Report on field quality in the main LHC dipole collared coils: July-August 2002

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This report gives data relative to field quality measured in collared coils during the period July 1st–August 31th 2002, comparison to beam dynamics targets and status of the production holding points. Updated graphs can be found in the LHC field quality observatory http://lhc-div-mms.web.cern.ch/lhc-div-mms/MMSPAGES/MA/Obs.html. Please note that the web address has changed.

What's new

- Available measurements: 45 collared coils, 18 cold masses, 10 cryodipoles.
- All the manufacturers are now producing collared coils with the new cross-section. Two collared coils with old cross-section still have to be measured (Ansaldo 11 and Noell 10). The total number of collared coils with the old cross-section will be 35 (Alstom 1-12 and 15, Ansaldo 1 to 11, Noell 1 to 11).
- We present for the first time graphs for the skew (a_2, a_3, a_4) and for the even multipoles (b_2 and b_4). Control limits on these multipoles are based on the LHC Project Report 501 and on communications of S. Fartoukh to the Magnet Evaluation Board.
- Control limits on collared coil data are set through correlations with measurements at 1.9 K of 10 cryomagnets made by LHC-MTA. Three more magnets have been added with respect to the previous report of July 1st 2002.

1. Measured magnets and assembly data

- 7 collared coils have been measured (collared coils 39th to 45th)
  - 3 Alstom (HCMB__A001-01000018, 19 and 21)
  - 1 Ansaldo (HCMB__A001-02000014)
  - 3 Noell (HCMB__A001-01000011, 12 and 13)

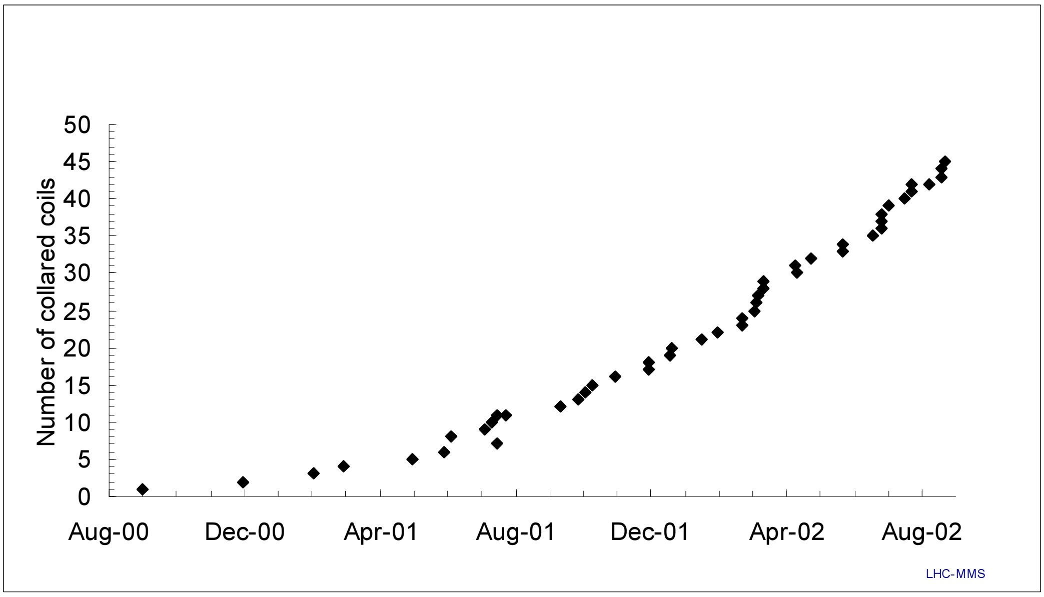

Fig. 1: Number of measured collared coils versus time

- Cross section: Noell 11 have X-section 1 (the old one); all the others have X-section 2.
- Shims (see table I and Fig. 2 for a summary over all the collared coils produced so far):
    - Azimuthal sizes of Ansaldo 14 coils are 0.1-0.15 mm larger than the nominal (both inner and outer layer), and therefore thinner shims have been used (see Table I). This was already observed in collared coil 12 and 13 (see report of May-June 2002). Actions have been taken by the project engineers to change the shims of the curing mould. We still expect a few coils with non-nominal shims.
    - Outer shim of Noell 11 (old cross-section) is 0.05 mm larger. This has a very limited impact on field quality.
    - The remaining collared coils have nominal shims.

