Report on field quality in the main LHC quadrupole collared coils and cold masses: June-July 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 June 1– July 31 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

Most of this work concerns measurements taken at the manufacturer at room temperature, at a current of 12.5 A. Some data on correlations to measurements at 1.9 K are given in Section 3.4.

- Available measurements: at room temperature we have 297 apertures (148.5 magnets) and 80 cold masses. At 1.9 K we have measurements of 6 cryoquadrupoles[1].
- In these two months, 44 apertures and 21 cold masses have been measured at room temperature.

The critical issues

Critical for beam dynamics:

- **Spread of field gradient:** is 30% higher than target. This spread is not due to the mixing of different cross-sections. One of the main reasons for this large spread is the collar permeability out of tolerance in the more recent production.
- **Systematic b6:** is now within target, after the introduction of cross-section 2 (additional mid-plane insulation of 0.125 mm) as a baseline.
- **Correlations:** even though the coherence of the present set of data is good, correlations should carefully monitored due to the limited number of available data. The more critical correlations are field the gradient at high field and b6 at injection.

Non-critical for beam dynamics:

- **Random b6:** is two times the target due to the mix of different cross-sections. An installation of homogeneous cross-sections in the same arc could cure the problem. Indeed, this target is not considered a hard limit.
- **Systematic b4:** the non-zero systematic component seen at the beginning of the production is disappearing. One should carefully check the trends of this multipole at 1.9 K.
- **Systematic a6:** there is a non-zero systematic component of a6 in all quadrupoles. One should check if the same is observed at 1.9 K. This component is not critical for beam dynamics.

CONTENTS

[1] These numbers refer to complete measurements carried out by AT-MTM at SM18, available in Oracle database. Measurements at Block4 are not included in the report.

PART I: MEASURED MAGNETS AND ASSEMBLY DATA

- 44 new apertures (i.e. 22 equivalent quadrupoles) and 21 cold masses have been measured at room temperature.
- Nearly three octants of apertures have been completed.

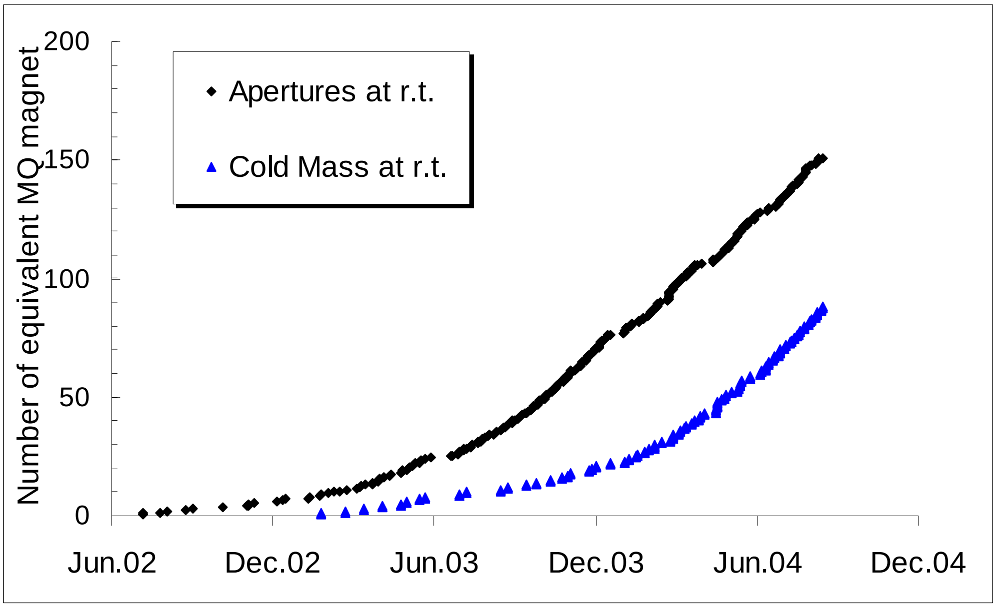

Fig. 1: Number of magnets measured at the manufacturers at room temperature at different stages of assembly procedure

- Cross-section: all apertures have X-section 2.
- Coil protection sheet[2]: all apertures have a coil protection sheet of 0.87 mm, with the exception of aperture 304 and 305 (0.95 mm).

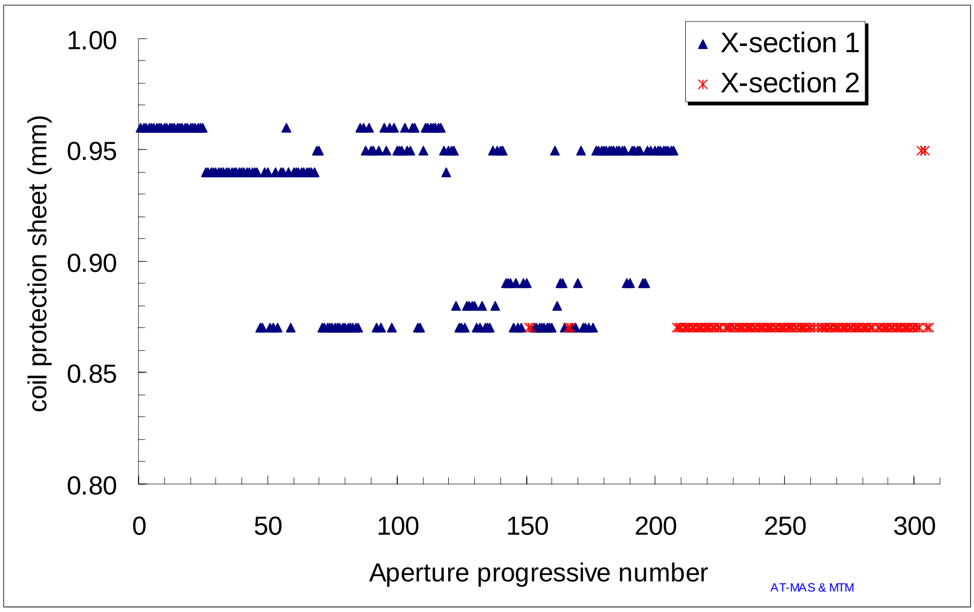

Fig. 2: Thickness of the coil protection sheet used in the apertures, separated according to different cross-sections.

[2] 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 2/3 of magnets with X-section 1 and 1/3 of X-section 2: this gives a systematic b6 of around 0.5 units larger than the targets. When the contribution of the different X-sections is separated, one finds that b6 in X-section 1 is 2.5 units larger than target, and that in X-section 2 it is well centred in the allowed range (with present hypothesis on correlations).
- Details on trends are given in Part III.

