Report on field quality in the main LHC quadrupole collared coils and cold masses: October-November 2004

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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 1– November 30 2004, 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 393 apertures (196.5 magnets) and 137 cold masses. At 1.9 K we have measurements of 16 quadrupoles.
- In these two months, 58 apertures (i.e., 29 equivalent quadrupoles) and 30 cold masses have been measured at room temperature, and 4 magnets at 1.9 K.

What's new

Issues critical for beam dynamics:

- **Spread of focusing strength:** already in room temperature data, the spread of focusing strength is 25% higher than target. This parameter continues to be the most critical for the quadrupoles.
- **Correlations for focusing strength and b6:** we had one case (magnet 120) that shows very poor correlation both in focusing strength and b6 (see pg. 12-14). The reason of this bad correlation has been traced back to the use of collars whose permeability is out of tolerance. This induces high focusing strength and lower b6 at room temperature, but at 1.9 K the effect disappears, thus giving bad correlations. This effect is worrying since the lack of correlation for these magnets implies a loss of knowledge of the field quality in operational conditions for the quadrupoles that will not be measured at 1.9 K (90% according to the revised baseline). This also limits the possibility of steering of the field quality based on measurements at room temperature.

Issues non-critical for beam dynamics:

- **Systematic b4:** from the more recent data, it is possible that the systematic component measured at room temperature in the early part of the production was a feature of the measuring system (wrong measurement).

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PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 58 new apertures (i.e. 29 equivalent quadrupoles) and 30 cold masses have been measured at room temperature (see Fig. 1).

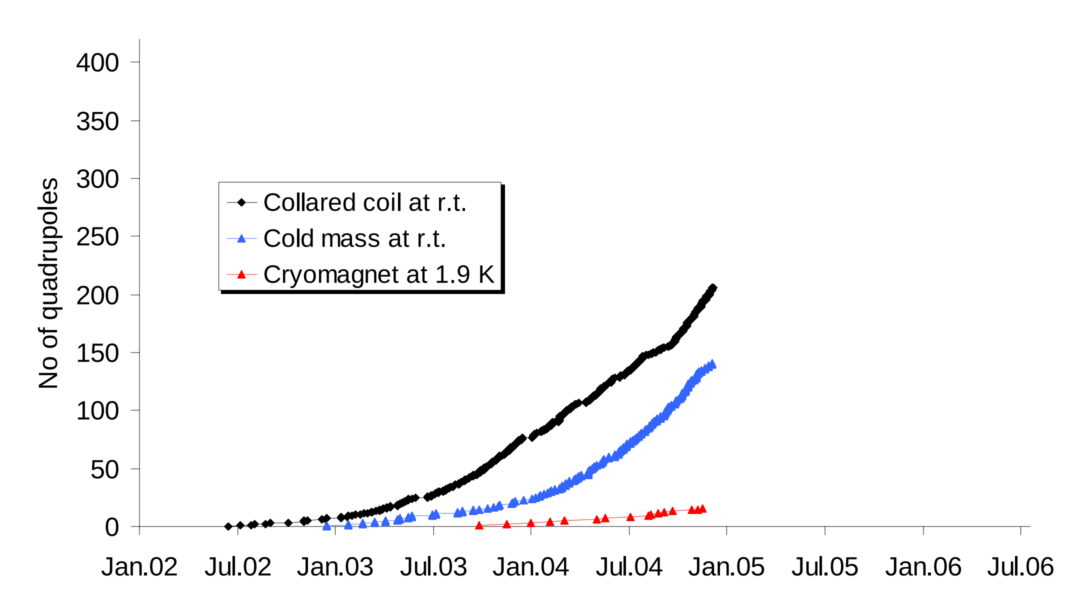

Fig. 1: Number of magnets measured at the manufacturers at room temperature and at 1.9 K in different stages of assembly procedure

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

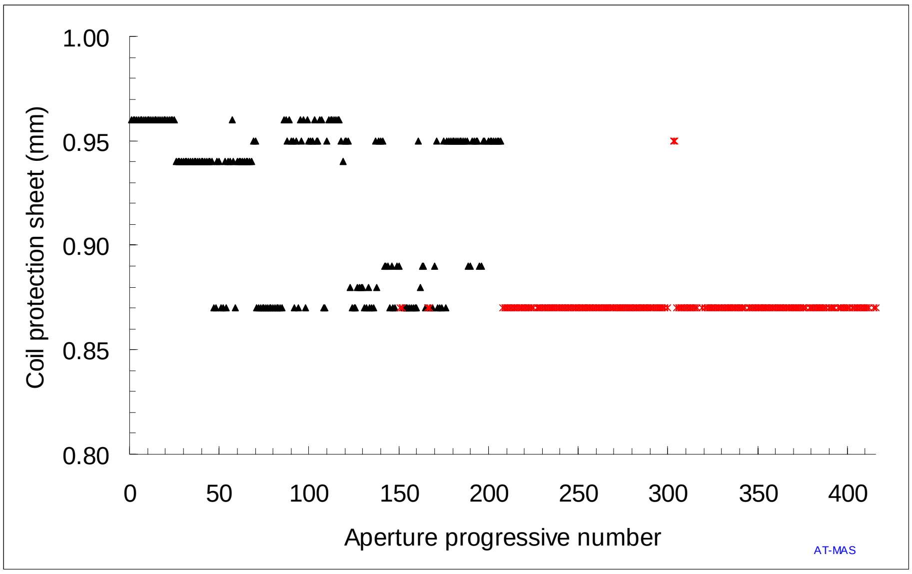

Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[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, with the exception of b6.
- For b6, the average is carried out over 202 apertures with X-section 1 and 191 of X-section 2: this gives a systematic b6 of 0.15 units larger than the targets. 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).
- Details on trends are given in Part III.

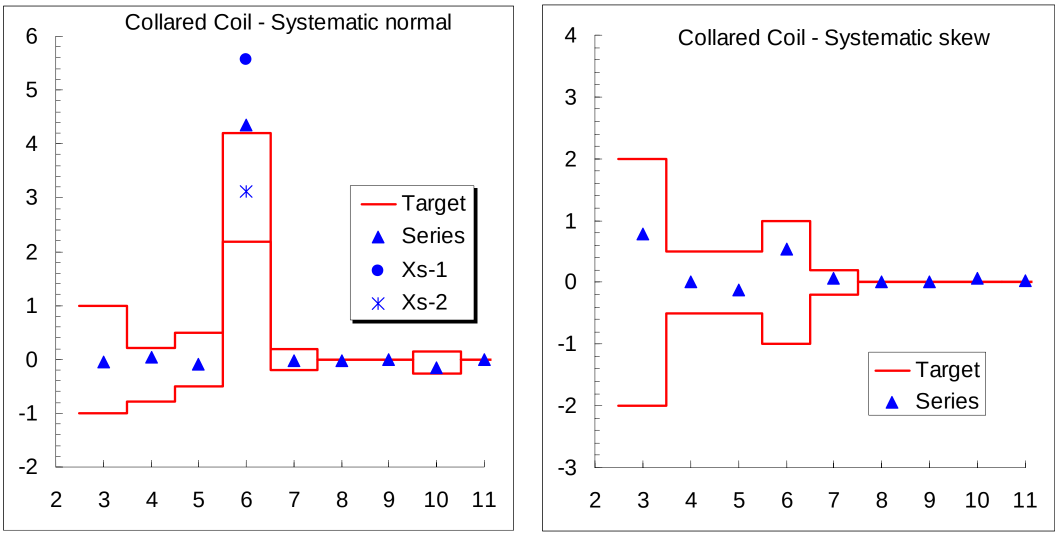

Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics targets (red line).

