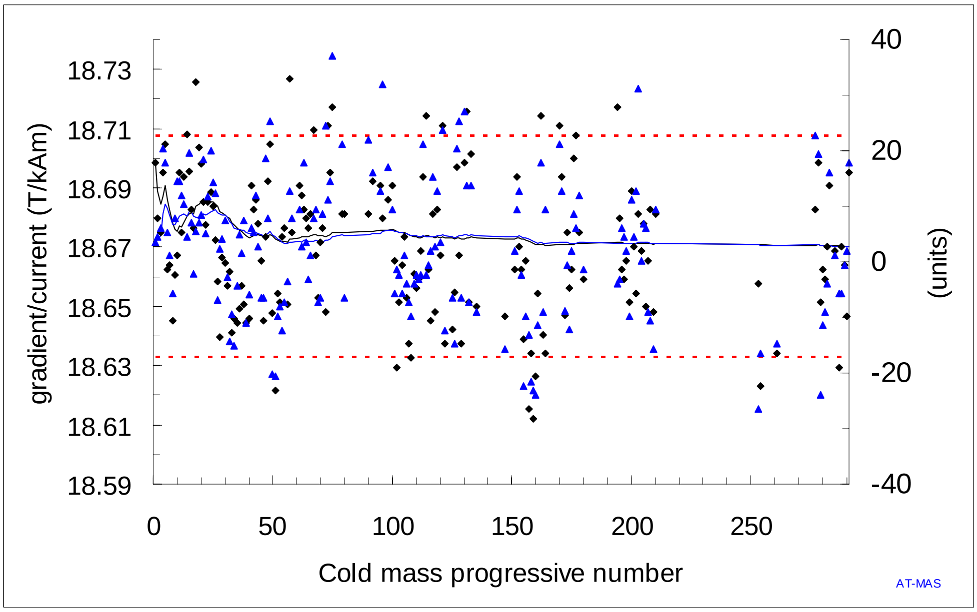

Fig. 8: Field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

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 12.7 units, and for the cold masses is 12.0 units.

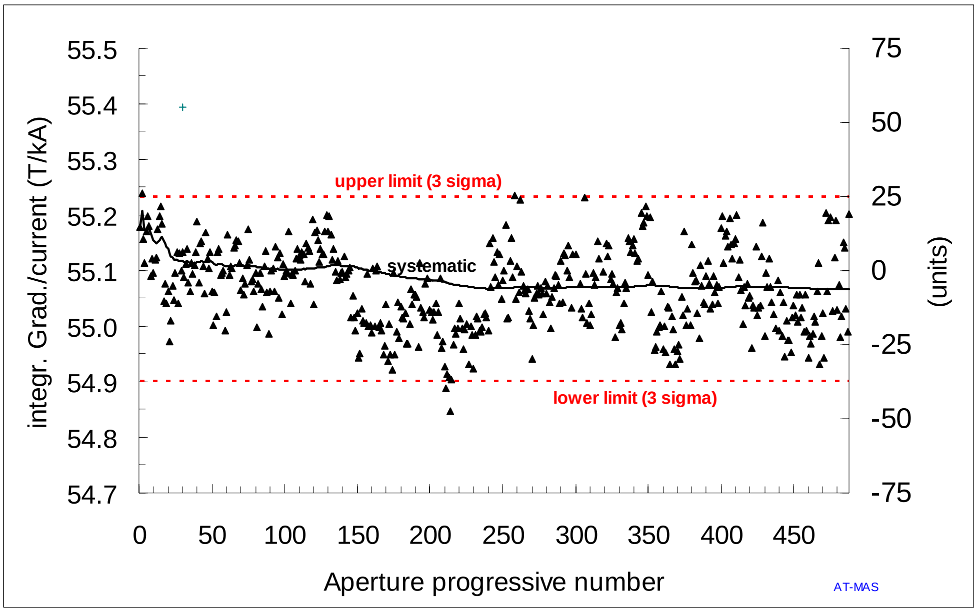

Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid lines, separated according to different cross-sections).