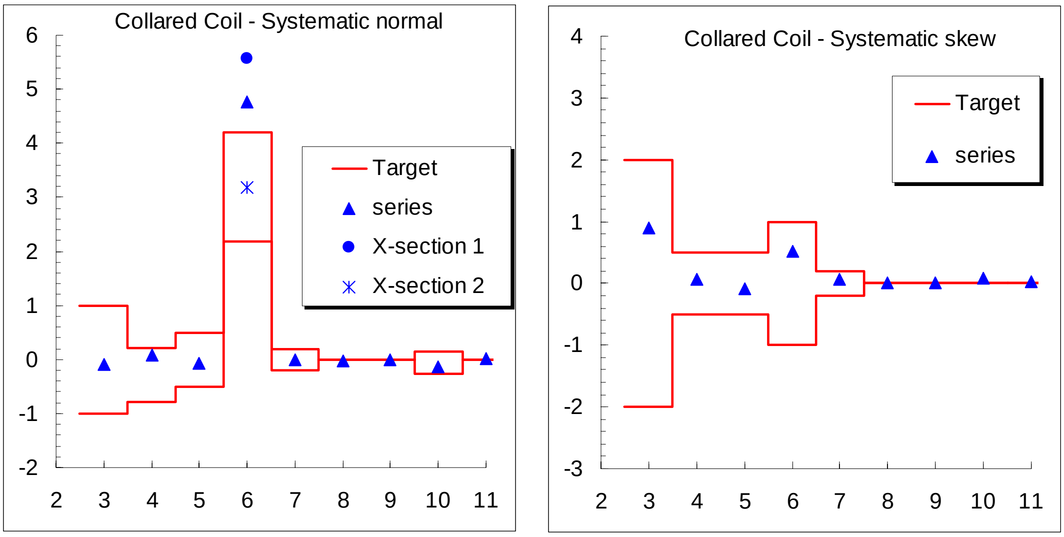

Fig. 3: Best estimate for systematic normal (left) and skew (right) multipoles versus beam dynamics limits (red line).

- 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 13 units, i.e. 30% 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 units. The situation is worse for X-section 2, where the spread is of 14 units. In this second case, we observe a strong correlation of b2 with b6 and b10, thus suggesting that a single effect is at the origin of this large spread. The collar permeability is considered as the cause of these large spreads. More information can be found in the Appendix.
- 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.

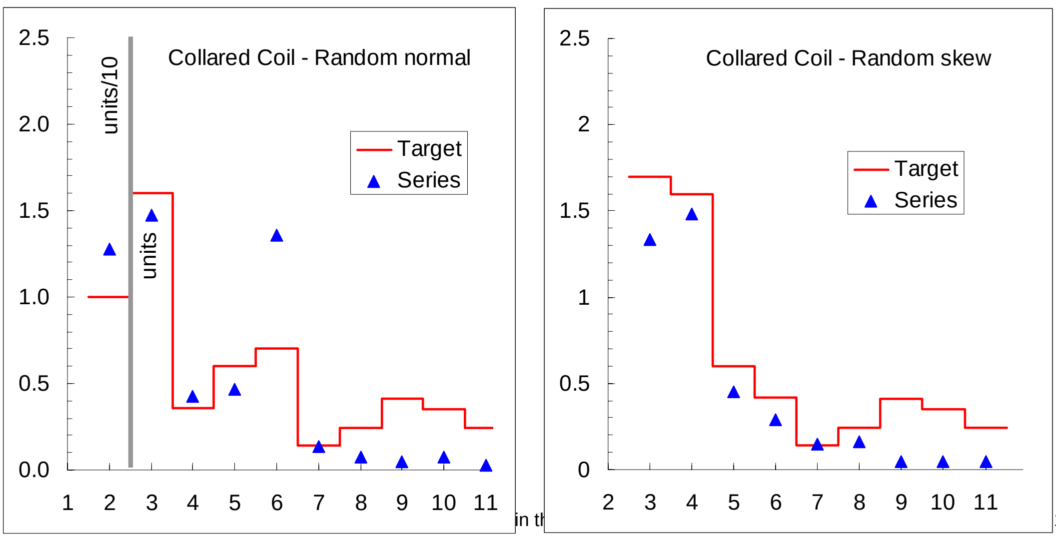

Fig. 4: Best ... in th ... 1.9 K.

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, after an initial trend (see Fig. 5). A small increase of the spread has been observed in the last 70 apertures. The standard deviation over all apertures is very small (2.0 units).

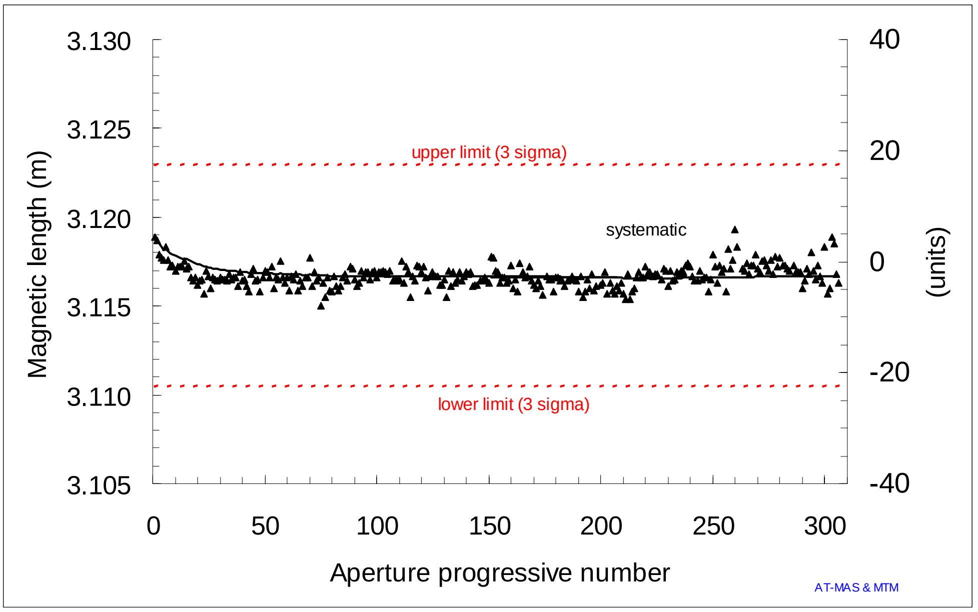

Fig. 5: Magnetic length of the measured collared coils (dots) and running average (solid line).

- Magnetic length of **cold masses** is also extremely stable (see Fig. 6). The standard deviation over all cold masses is 1.5 units.