- Best estimate of the random component is given in Fig. 4. All values are within targets with the exception of b2 and b6.
- The standard deviation of b2 (integrated field gradient) is 12.6 units, i.e. 25% more than the upper limit of 10 units. This 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 13.5 units. The analysis of the sources of spread is given in Section 3.1.
- The spread of b6 over all apertures (1.4 units) is mainly due to the mixing of the two different X-sections. Data of X-section 1 have a spread of 0.7 units, and one has a similar value for X-section 2, i.e. within targets. Indeed, the target for beam dynamics on random b6 is not a hard limit.

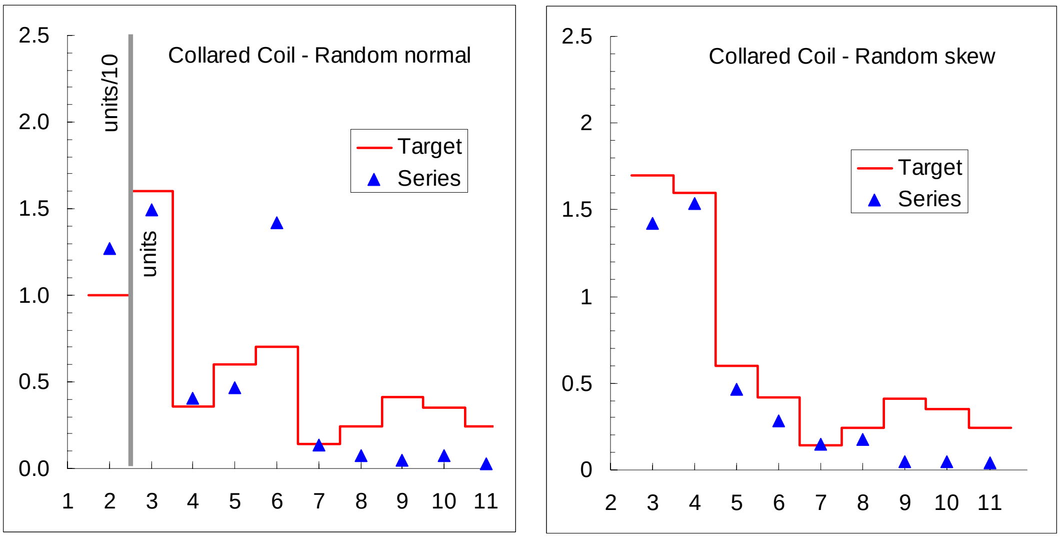

Fig. 4: Best estimate for random normal (left) and skew (right) component in the measured collared coils compared to targets for random at 1.9 K.

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). A small increase of both the systematic and the random have been observed after aperture 200th. The standard deviation over all apertures is indeed very small (2 units).

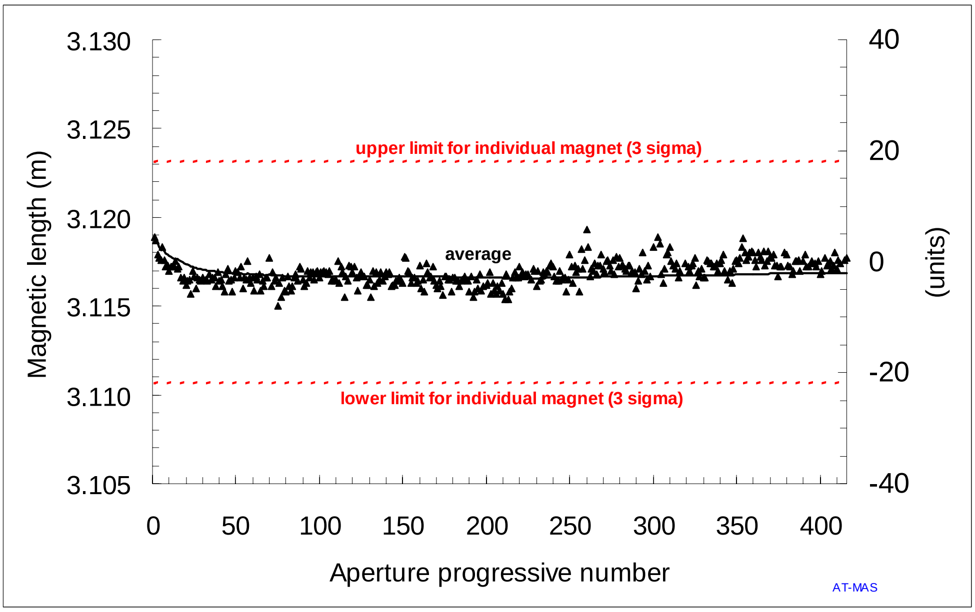

Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

- Magnetic length of **cold masses** is also extremely stable (see Fig. 6)[2]. The standard deviation over all cold masses is 1.7 units.

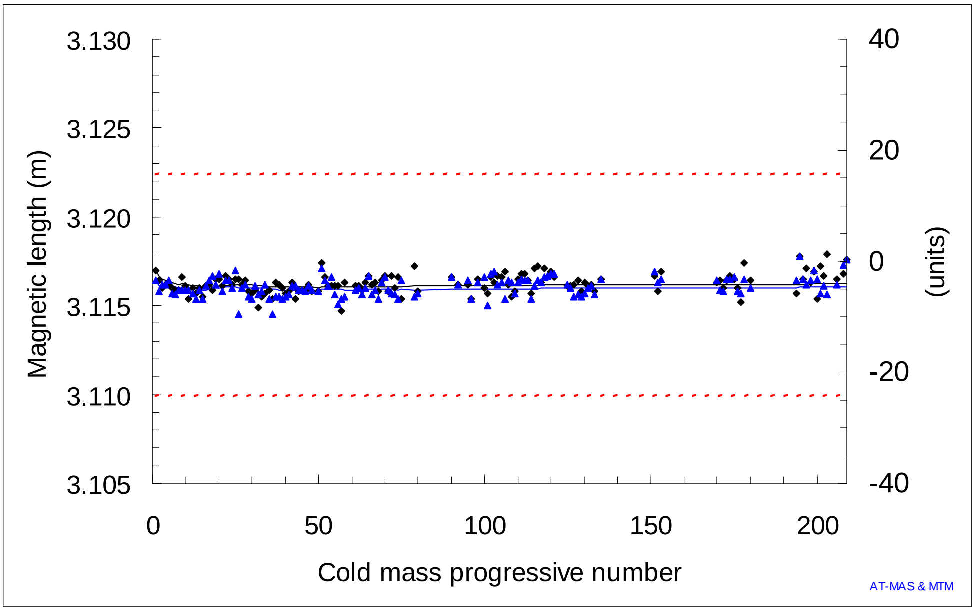

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Fig. 6: Magnetic length of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

[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 large (see Fig. 7). A drop of around 20 units has been seen after aperture 140, with the introduction of X-section 2, against an expected value of 6 units. An increase has been seen after aperture 240, traced back to a significant out of tolerance of collar permeability (for instance, apertures 256th and 258th, indicated by a red circle in the figure). It is also found[3] that magnets using cable C have a focusing strength that is 20 units higher than average (see also Appendix A).