Table I: Shims thickness and coil cross-section type of measured collared coils.
Nominal shims: 0.2 mm inner layer, 0.8 mm outer layer

Magnet Number	Magnet name		Shim (mm)		X-section
			Inner	Outer	
39th	HCMB__A001	1000018	0.20	0.80	2
40th	HCMB__A001	1000019	0.20	0.80	2
41st	HCMB__A001	2000014	0.10	0.70	2
42nd	HCMB__A001	1000021	0.20	0.80	2
43rd	HCMB__A001	3000011	0.20	0.85	1
44th	HCMB__A001	3000012	0.20	0.80	2
45th	HCMB__A001	3000013	0.20	0.80	2

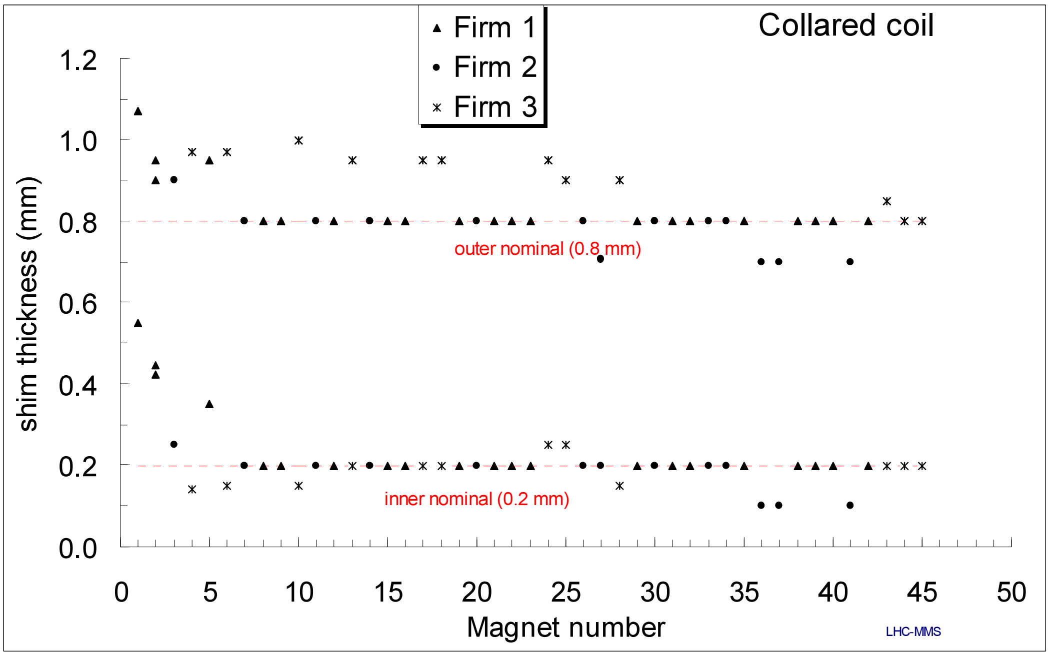

Fig. 2: Thickness of the polar shims used in the collared coils

2. Magnetic length and transfer function

- Magnetic length of collared coils 39th to 45th are within targets (see Fig. 3). No difference between old and new cross-section is observable, as expected. A small systematic difference of about 10 units between Noell and Ansaldo values is observable in the last 25 coils, Alstom values being placed in between.