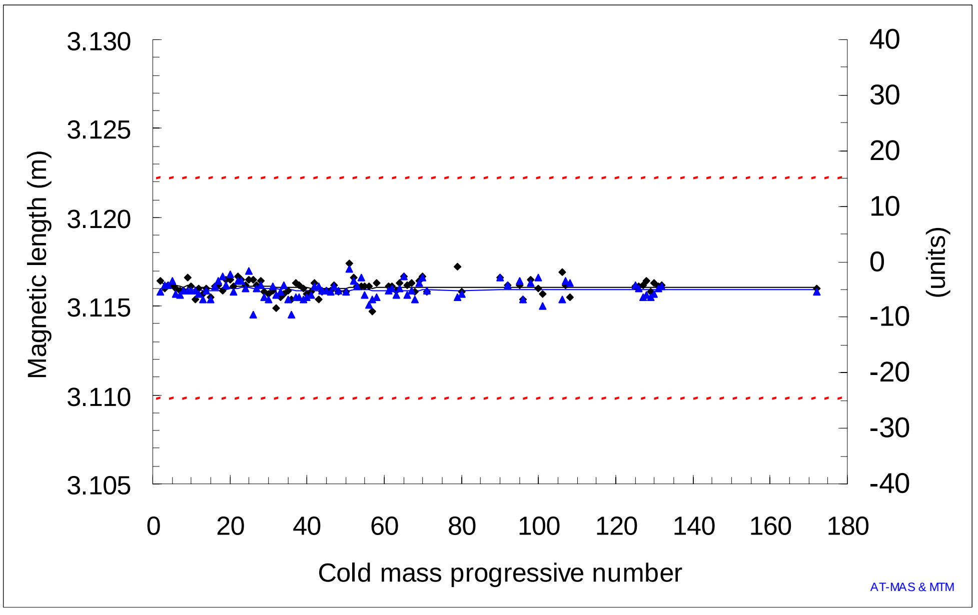

Fig. 6: Magnetic length of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

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 of around 10 units has been seen after aperture 240, and more recent apertures feature a very high field gradient, mainly due to the high permeability of collars (see Appendix).

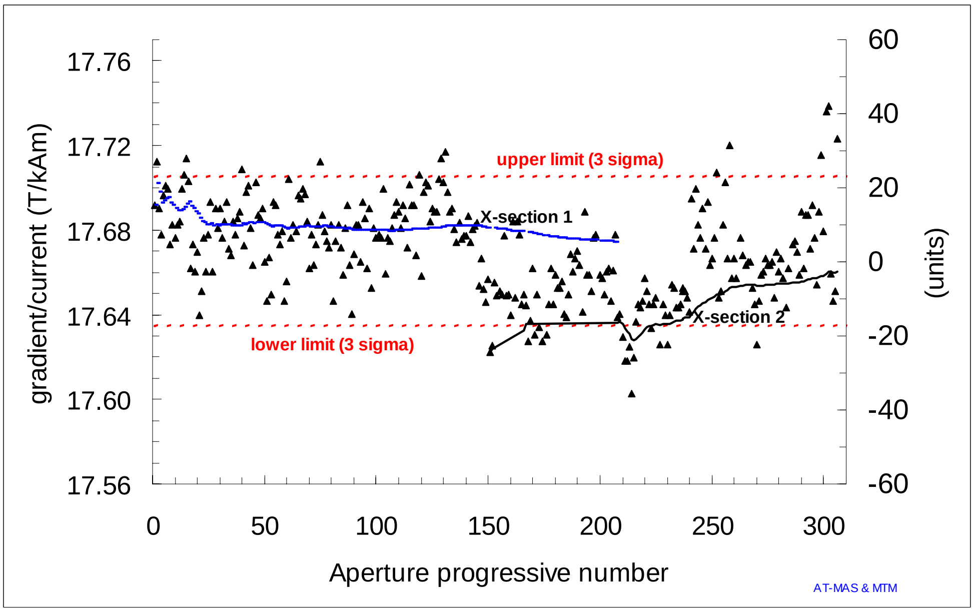

Fig. 7: Field gradient of the measured apertures (dots) and running average (solid lines, separated according to different cross-sections).

- The large spread observed in apertures (13 units) is confirmed by **cold mass** data, where it is around 13 units (see Fig. 8)[3]. Please note that only 4 cold masses have cross-section 2, and therefore a unique running average is presented in the plot.

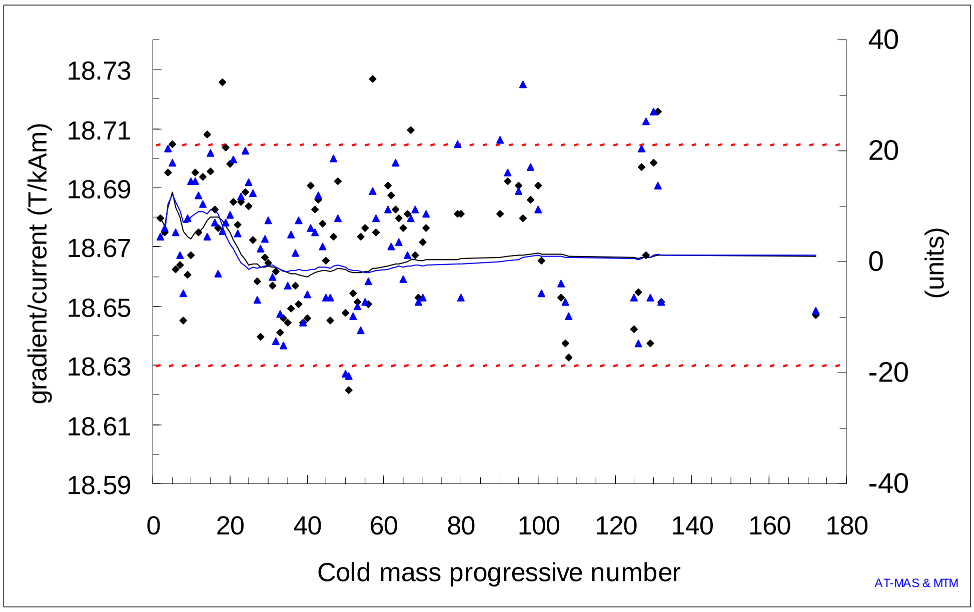

Fig. 8: Field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

[3] 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.

3.1.3 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 Fig. 9 and 10).

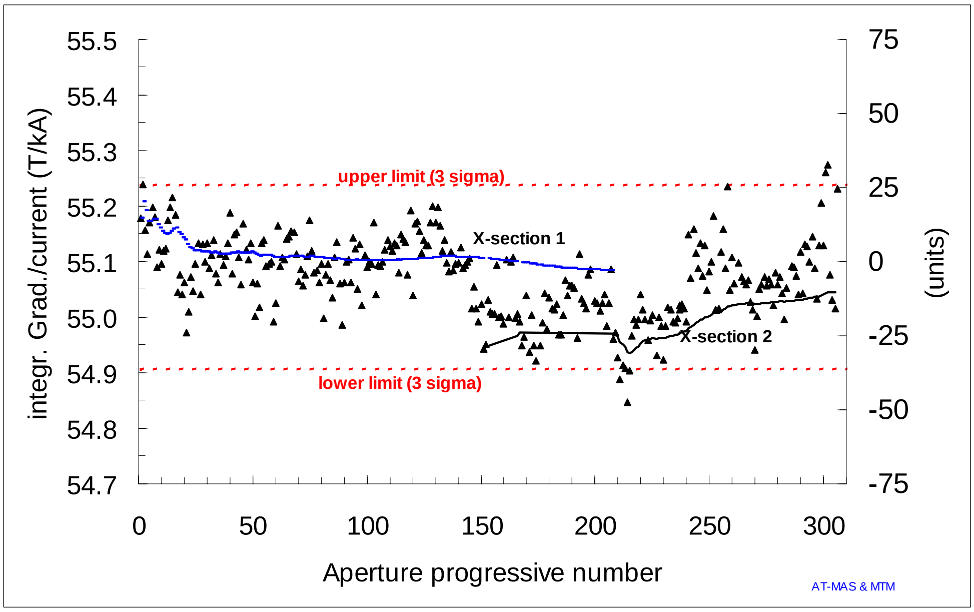

Fig. 9: Integrated gradient of the measured collared coils (dots) and running average (solid lines, separated according to different cross-sections).