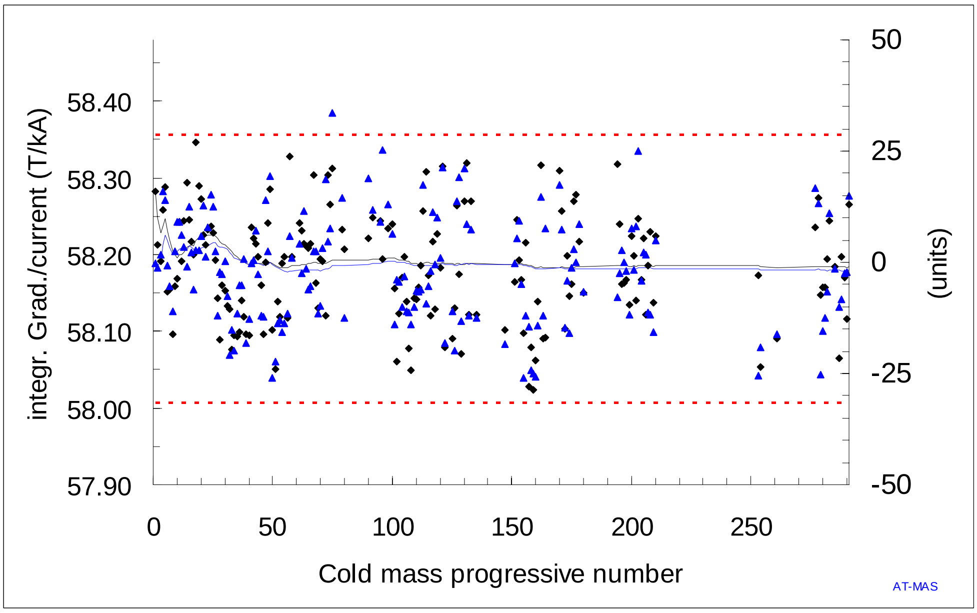

Fig. 10: Integrated field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

3.2 Trends in allowed multipoles

- Systematic b6 has dropped from 5.5 units to about 3 units with the introduction of cross-section 2 (see Fig. 11). In the production of these two months, there is an increase of about 0.5-1 units whose origin is under analysis. The systematic value of cross-section 2 is within targets. The very low values observed between 250th and 400th, due to high collar permeability, are not seen any more. Indeed, in the recent production only two apertures (478th and 479th) have been manufactured with collars magnetic permeability out of tolerance; they have a lower b6 (see Fig. 11) as expected.