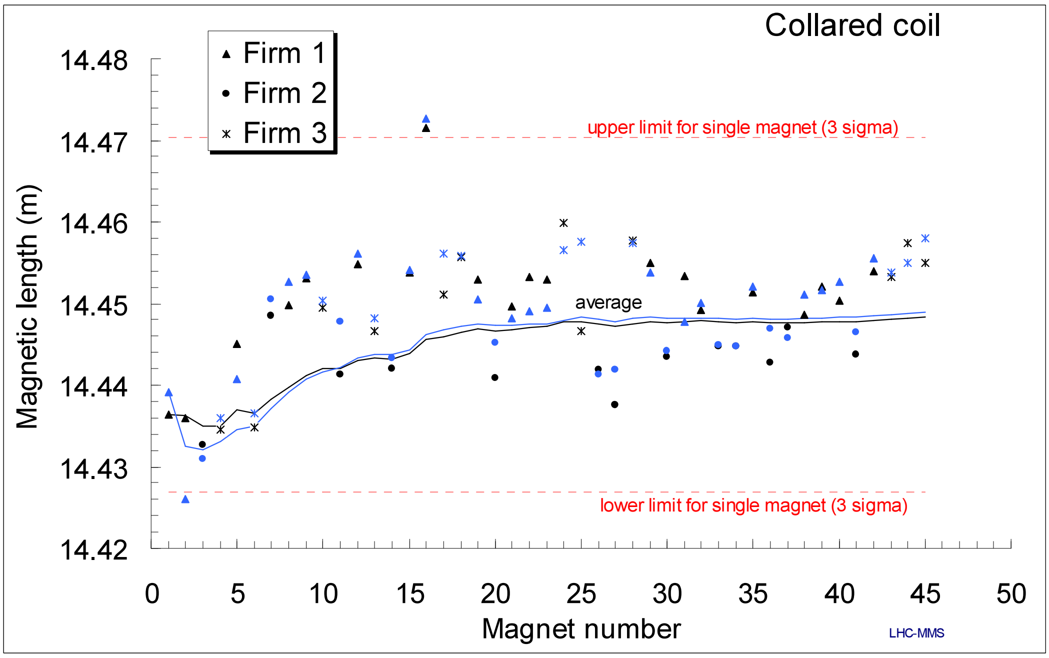

Fig. 3: Magnetic length of the measured collared coils

- Main field in the central part of Ansaldo 14 (collared coils 41st in Fig. 4) is 4 sigma lower than the average. This is partly due to the non-nominal shims (0.1 mm less on both layers), as it happened in Ansaldo 12 and 13 (36th and 37th in the figure, see also report of May-June 2002). When this effect is corrected, collared coils 41st fall in the lower part of the 3 sigma range (see Fig. 5). A corrective action will be taken: ferromagnetic laminations will be added to increase the magnetic length.
- Difference between average main field in old and new cross-section is small (less than 5 units), as expected from simulations (see Fig. 5).
- Noell coils have a main field of about 15 units higher than Alstom or Ansaldo (see Fig. 5). This systematic difference is half of the allowed range at three sigma (30 units).
- All produced collared coils fit within the 3 sigma limit when data are reduced to nominal shims (see Fig. 5).