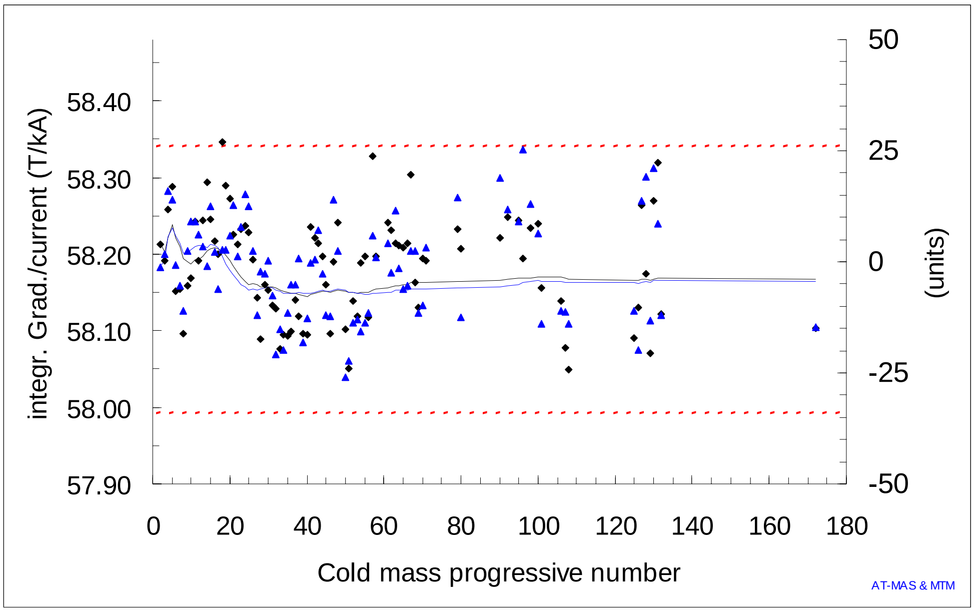

Fig. 10: Integrated field gradient of the measured **cold masses** (black dots Aperture1, blue dots Aperture 2) and running average (solid line).

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 more recent production, we have a few magnets with very low values of b6 that are associated to a high field gradient (more information can be found in the Appendix).

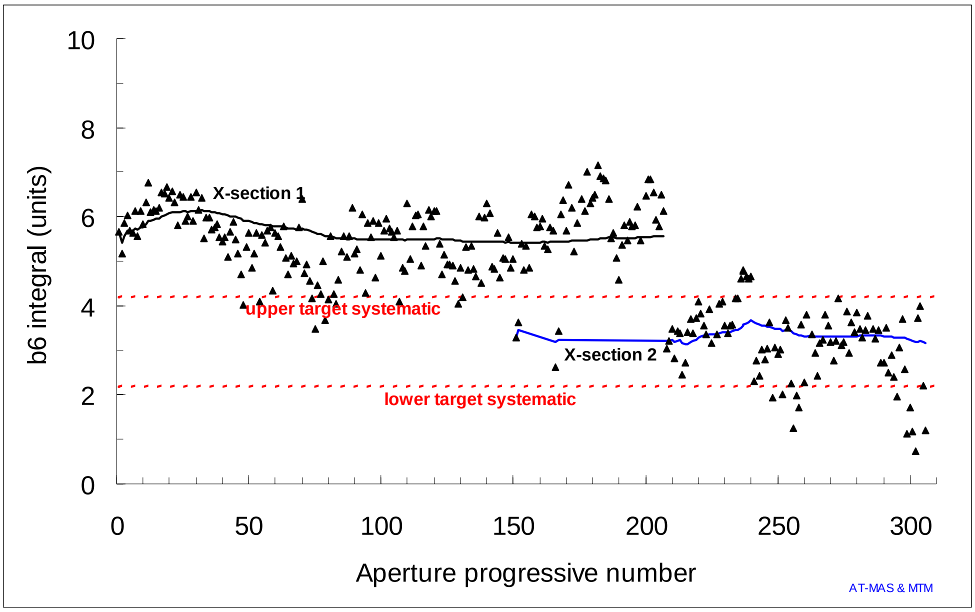

Fig. 11: Integral b6 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 5 cryoquadrupoles.

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

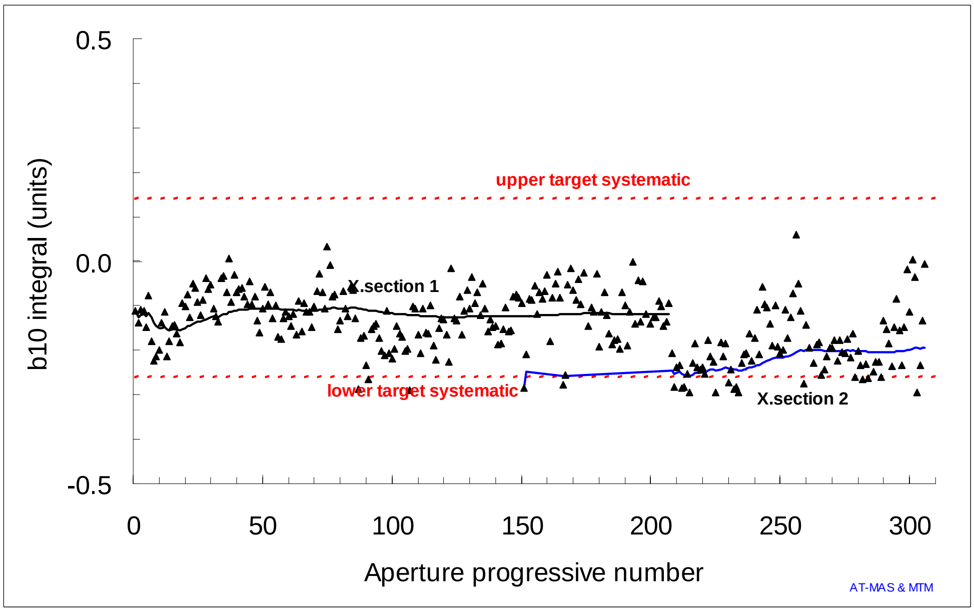

Fig. 12: Integral b10 in the apertures (markers) running averages per cross-section (solid lines), and beam dynamics targets for the systematic (red lines) based on correlations with 5 cryoquadrupoles.