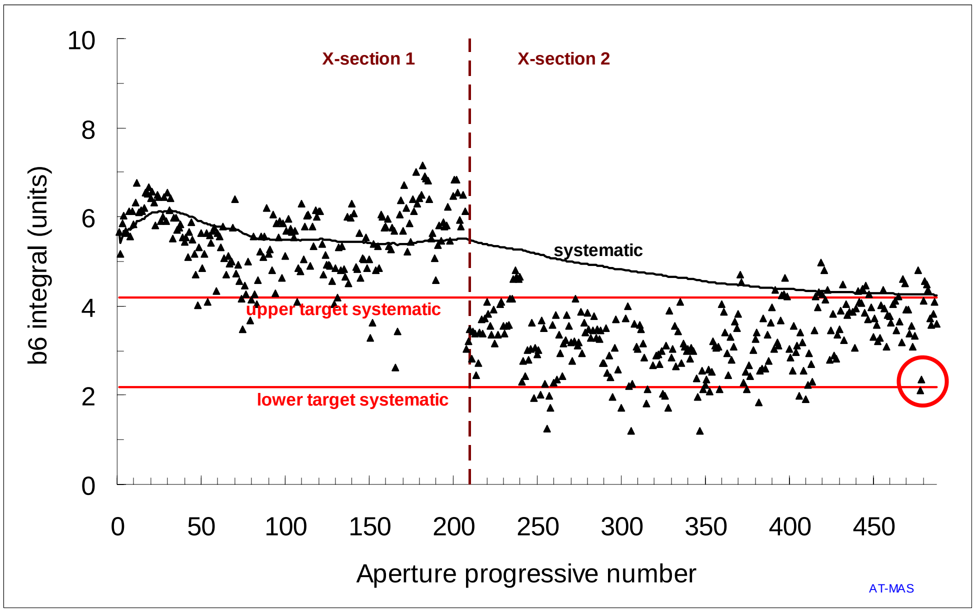

Fig. 11: Integral b6 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 16 cryoquadrupoles. Apertures 478th and 479th are marked by a red circle.

- Systematic b10 is well within targets, and the impact of the cross-section change is small (0.2 units, see Fig. 12).

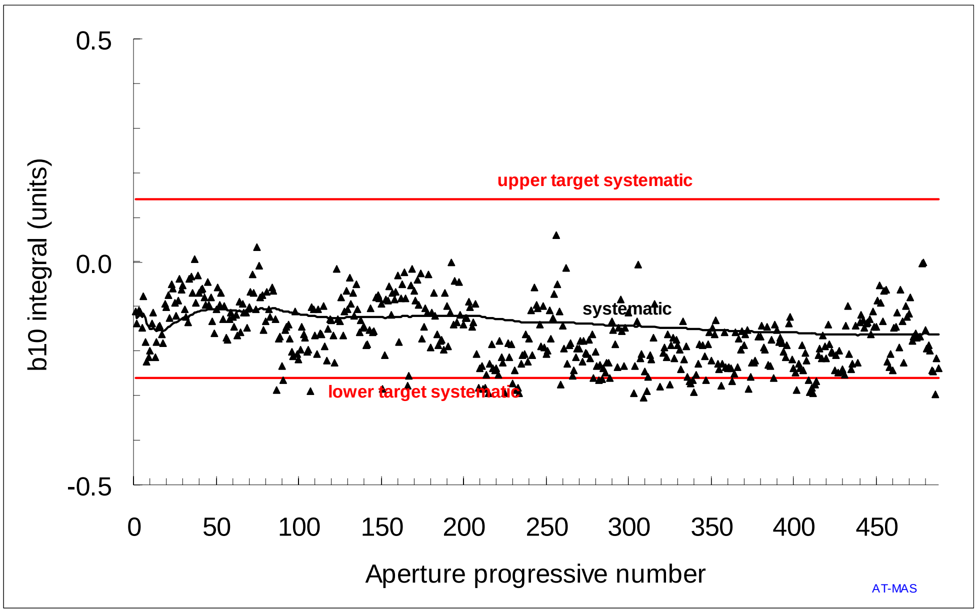

Fig. 12: Integral b10 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 16 cryoquadrupoles.

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. Very large values (around 6 units) have been found in 413th and 445th.