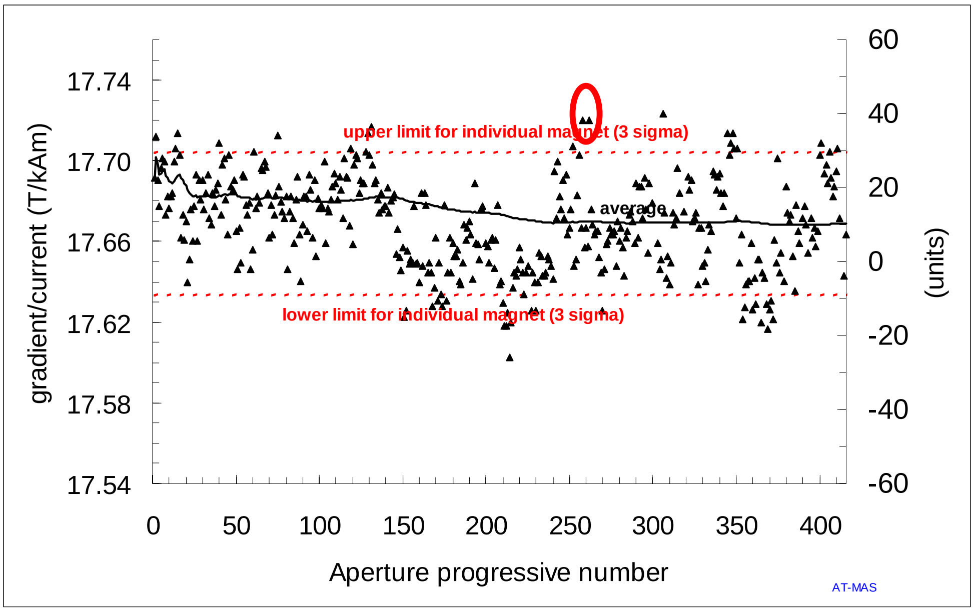

Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines, separated according to different cross-sections). Apertures 256th and 258th are marked by a red circle.

- The large spread observed in apertures (12.6 units) is confirmed by **cold mass** data, where it is 11.5 units (see Fig. 8).

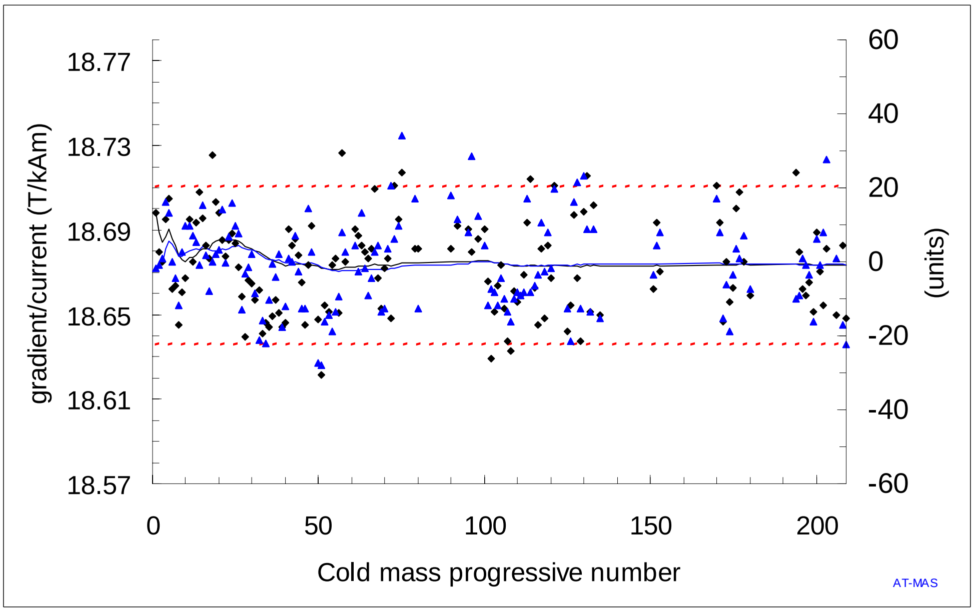

Fig. 8: Field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

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[3] F. Simon, private communication

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 collared coils and in cold masses (see Fig. 9 and 10).

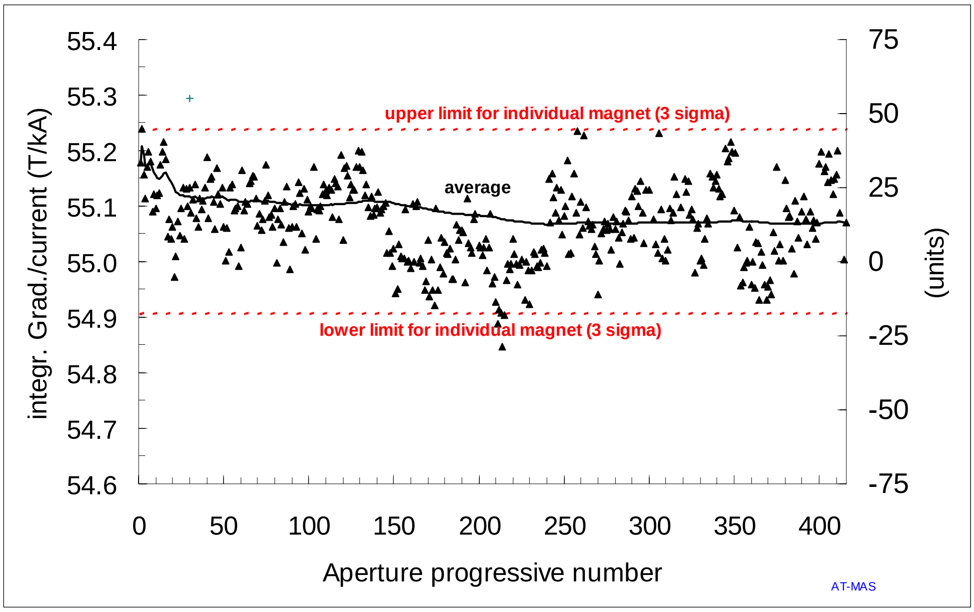

Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid lines, separated according to different cross-sections).

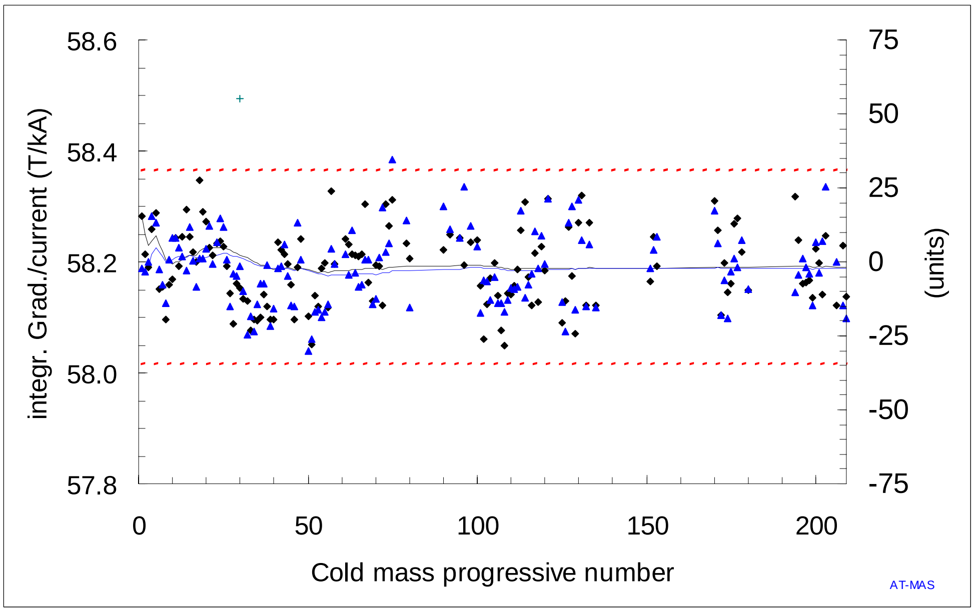

Fig. 10: Integrated field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

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, the situation is rather stable. Very low b6 values are mainly due to the use of a collar permeability out of tolerance (for instance, apertures 256th and 258th, indicated by a red circle in the figure).