3.3 Trends in non-allowed multipoles

3.3.1 Normals: b3, b4, b5, b7

- Systematic values of b3, b5 and b7 are close to zero as expected by the symmetry, and well within targets (see Figs. 13, 15 and 16). No trends are observed.
- The multipole b4 had a systematic component of about 0.5 units at the beginning of the production that is now disappearing (see Fig. 14).

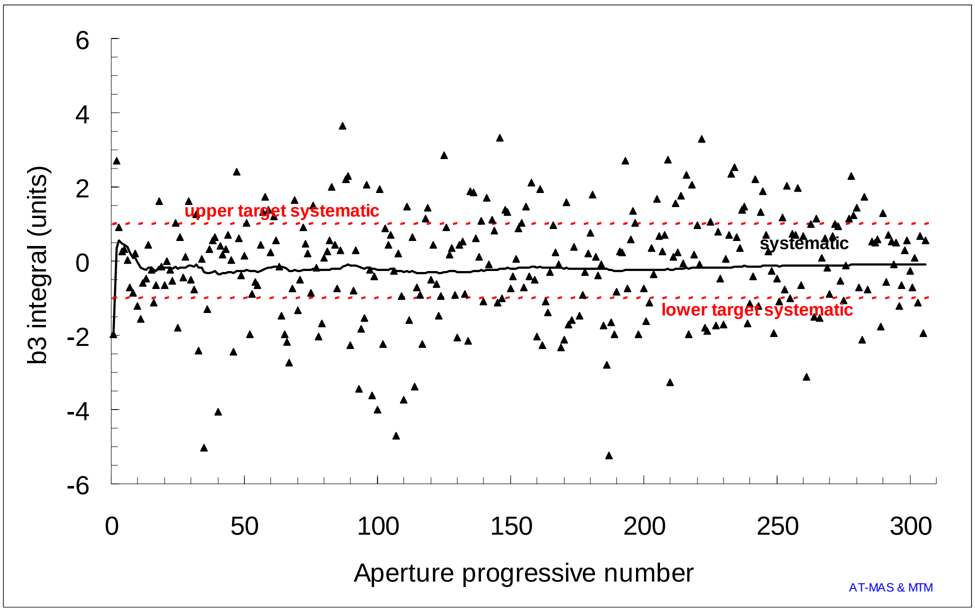

Fig. 13: Integral b3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

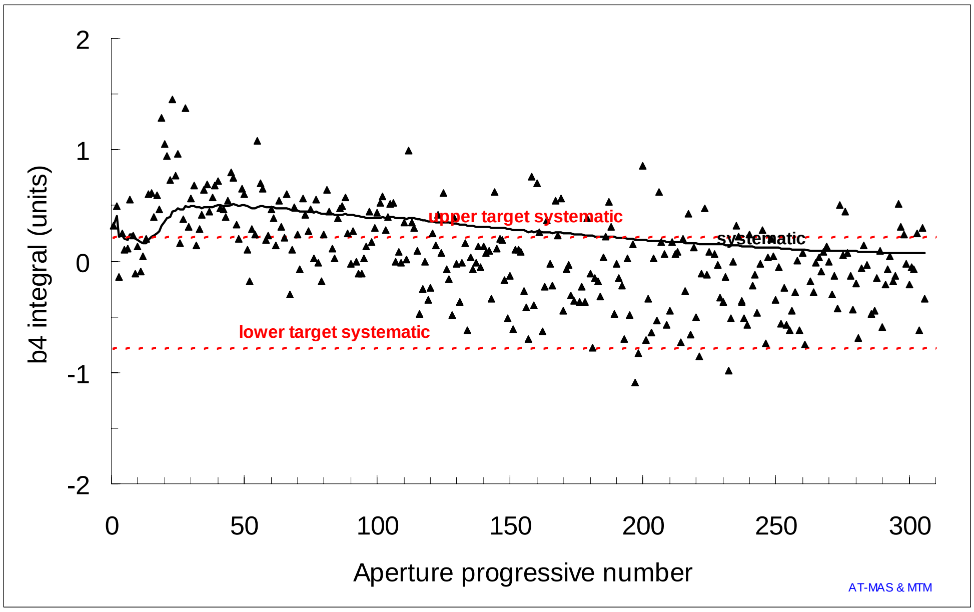

Fig. 14: Integral b4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

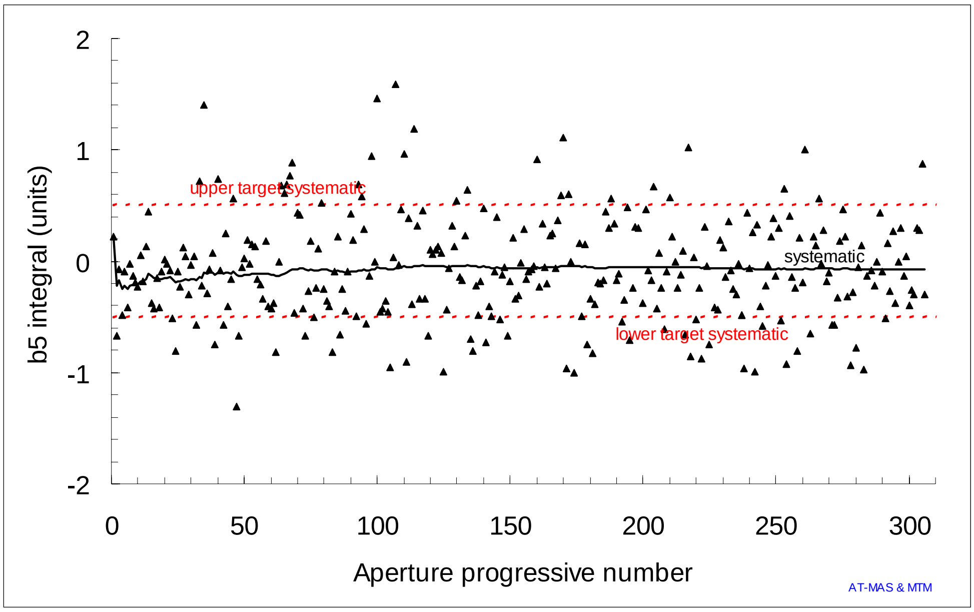

Fig. 15: Integral b5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

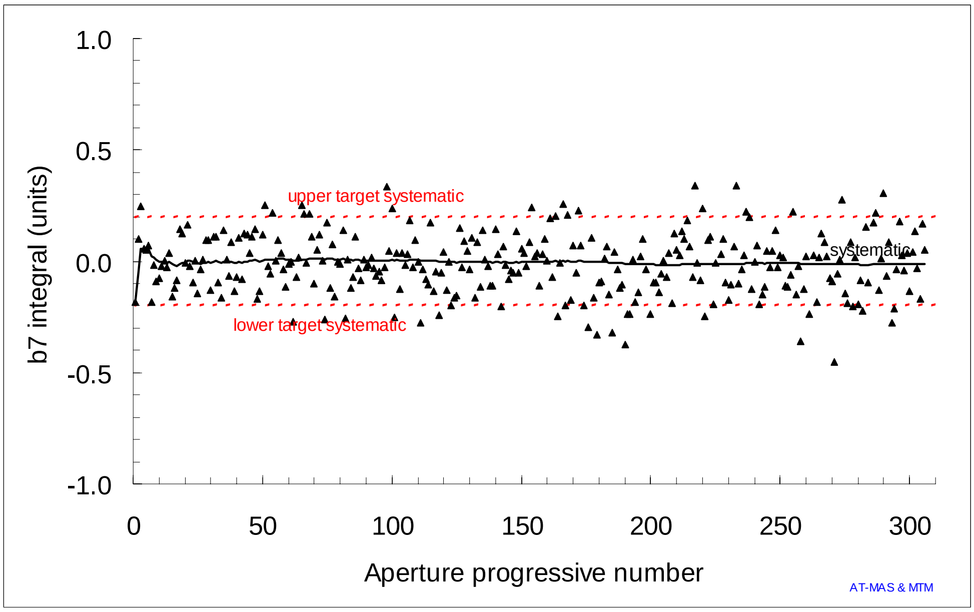

Fig. 16: Integral b6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

3.3.2 Skews: a3, a4, a5, a6

- Systematic values of a3, a5 and a5 are close to zero as expected by the symmetry, and well within targets (see Figs. 19-21). No trends are observed.
- The multipole a6 has a systematic component of about 0.5 units since the beginning of the production (see Fig. 22). This unexplained component, which has trends along the production, is not critical for beam dynamics.