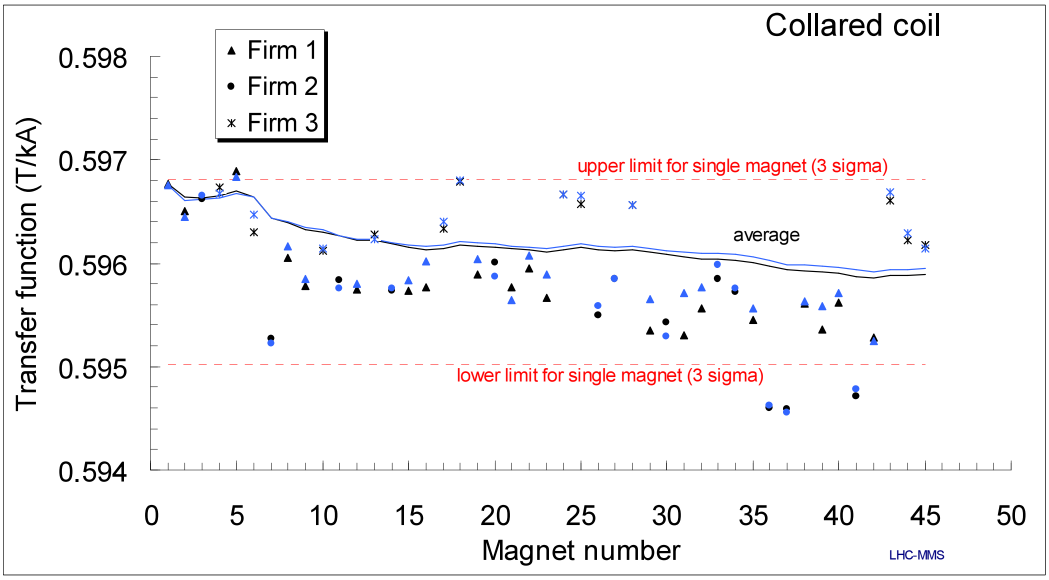

Fig. 4: Average main field in the straight part of the measured collared coils

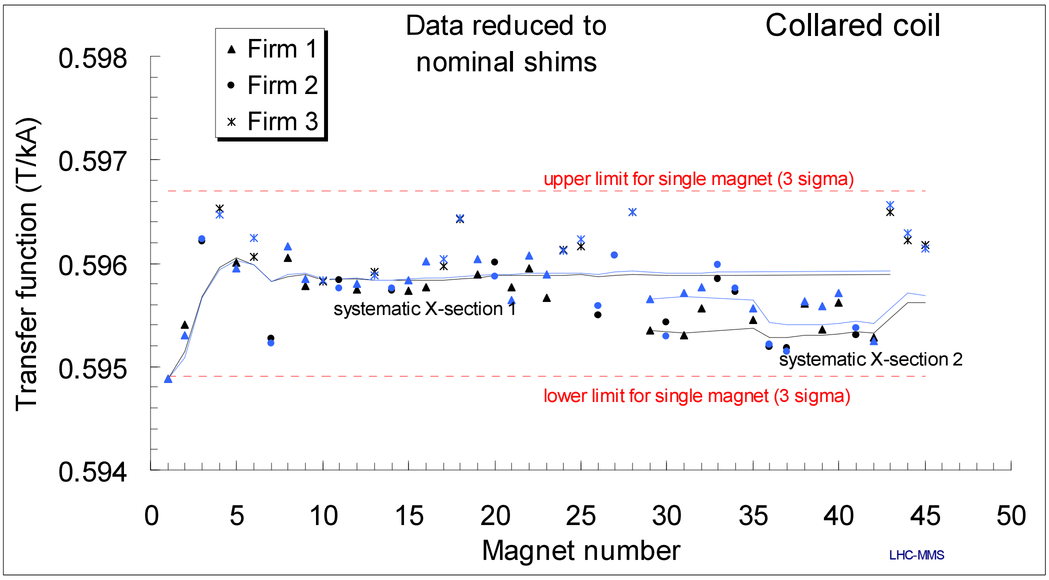

Fig. 5: Average main field in the straight part of the measured collared coils. Data reduced to nominal shims

- Integrated transfer function of magnets 39th to 45th is within the 3 sigma budget of the allowed random per arc (see Fig. 6).
- When data are reduced at nominal shims (see Fig. 7), one finds some systematic difference (around 20 units) between Noell and Ansaldo-Alstom. This is well within the total width of the band allowed by beam dynamics (at three sigma) in the hypothesis of a complete mixing of the manufacturers.

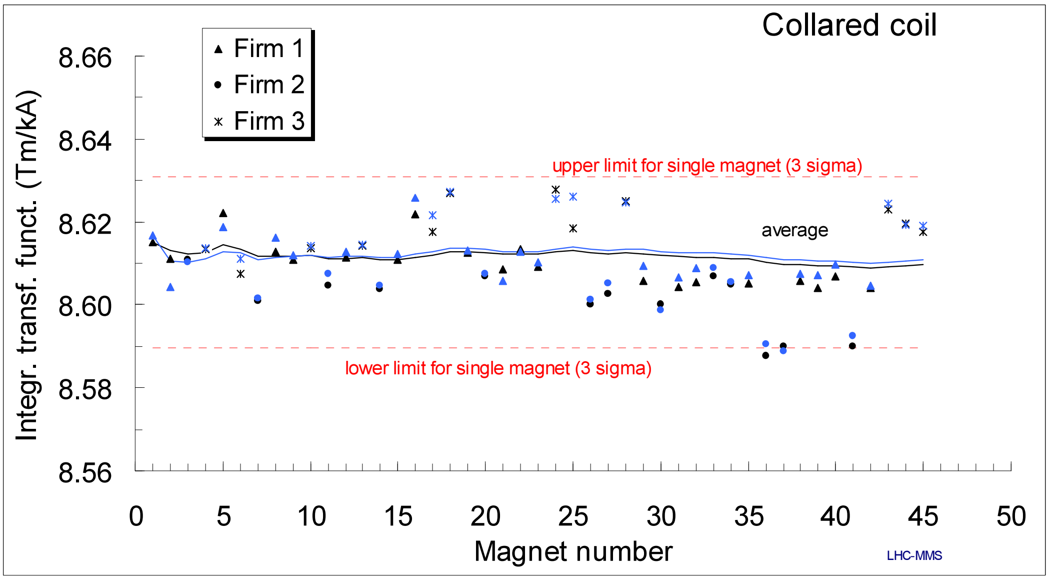

Fig. 6: Integrated transfer function in the measured collared coils.