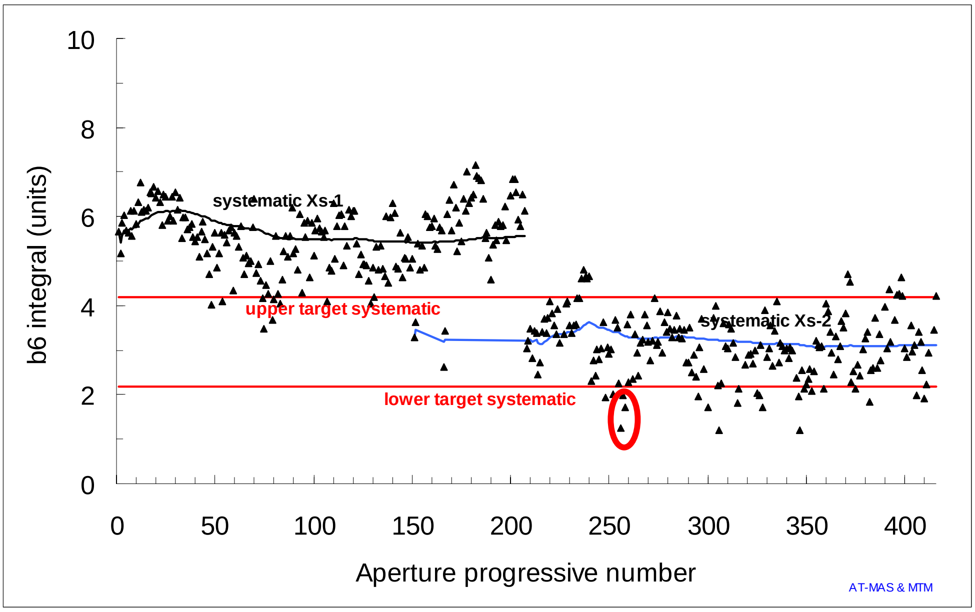

Fig. 11: Integral b6 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 16 cryoquadrupoles. Apertures 256th and 258th are marked by a red circle.

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

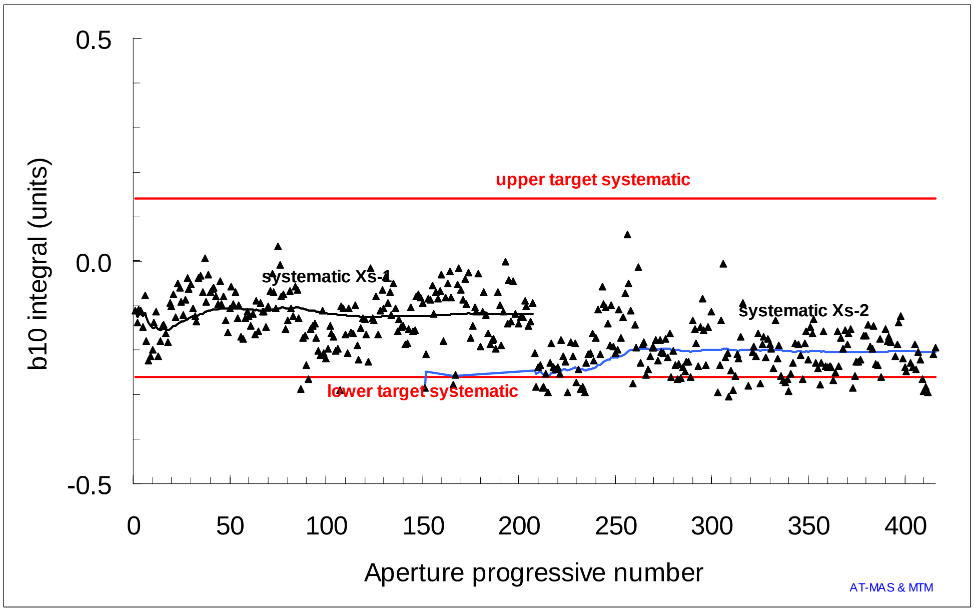

Fig. 12: Integral b10 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 16 cryoquadrupoles.

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 well within targets (see Fig. 13). No trends are observed.

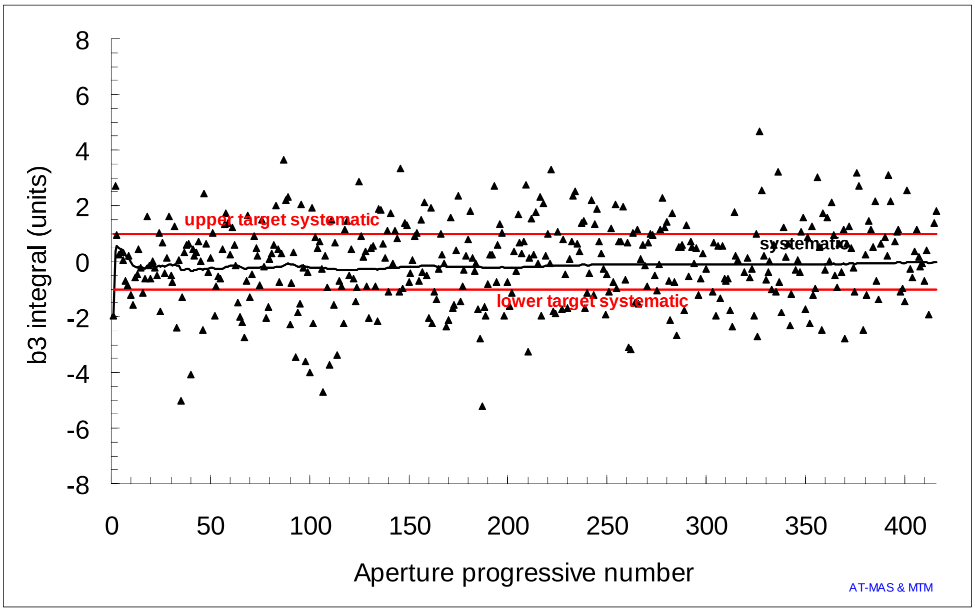

Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

- 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 (see Section 3.4, pg. 14).

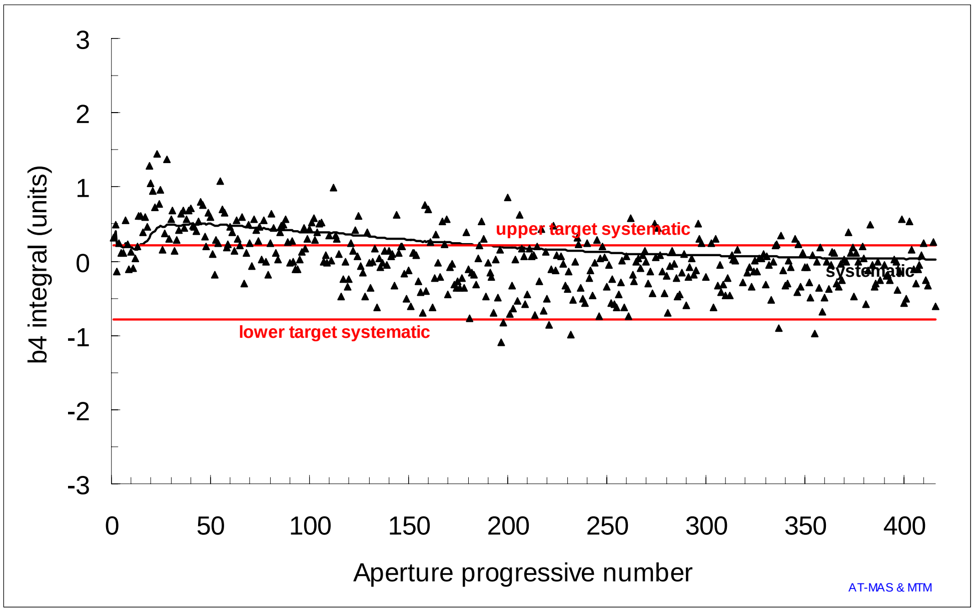

Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

- 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.