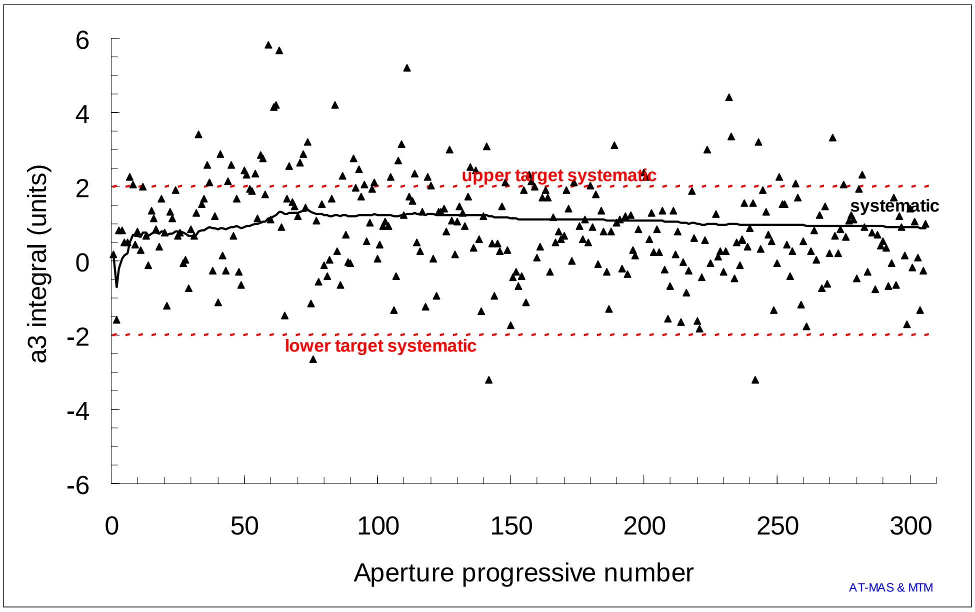

Fig. 17: Integral a3 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

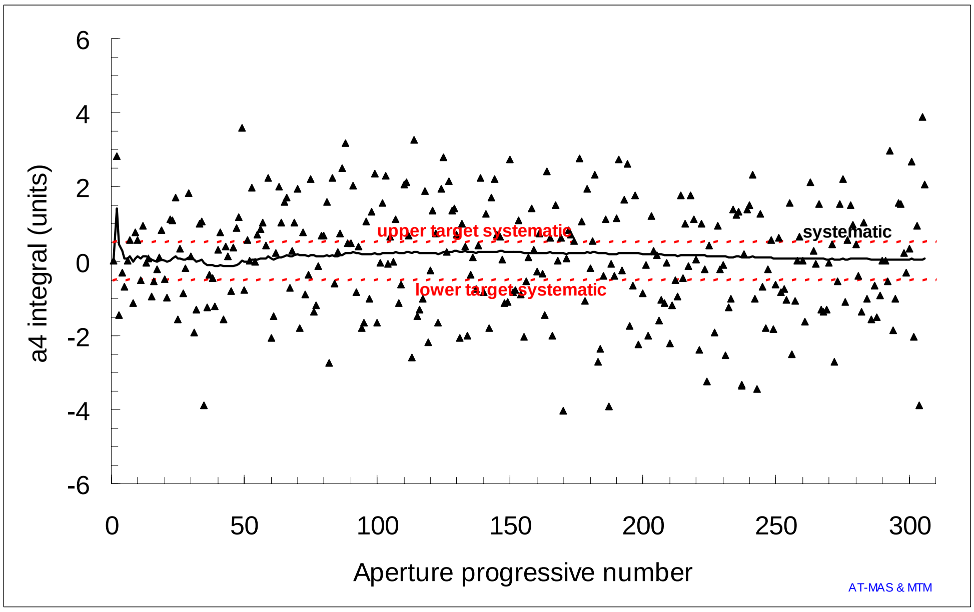

Fig. 18: Integral a4 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

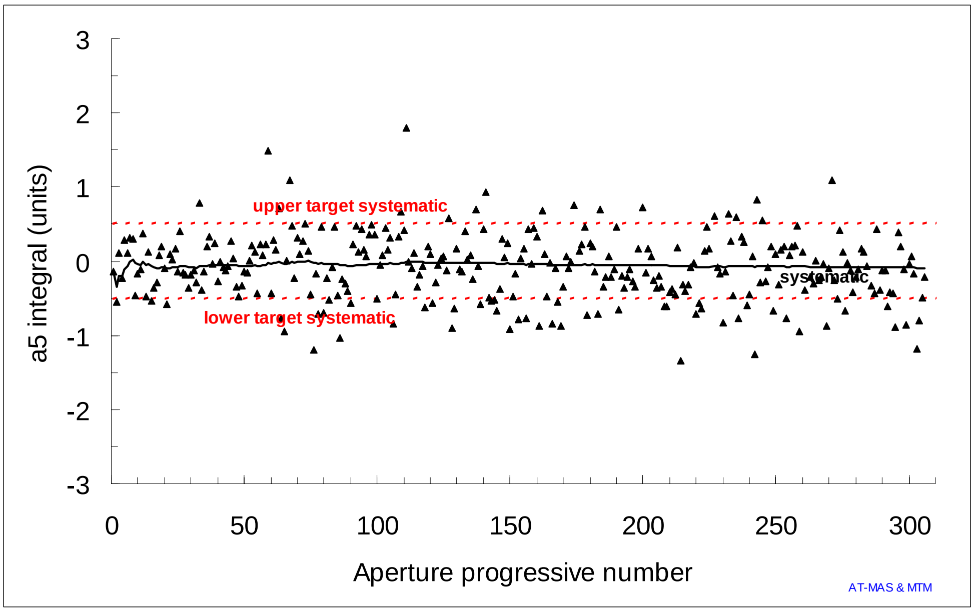

Fig. 19: Integral a5 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

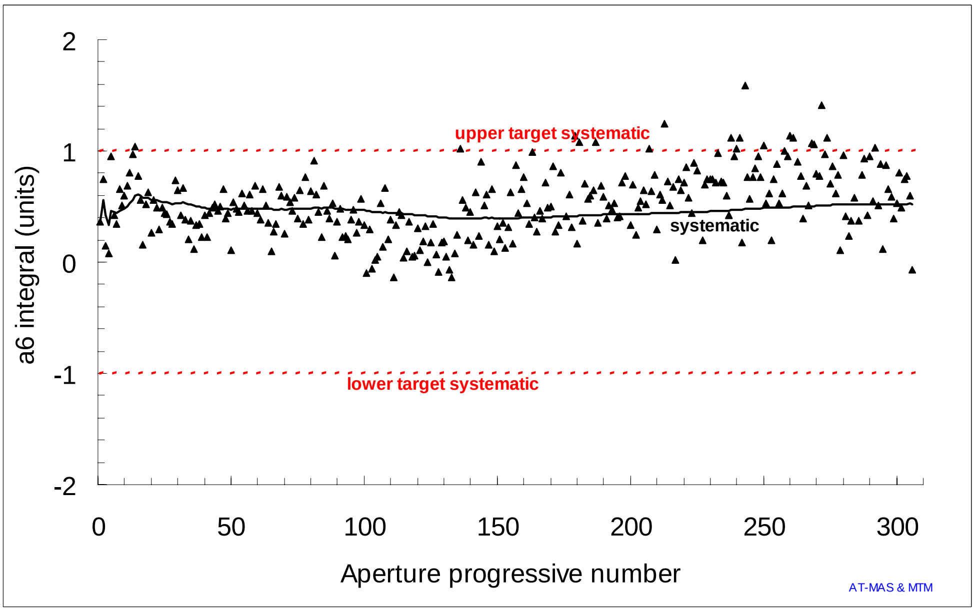

Fig. 20: Integral a6 in the apertures (markers), running average (solid line), and beam dynamics targets for the systematic (red dotted lines) based on correlations with 6 cryoquadrupoles.

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. 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 95[4]), and allows to detecting trends in correlations along the production.

- For the focusing strength the difference between values measured at high field at 1.9 K and in the collared coil at 12.5 A is around 3.3 T/kA. This offset is mainly due to