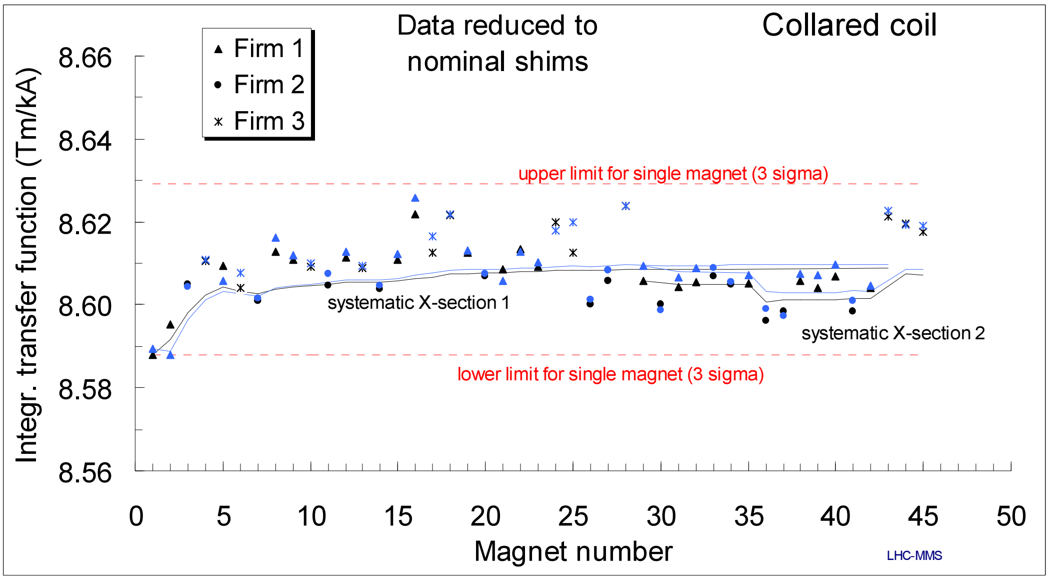

Fig. 7: Integrated transfer function in the measured collared coils. Data reduced at nominal shims.

3. Estimated coil waviness

- Coil waviness estimated from the variation of the multipole along the axis is still anomalous for Alstom 18 and 19 (see Fig. 8, collared coils 39th, 40th). Corrective actions have been taken and Alstom 21 (see Fig. 8, collared coil 42th) is within the 30 micron limit, but still considerably higher than previous Noell and Ansaldo, that were around 15 microns.
- Some small deterioration of coil waviness has been observed in Noell 12 and 13 (see Fig. 8, collared coils 44th and 45th).

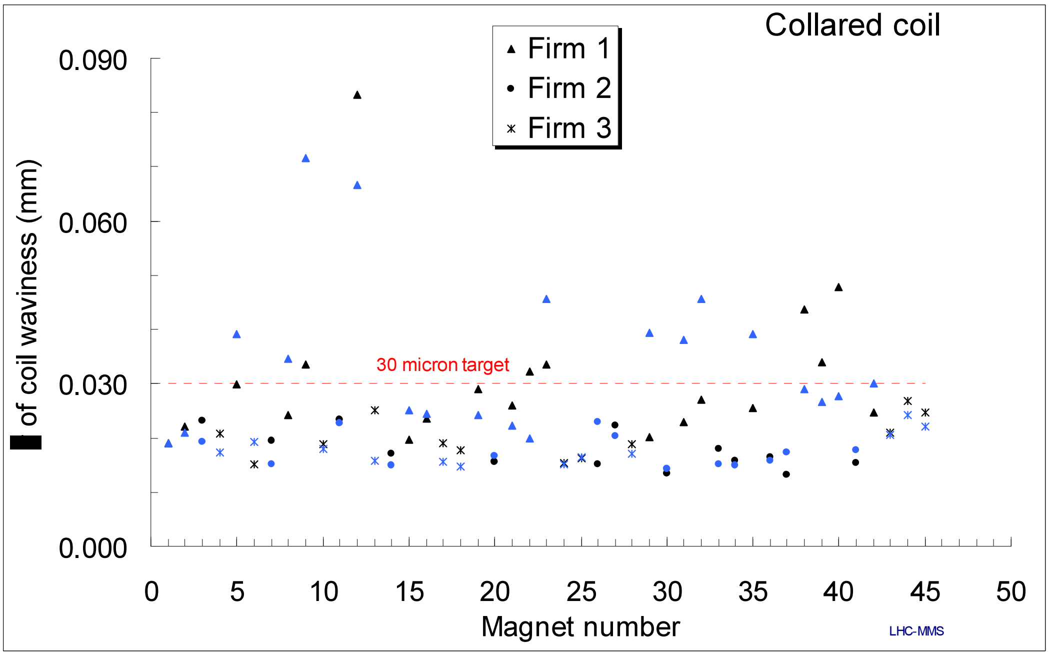

Fig. 8: Estimated coil waviness in the straight part of the measured collared coils.