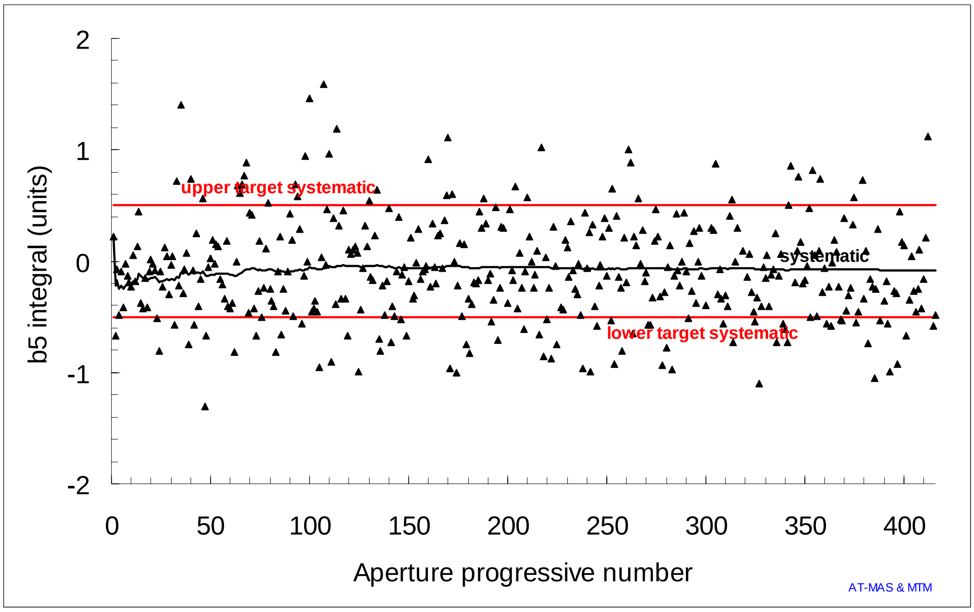

Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

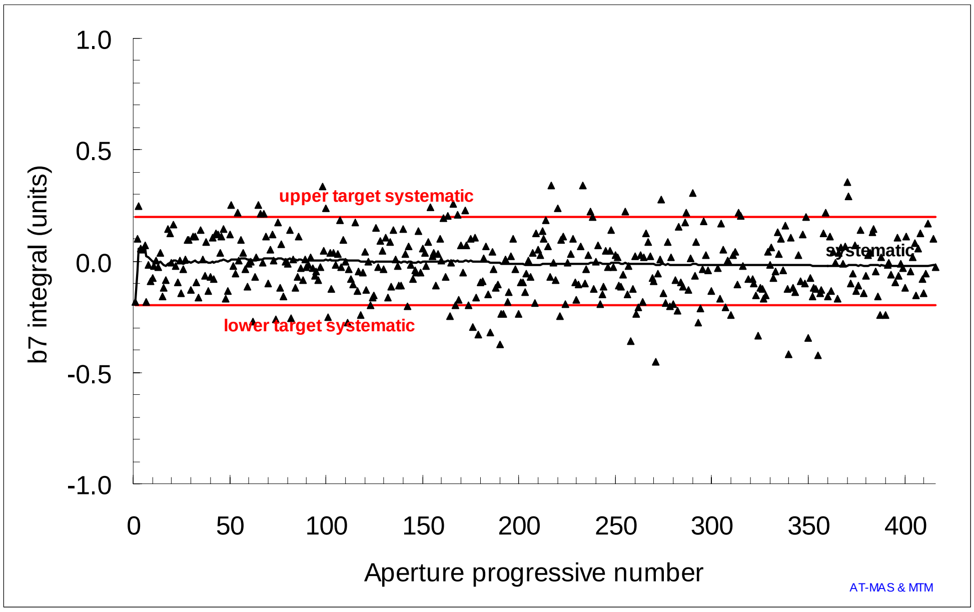

Fig. 16: Integral b7 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

3.3.2 Skews: a3, a4, a5, a6

- A systematic component of 1 unit is observed for a3 (see Fig. 17).
- Systematic values of a4 and a5 are close to zero as expected by the symmetry, and well within targets (see Figs. 18-19).
- 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.