the effect of the iron yoke. On the right axis we give a scale in units with respect to the nominal value of around 58 T/kA. The spread of the offsets is small (±10 units) compared to the large spread of Figs. 7 and 8.

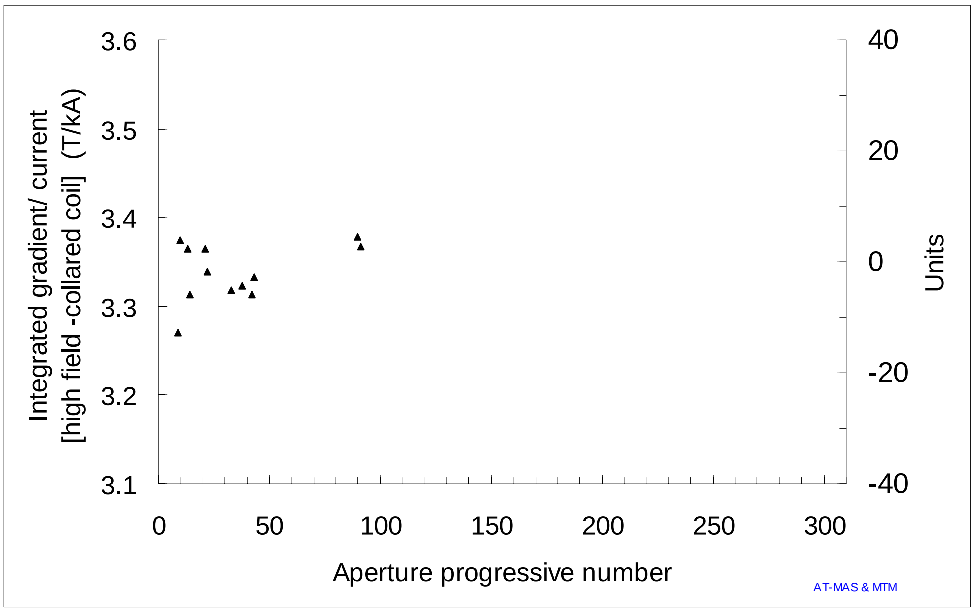

Fig. 21: Difference between integrated field gradient divided by current between high field at 1.9 K and collared coil at room temperature versus aperture progressive number

- For the b6 the offset between collared coil and injection is around –4 units, mainly due to the effect of the persistent currents. The spread of the offsets is small (±0.5 units) compared to the large spread of Fig. 9.

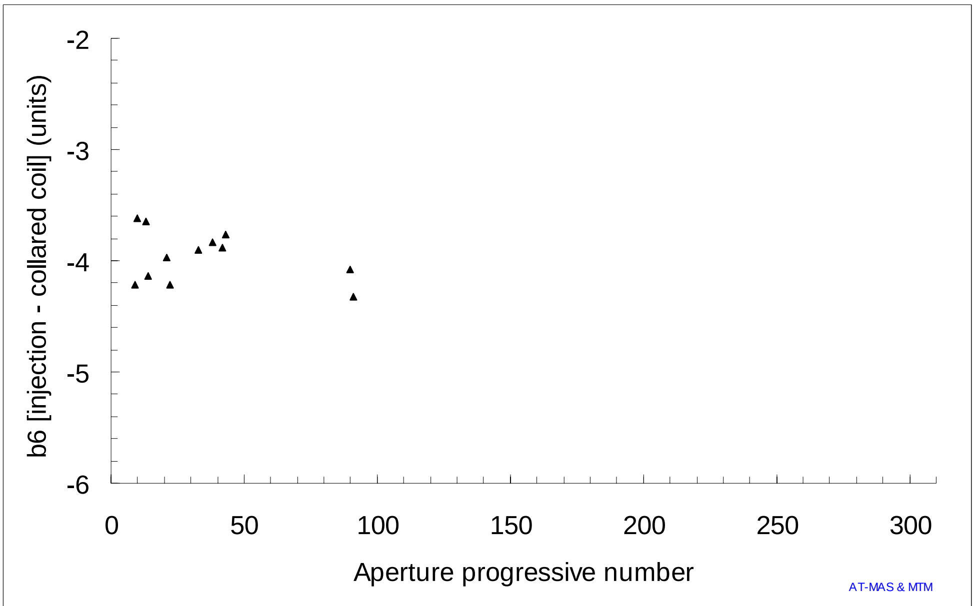

Fig. 22: Difference between integrated b6 between injection field at 1.9 K and collared coil at room temperature versus aperture progressive number

[4] Please note that measurements of cold masses at block4 are not included in this analysis.