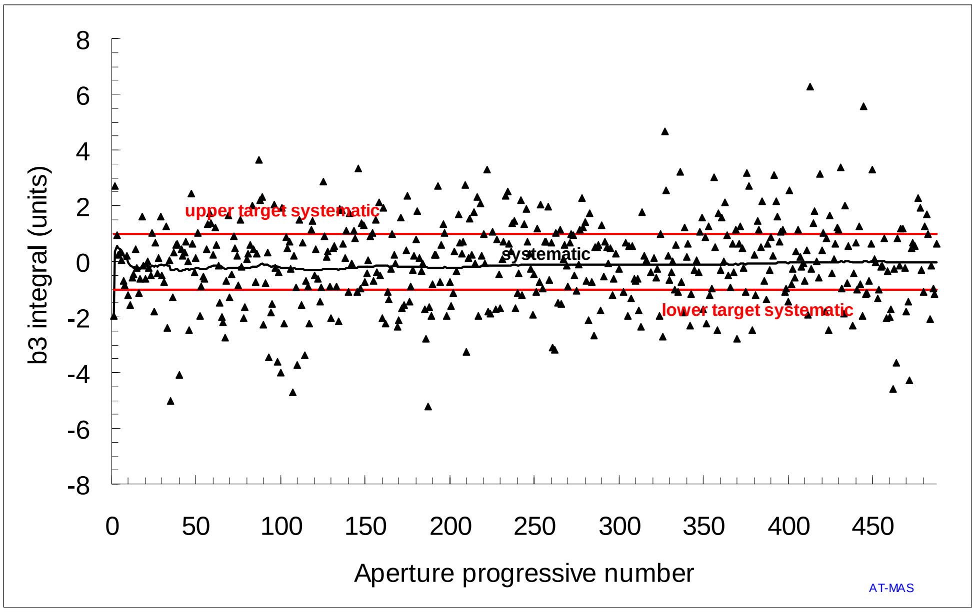

Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

- 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.

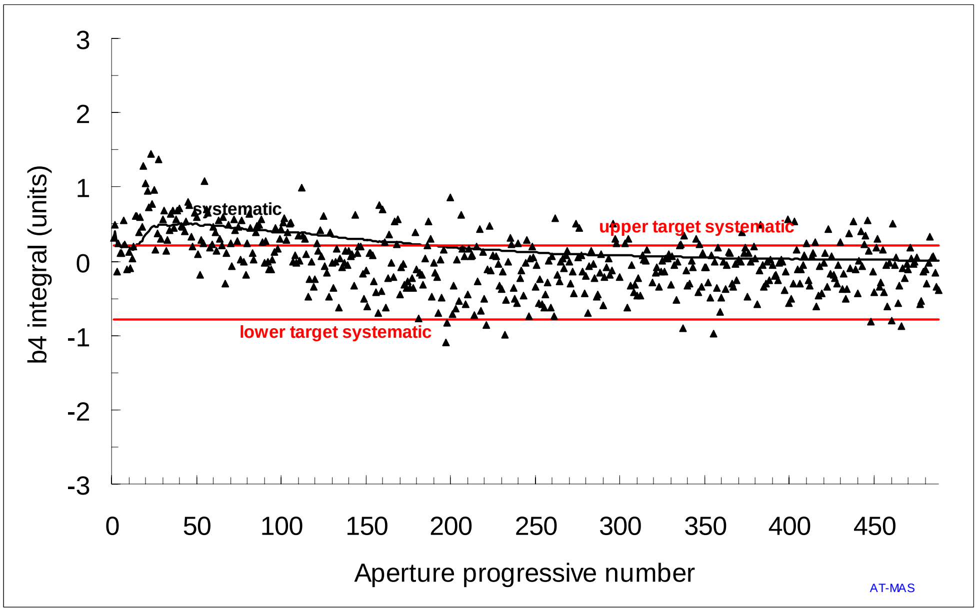

Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

- 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. A large b5 value (-1.8 units) has been found in 445th.