4. Summary of systematics

- Best estimates of skew and even normal systematics are given in Fig. 9, with an error at 95% confidence limit (two sigma). All the multipoles are within specifications. Details are given in Sections 5 and 6.

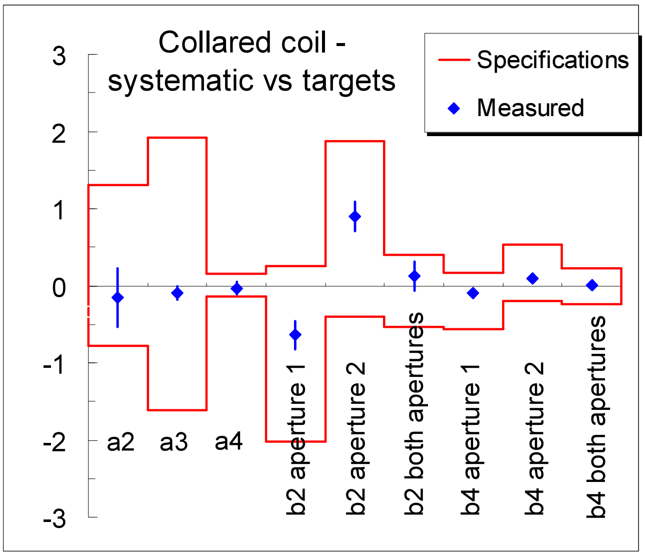

Fig. 9: Best estimate for systematic skew multipoles and even normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics.

- Best estimates for systematic odd multipoles are shown in Fig. 10. In the left part, raw data are plotted. This gives the actual situation for the manufactured collared coils: b_3 and b_5 are larger than the upper specifications of 3 and 1 units respectively.
- In the left part of Fig. 10, data are reduced to nominal shims and separated according the two cross-sections (33 collared coils have cross-section 1, 12 have cross-section 2). The change of cross-section under-corrected b_3 and b_5, and overcorrected b_7. Errors associated to the best estimate for the systematic are still large for b_3 and b_5, but it is likely that odd multipoles are outside the specification. Details are given in Section 7.

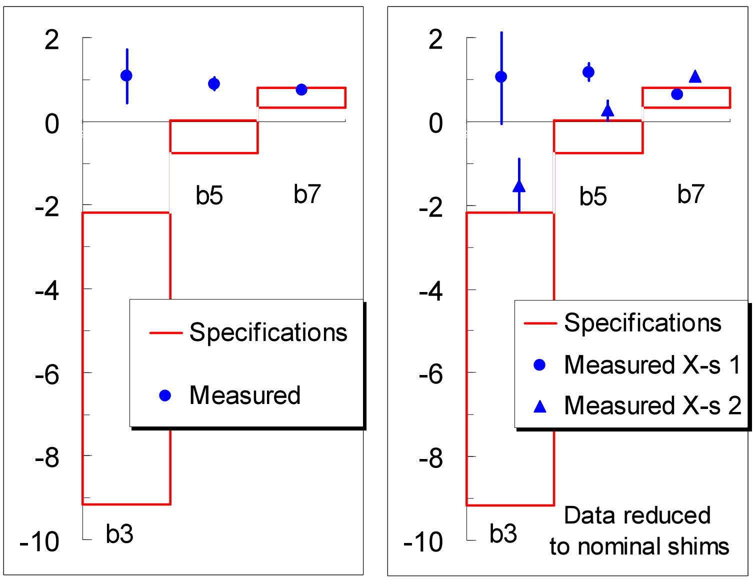

Fig. 10: Best estimate for systematic odd normal multipoles (markers) versus beam dynamics limits (red line). An error of two sigma (95% confidence limit) is associated to the best estimates of systematics. Raw data (left) and data reduced to nominal shims and separated according to different cross-sections (right).