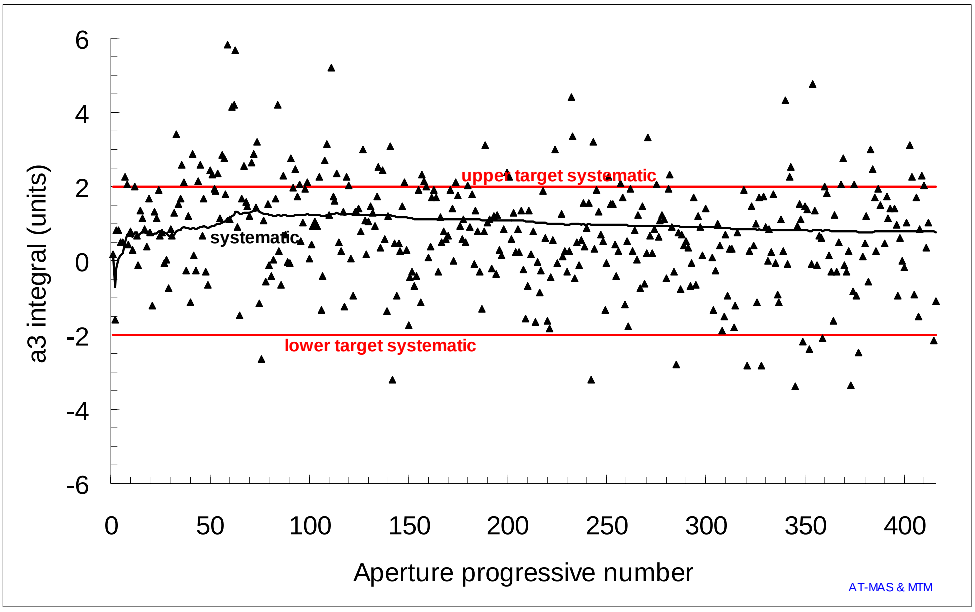

Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

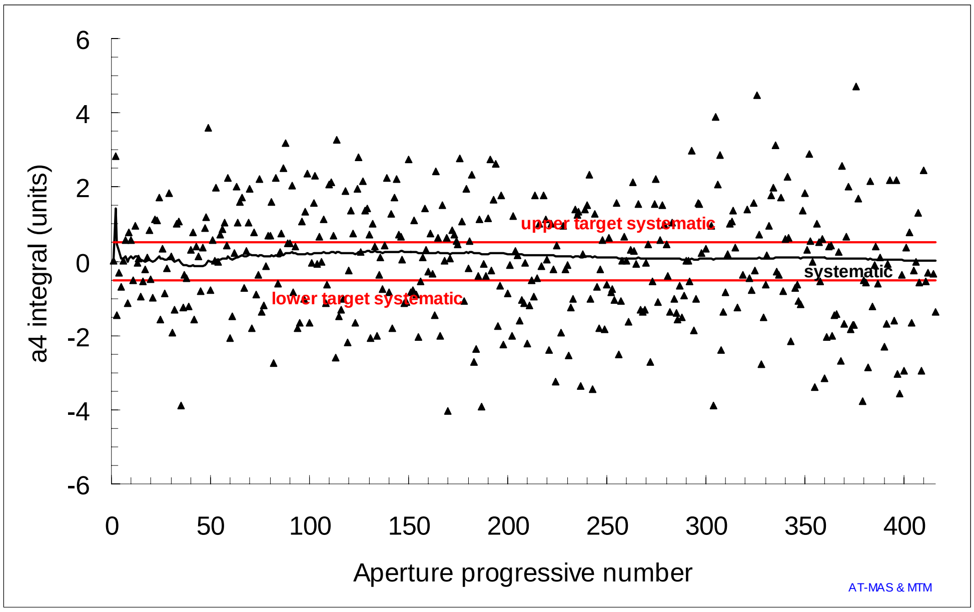

Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

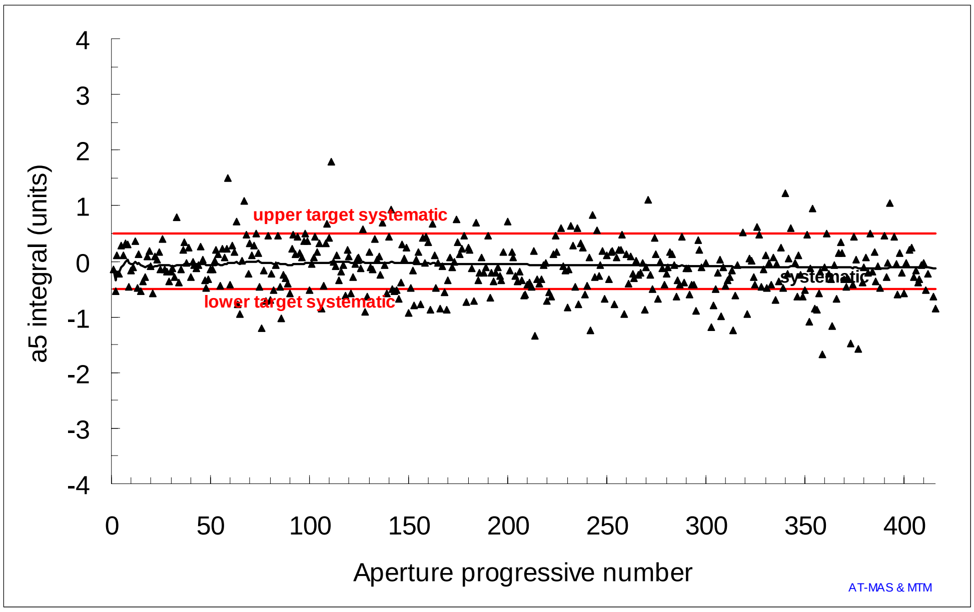

Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

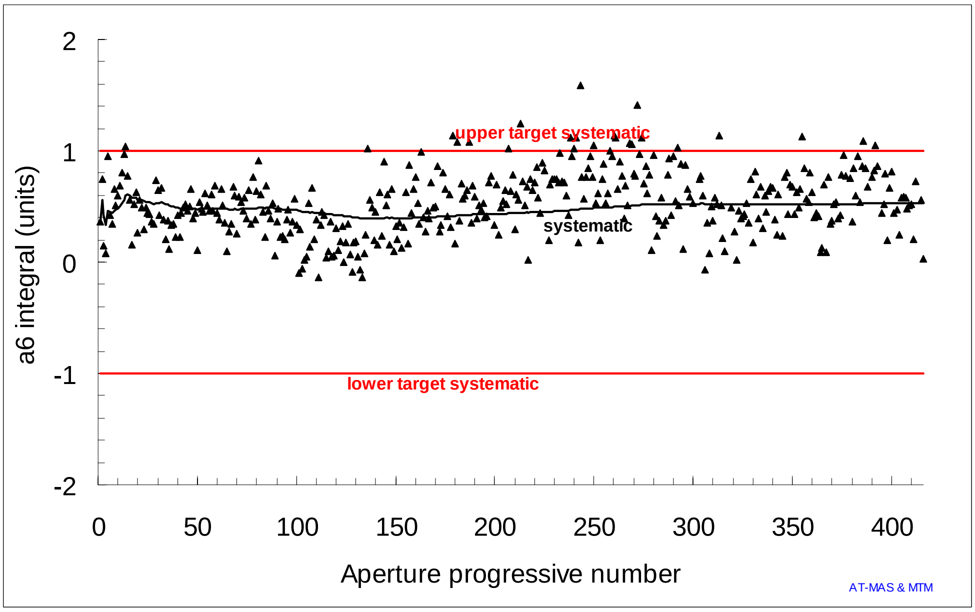

Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 16 cryoquadrupoles.

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, plus b4 and a6, which show some anomalies at room temperature. 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 (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 80 quadrupoles between room temperature measurements of collared coil and test at 1.9 K[4], equivalent to 6 months of production), and allows to detecting trends in correlations along the production.

- Integrated field gradient: we present data of 12.5 measured quadrupoles (25 apertures). We plot the difference between the integrated gradient at room temperature and at high field. Both the case of the collared coil and of the cold mass measurement are shown.
    - The offset between apertures at room temperature (i.e., without iron yoke) and quadrupoles at 1.9 K is shown in Fig. 21. In the abscissa on the right, values are given in units relative to the nominal value of 58.5 T/kA. The average increase of 3.3 T/kA is mainly due to the field increase due to the iron yoke (approximately 5%).
    - Two apertures, corresponding to magnet 004, have a rather low offset compared to the other ones (around 3.15 T/kA, i.e. 30 units less). Indeed, the analysis of data at 1.9 K does not present any anomalies justifying a rejection of the measurement[5].
    - Magnet 120, corresponding to apertures 256th and 258th, have a lower offsets (40 to 50 units less). These apertures had collars with high permeability, thus leading to a higher value of the focusing strength at room temperature (see Fig. 7). This effect disappears at 1.9 K, thus leading to a much lower offset for these apertures. This feature of quadrupoles manufactured with collar having high permeability, to be confirmed by further measurements, has been observed also in measurements of bare quadrupoles at Block4[6].

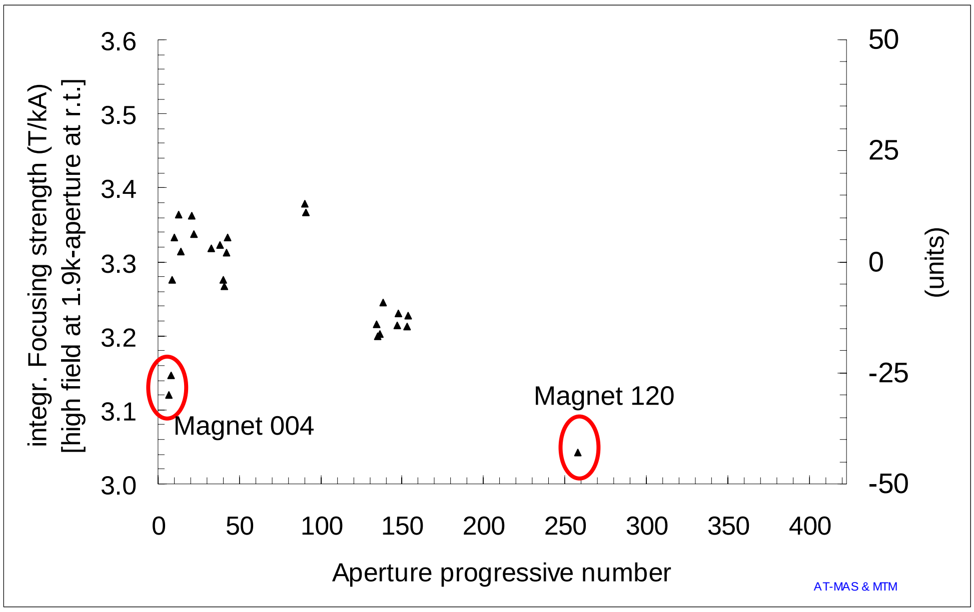

Fig. 21: Difference in focusing strength between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