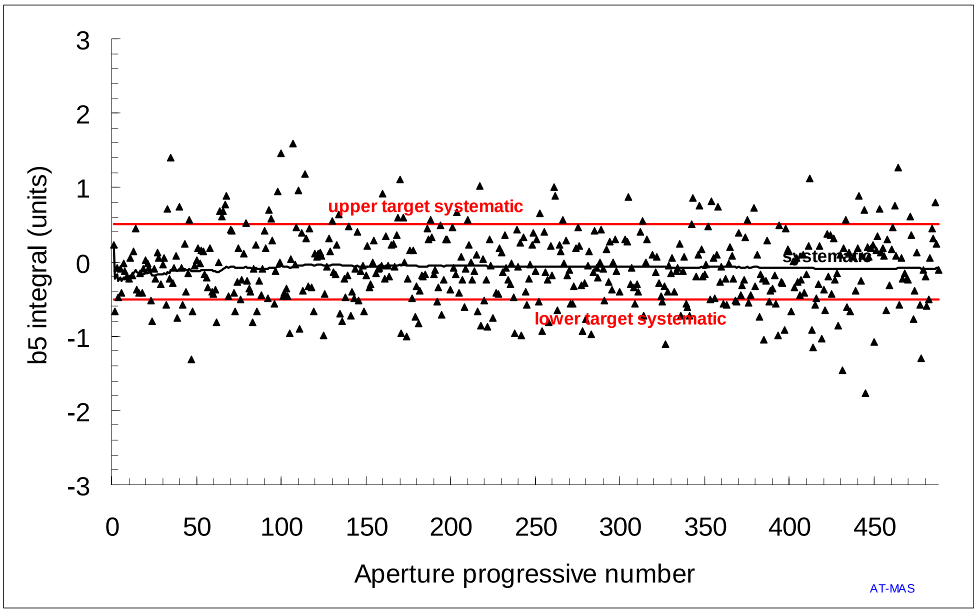

Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

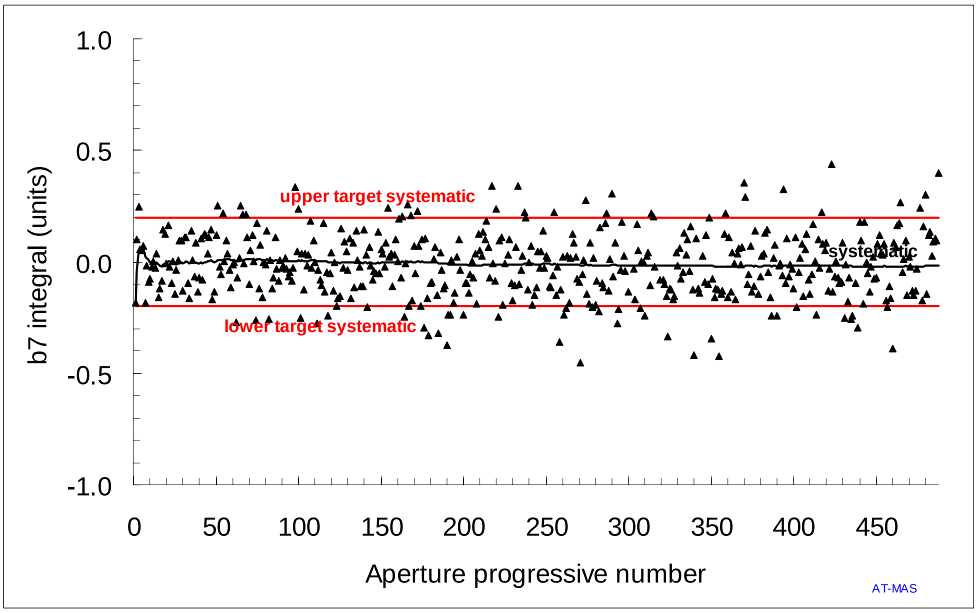

Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

3.3.2 Skews: a3, a4, a5, a6

- A systematic component of 0.6 units is observed for a3 (see Fig. 17). In the recent production, large values of a3 (5 to 6 units) have been found for 402nd, 457th, 464th
- Systematic values of a4 and a5 are close to zero as expected by the symmetry, and well within targets (see Figs. 18-19). A very large value of a4 (-7 units) has been found for apertures 389th and 445th.
- 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.