3.5 Trends in coil waviness

- The coil waviness estimated from the variation of the multipoles along the axis has been below 30 microns for the first 100 apertures, and has increased in the more recent production (see Fig. 33).

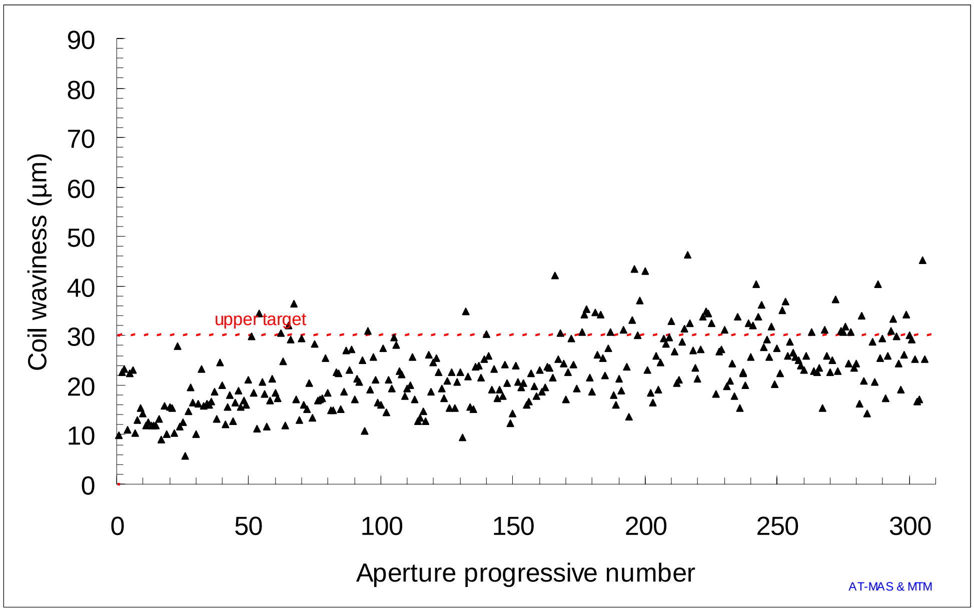

Fig. 21: Estimated coil waviness in the straight part of the measured collared coils (black dots: aperture 1, blue dots: aperture 2).

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. We acknowledge M. Durante, W. Scandale, K. Schirm, F. Simon, T. Tortschanoff for support and discussions. We finally acknowledge P. Hagen, A. Lombardi, and T. Tortschanoff for comments on this manuscript.

Appendix: trends in b2 and b6

To better understand the origin of the recent trends in field gradient and b6, we analyse correlations between these two quantities and to b10 (the next allowed multipole). One finds that for X-section 2 there is a rather good correlation between these values, thus suggesting that a unique cause is at the origin of the large spread of these quantities (and therefore that, in principle, the spread could be reduced). On the other hand, a much worse correlation is found for the magnets with X-section 1. This means that only the last part of the production is affected by these phenomena.

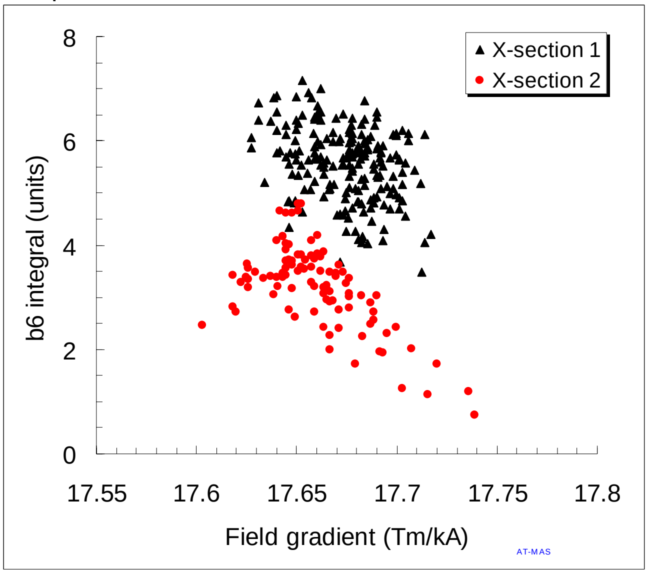

Fig. 22: Field gradient versus b6 in the measured apertures, separated according to different cross-sections

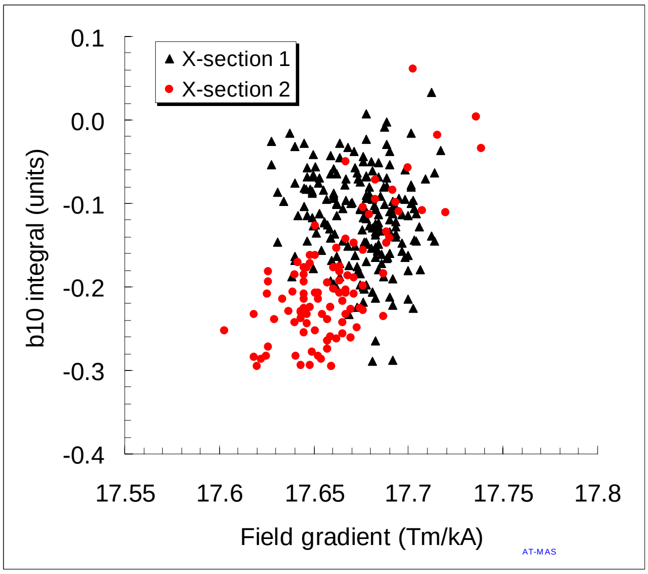

Fig. 23: Field gradient versus b10 in the measured apertures, separated according to different cross-sections

The origin of the problem has been traced back by F. Simon to the too high collar permeability. The worse cases show a shift in field gradient, b6 and b10 that is in agreement with a permeability increase of 0.010 to 0.015 (see also Table I). Measurements done at the manufacturer confirm this analysis, showing that the collar permeability in some cases is up to 1.02, against a specified value of 1.003±0.002.

Table I: Shift in the main field and multipoles induced by an increase of collar permeability of 0.01 (courtesy by B. Auchmann and S. Russenschuck)

	Dmu=0.01
Db2	29.0
Db6	-2.5
Db10	0.2