[4] Please note that measurements of cold masses at block4 are not included in this analysis.
[5] S. Sanfilippo, private communication
[6] W. Venturini, private communication

- o The offset between cold masses (i.e., with iron yoke) at room temperature and quadrupoles at 1.9 K is shown in Fig. 22. In the right part, values are given in units relative to the nominal value of 58.5 T/kA. The average value of 0.25 T/kA.m (i.e., approximately 0.4%) is mainly due to the field increase due to the thermal contraction.
- o The main features observed in the collared coils (previous plot) are confirmed by the cold mass data. In particular, magnet 120 (identified by the cold mass progressive number 75th in Fig. 22) has a much lower offset compared to the previous ones.

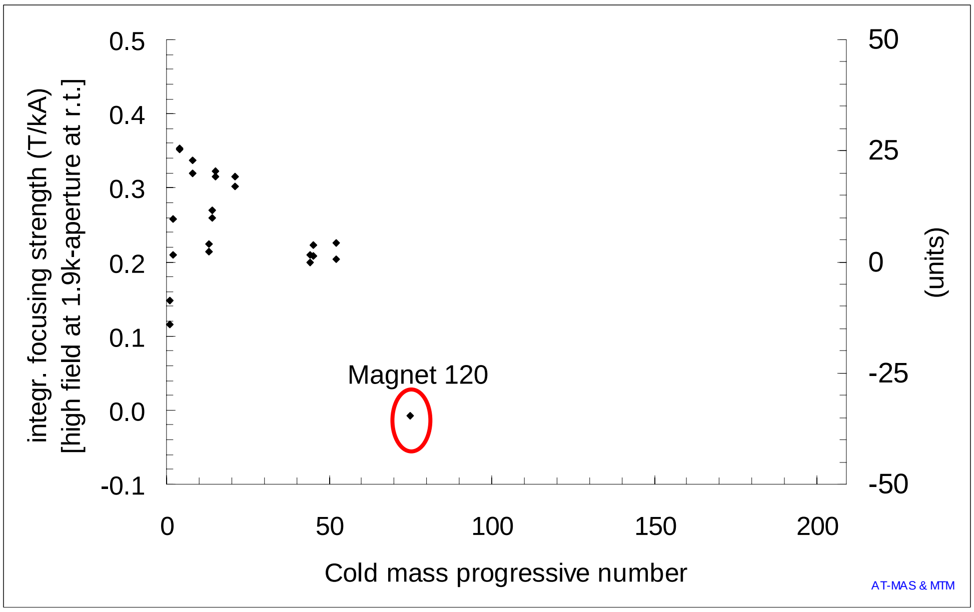

Fig. 22: Difference between integrated field gradient divided by current between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

- Allowed multipole b6: over the 16 available measurements (32 apertures), we see a difference between injection field at 1.9 K and collared coil at room temperature (no iron yoke) of -3.5 to –4.5 units. The measurements relative to apertures 256th and 258th (that were assembled in cold mass 120) show a much lower offset (2 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.

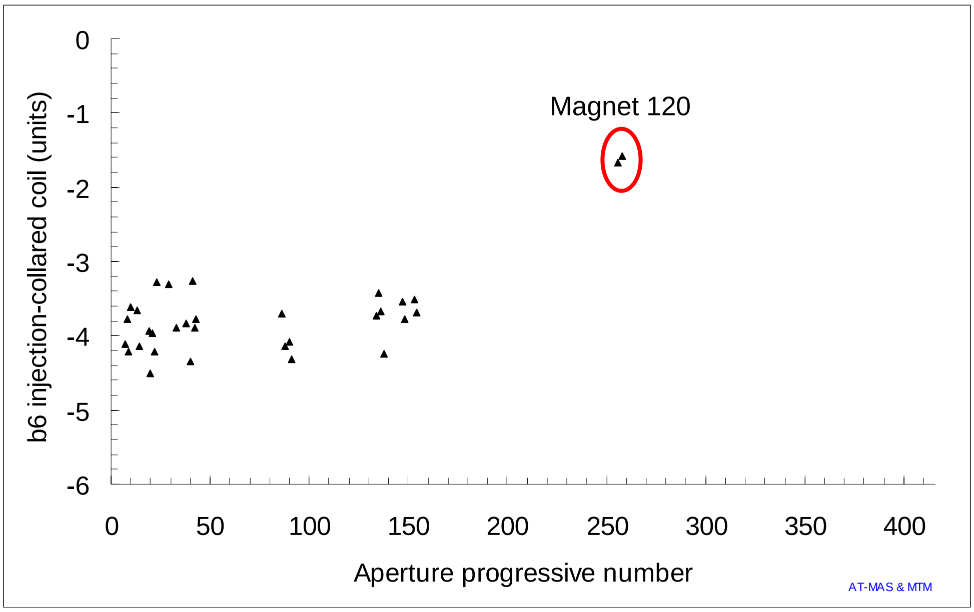

Fig. 23: Difference in integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

- Not allowed multipole b4: we see an unexplained feature of the offset, which for apertures 20 to 40 is not centred on zero. In the more recent production (from magnet 70th onward), the offset is centred on zero as expected (see Fig. 24). The spread of the offset is similar to the spread of the measurements at room temperature (0.4 units), i.e. there is not correlation. This could be explained by assuming that the positive values of b4 measured at the beginning of the production (see Fig. 14) were not correct, thus leading to a bad correlation. If we consider only the magnet from 70th onward, the spread of the offset goes down to 0.13 units, and a good correlation is recovered.

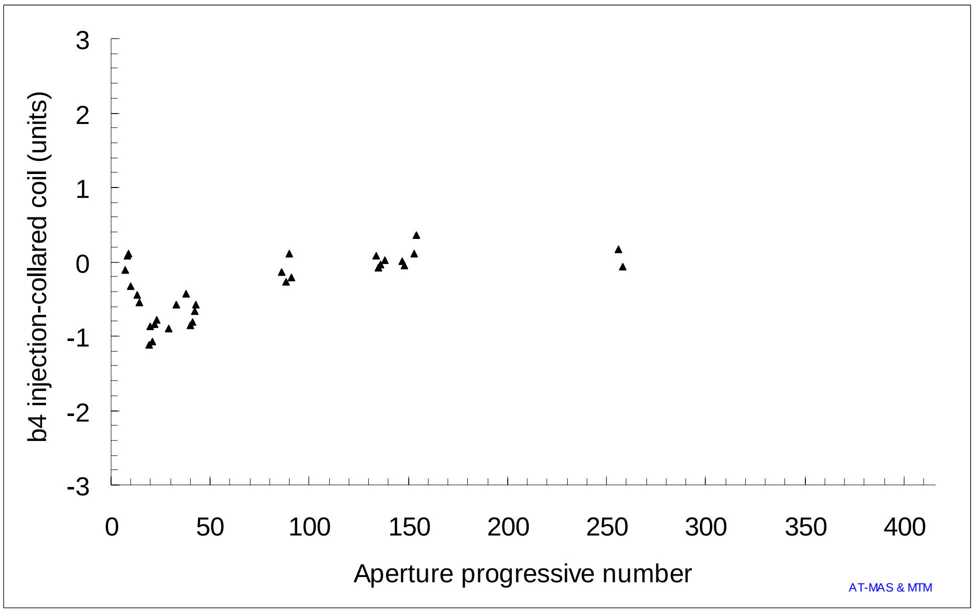

Fig. 24: Difference between integrated b4 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

- Not allowed multipole a6: over the 16 available measurements (32 apertures), we see a very stable offset between warm and cold measurements, centred around zero (see Fig. 25). The spread of the offset (0.12 units) is much smaller than the spread observed in the apertures (0.28 units).