The cross-section change has considerably improved the foreseen machine performaces: a LHC made with dipoles with cross-section 1 would have had severe limitations, due to b_3 and b_5:

- At high field a systematic b_3 of 7 units would have caused major problems in the chromatic correction (maximum specification is 3 units).
- At injection a systematic b_5 of 2.1 units would have given major problems in dynamics aperture (maximum specification is 1.1 units).

On the other hand, a machine made with dipoles with cross-section 2 could have minor performance limitations due to b_5 and b_7:

- At injection a systematic b_5 of 1.3 units could reduce dynamic aperture (maximum specification is 1.1 units).
- At injection a systematic b_7 of 0.35 units could reduce dynamic aperture (maximum specification is 0.1 units). Simulations summarized in LHC project report 501 show that a systematic b_7 of 0.22 units may have a very limited impact on dynamic aperture at injection (reduction of 0.4-0.8 sigma), whilst a systematic b_7 of 0.4 units reduces the dynamic aperture of 2 sigma.
- At high field a systematic b_3 of 3.5 units is outside the specification of 0.5 units, but it is within the hard limit of 4.2 units given by the strength of chromatic correctors.

Notwithstanding this relevant improvement, we are still far from optimal values. The best estimates for the correction needed on the cold mass is the following (for the collared coil, values should be multiplied by a factor 1.2):

- b_3 correction: -3.5 units
- b_5 correction: -0.5 units
- b_7 correction: -0.35 units

At the moments two options are considered: a further correction of the cross-section or an increase of the mid-plane insulation. The action on b_5 and b_7 is critical since the needed correction is 1 to 1.5 times the natural sigma of the multipoles, given by manufacturing tolerances. At the same time, actions are being taken to understand the drift in b_3 (see section 7.1) and the unexpected jump of b_7 (see section 7.3).

5. Systematic skew multipoles

- Systematic skew multipoles a_2 a_3 and a_4 are within beam dynamics limits (see Figs. 11-13). We have a large margin for the a_3, whilst beam dynamics limits are tighter for a_2 and a_4.

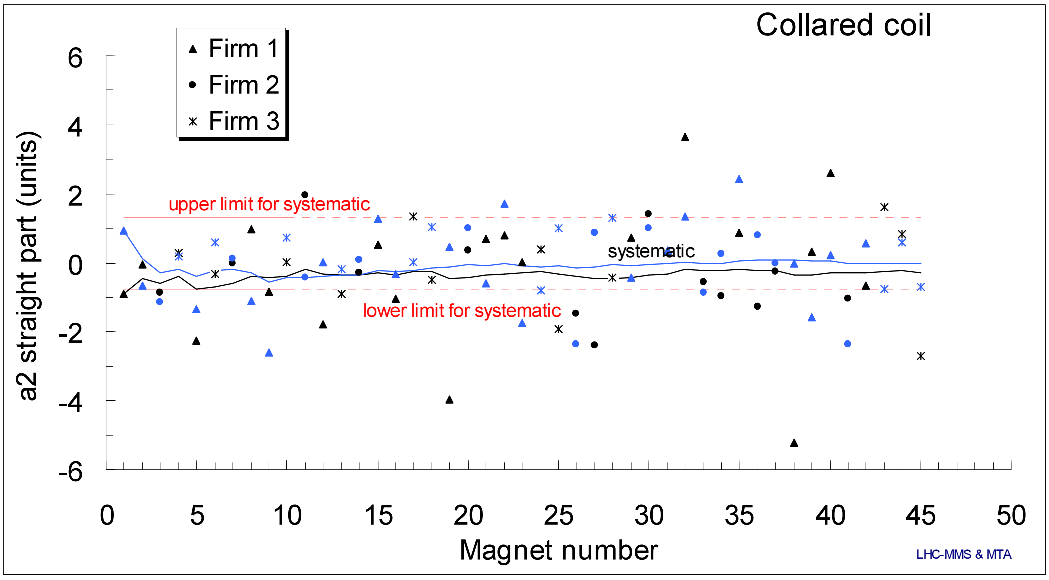

Fig. 11: Average a_2 in the straight part of the collared coils (dots), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