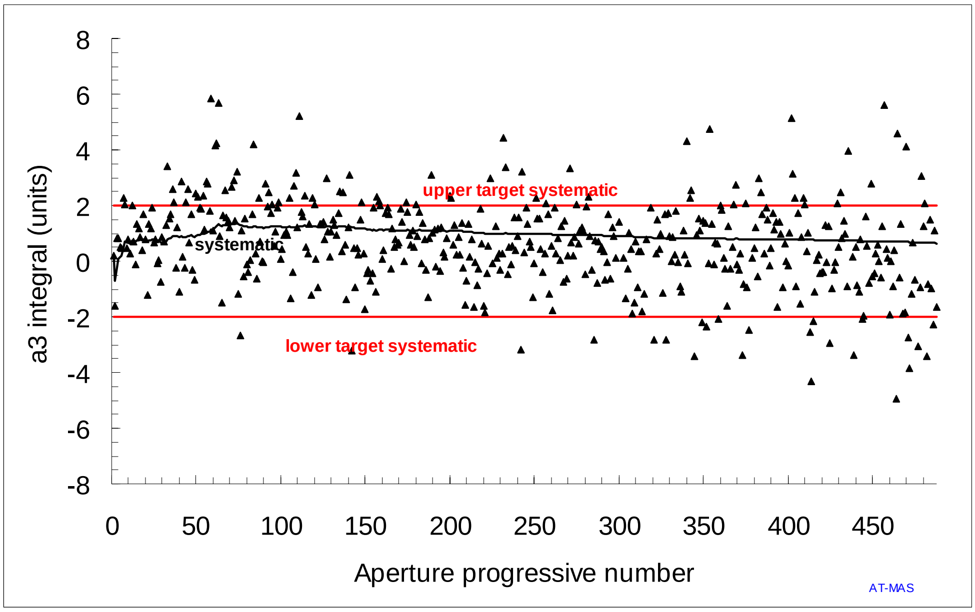

Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

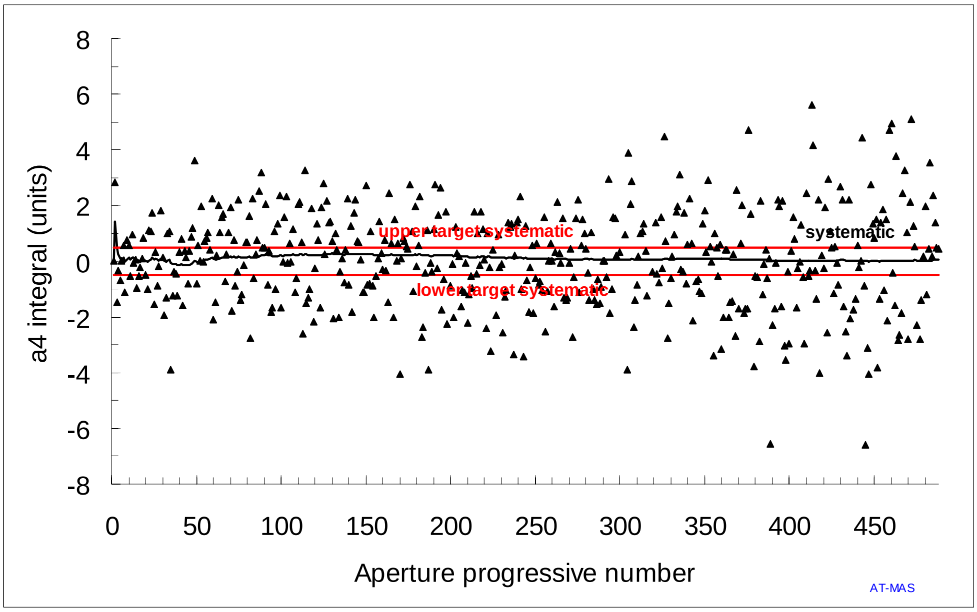

Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

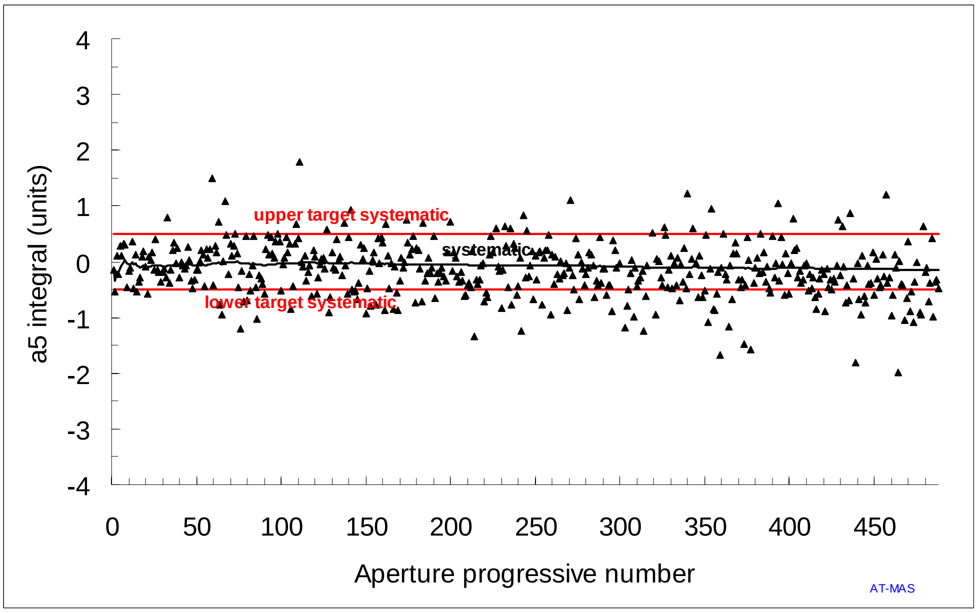

Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

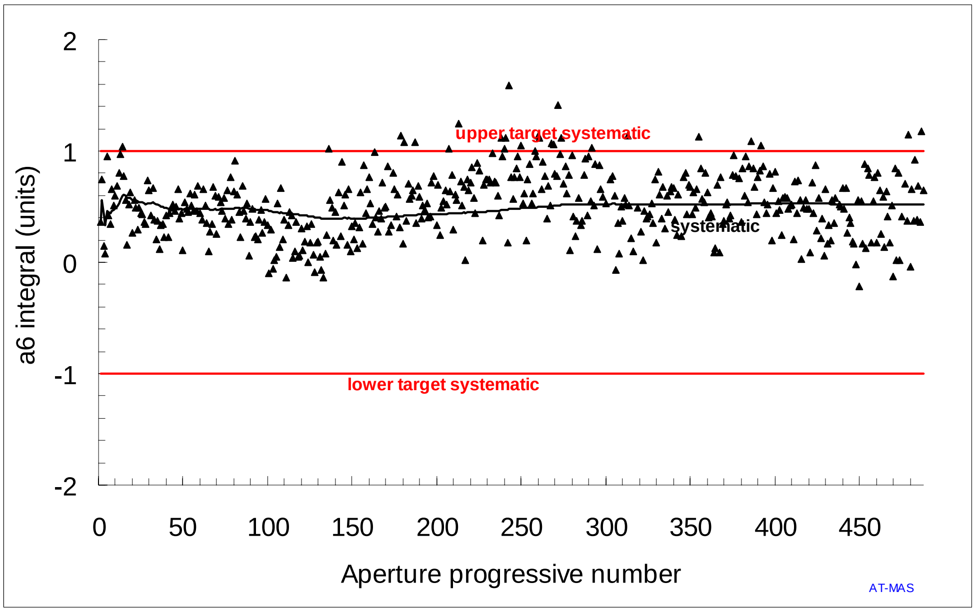

Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines).

3.4 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. 21).