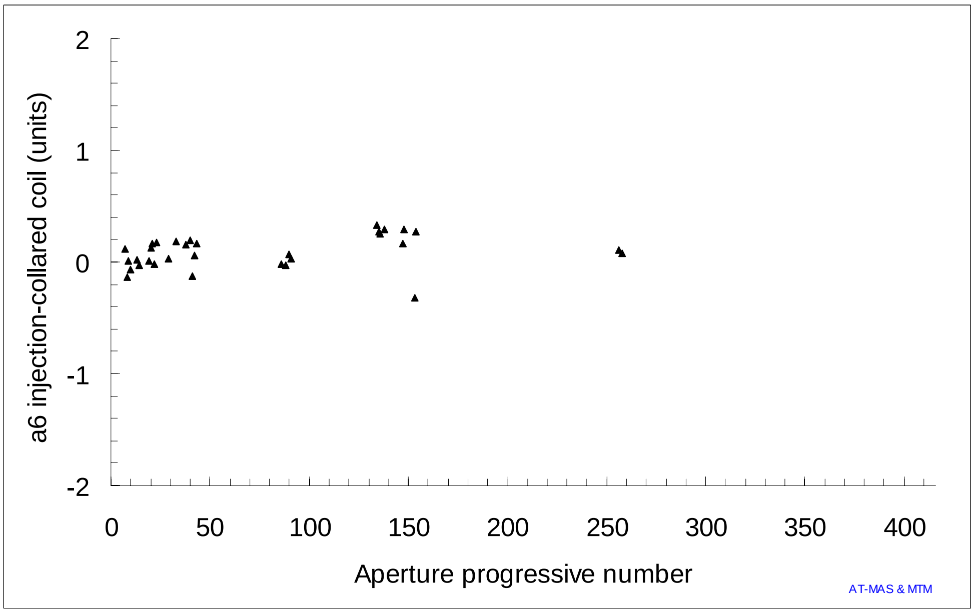

Fig. 25: Difference between integrated a6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

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 40 micron in the more recent production. The situation is stable in the last 200 apertures (see Fig. 24).

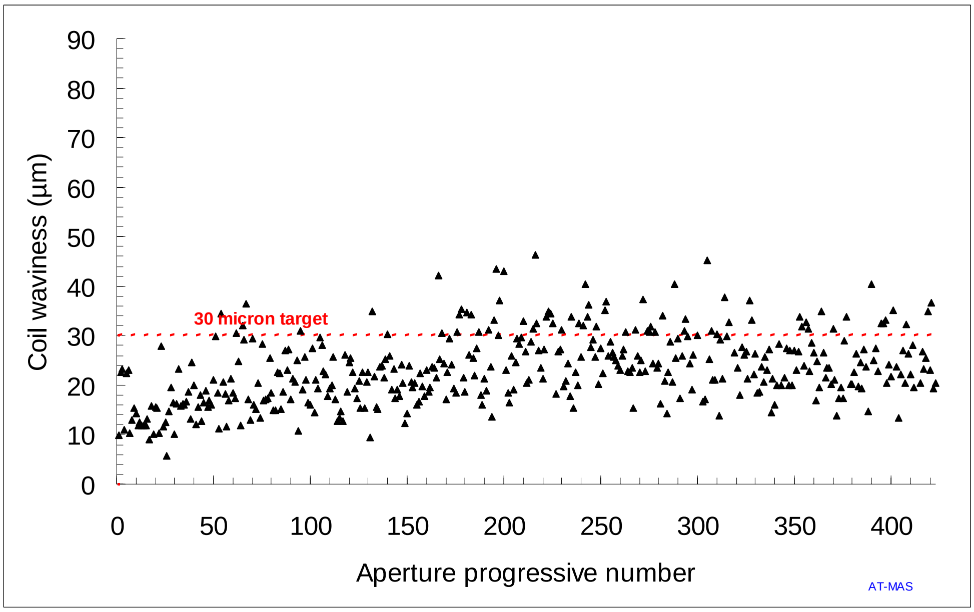

Fig. 24: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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, and L. Oberli, S. Sanfilippo, F. Simon, V. Venturini for useful discussions. We acknowledge T. Tortschanoff for support to this work, and for comments on this manuscript.

Appendix A: dependence of field quality on cable manufacturer

The apertures 335th-342nd, 344th-359th, 351st, 364th, 375th, 400th to 412th have been manufactured with cable C. According to the measurements, these apertures have a higher focusing strength (20 units more). The situation is summarized in Fig. 25, where data of cross-section 2 only are given.

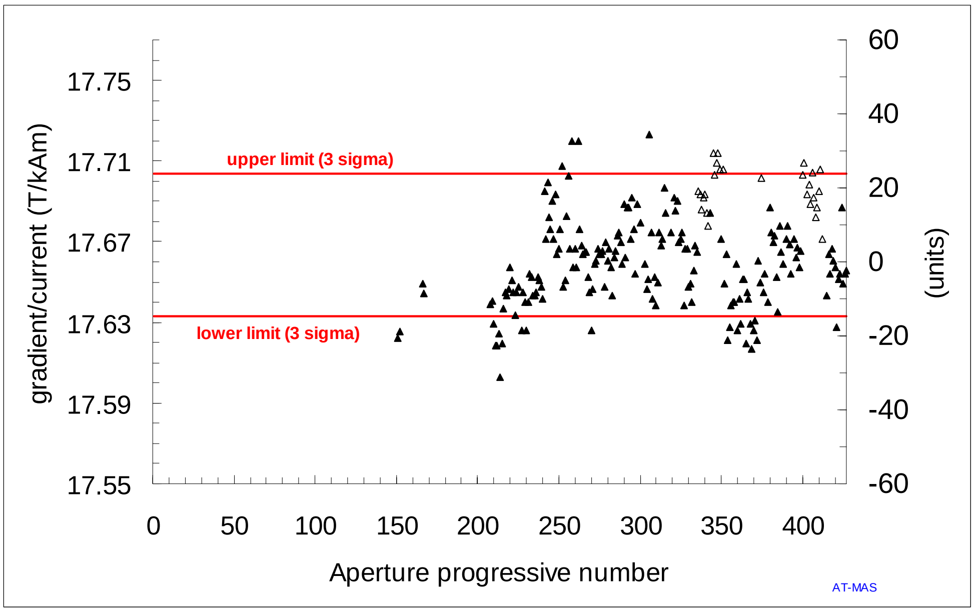

Fig. 25: focusing strength in all quadrupoles with cross-section 2 (empty markers: apertures manufactured with cable C)

The analysis of the geometric dimension of the cable C shows that they are well in tolerances and they do not differ significantly from the other manufacturers[7]. In order to obtain 20 units more in focusing strength one should assume that the cable width is 30 micron larger than nominal. This is not observed in the measurements of the cable before winding, which gives values within 10 micron. For the moment it has been decided to avoid coupling cable C with collars with bad permeability to keep the spread of b2 at a reasonable value.

[7] L. Oberli, private communication.