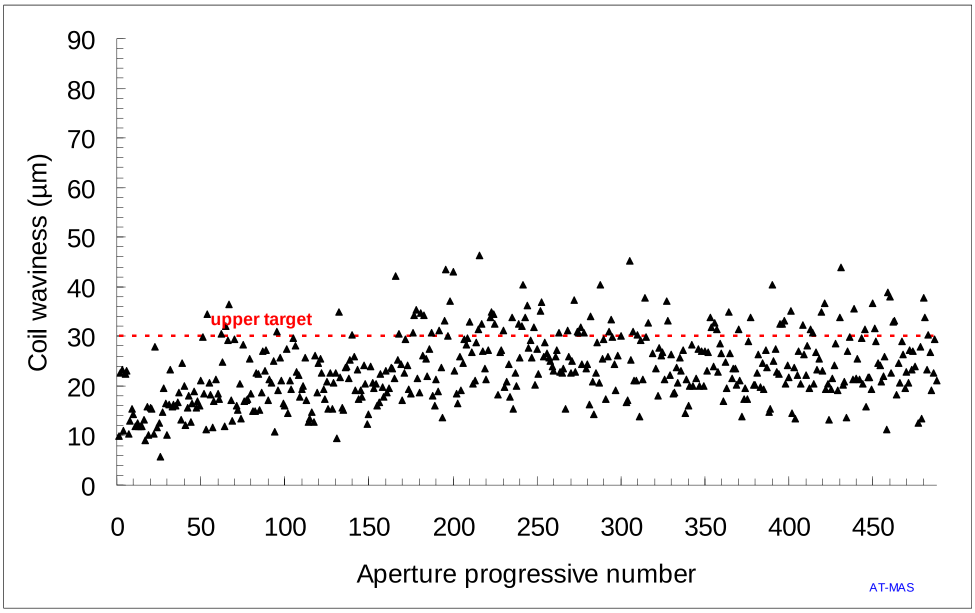

Fig. 21: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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, F. Simon for several comments and information about the MQ production steering, and A. Verweij for useful discussions about cable geometrical dimensions and field quality.

Appendix A: dependence of field quality on cable manufacturer

In the previous report, a dependence of the focusing strength on cable manufacturer has been observed, namely aperture manufactured with cable C featured 20 units more than the others. In the production of the last two months, cable G and B have been used, and only a few apertures have been made with cable C. Data are shown in Figure 25, where only cross-section 2 magnets are shown. Data confirm a difference of 25 units between cable C and B, with cable G in between.

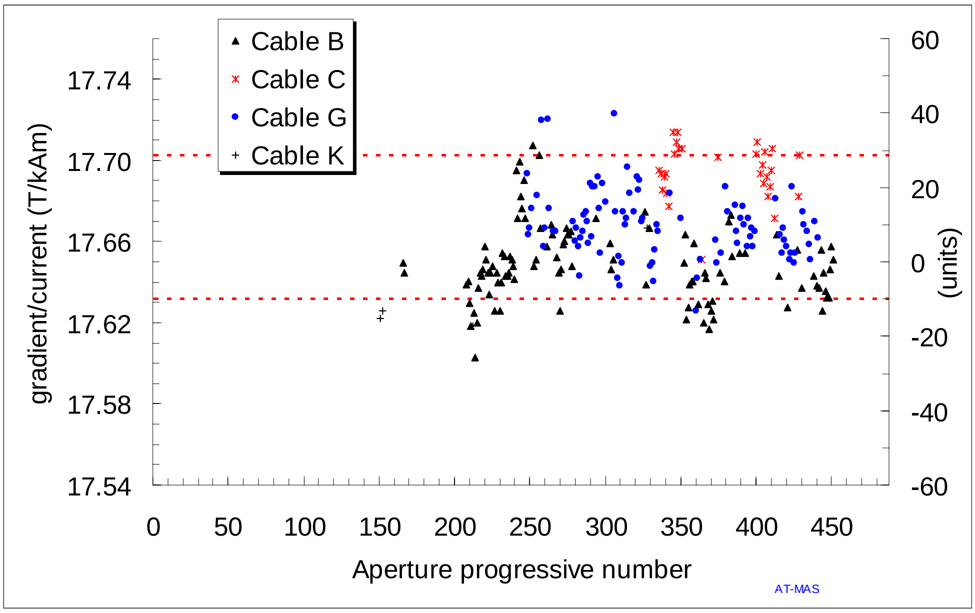

Fig. 25: focusing strength in all quadrupoles with cross-section 2, separated according to cable manufacturer

We remind the reader that 20 units more in focusing strength can be obtained by a cable width 30 microns larger than nominal. Recent analysis[3] shows that the average width of cable C is 12 microns larger than cable B. Therefore, 40% of the variation of field gradient can be explained in terms of geometrical dimension of the cables.

[3] A. Verweij, AT-MAS Technical Note 2005-03.