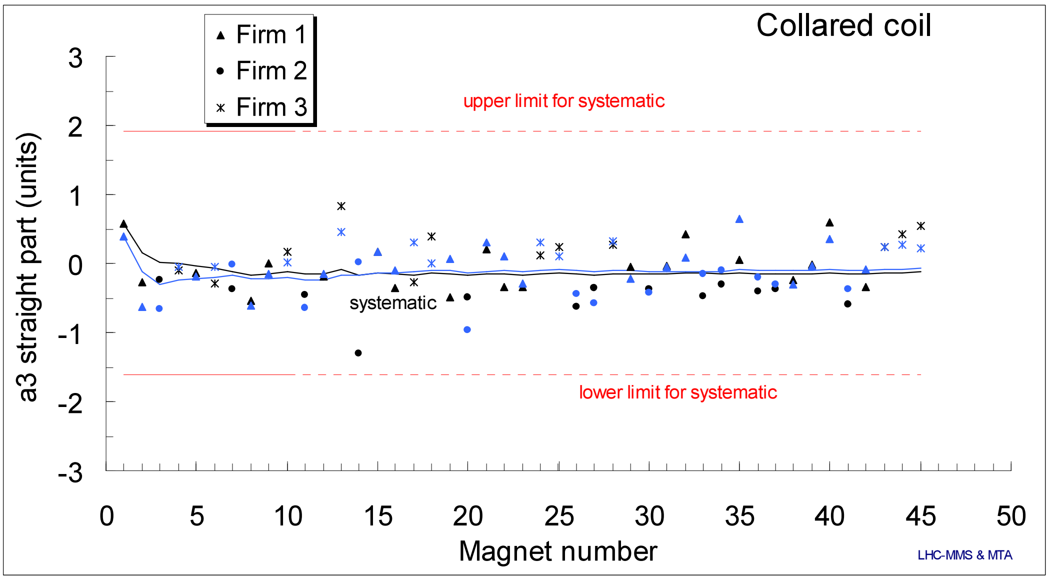

Fig. 12: Average a_3 in the straight part of the collared coils (dots), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

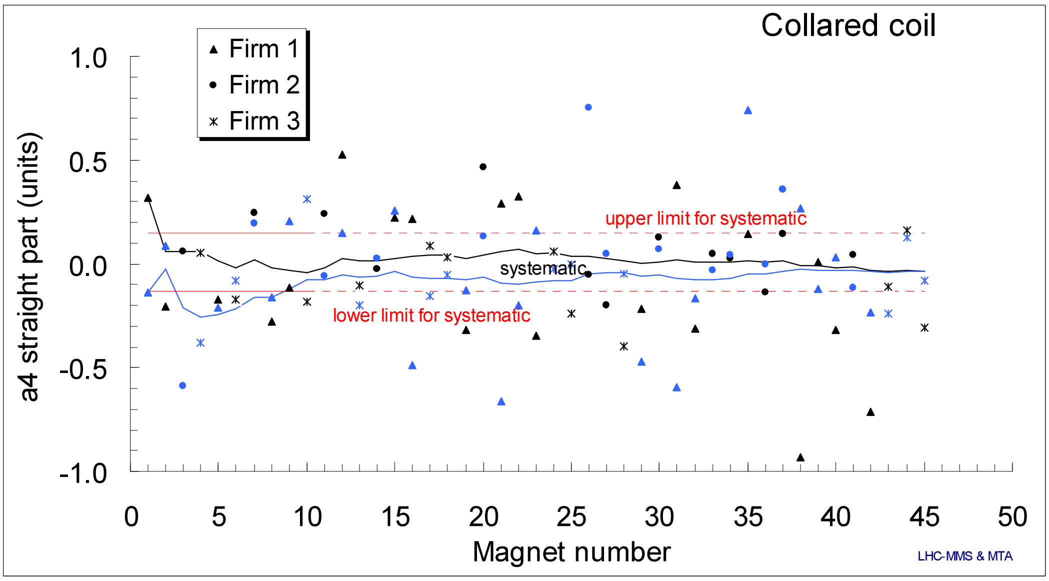

Fig. 13: Average a_4 in the straight part of the collared coils (dots), best estimate for systematic in each aperture (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

6. Systematic even multipoles

For each multipole subject to beam dynamics specifications, we present two separated plots for the systematic per aperture, and a plot of the systematic per beam, i.e. the average of both apertures (that should be zero due to two-in-one symmetry).

6.1 Normal quadrupole

- The systematic per aperture is within specifications in both apertures (see Figs. 14 and 15).
- Noell 12 and 13 (collared coils 43rd and 44th) have rather large values of normal quadrupoles. The problem is under investigation. Noell 14 collared coil features better values of the normal quadrupole (see Figs. 14 and 15, collared coil 45th).

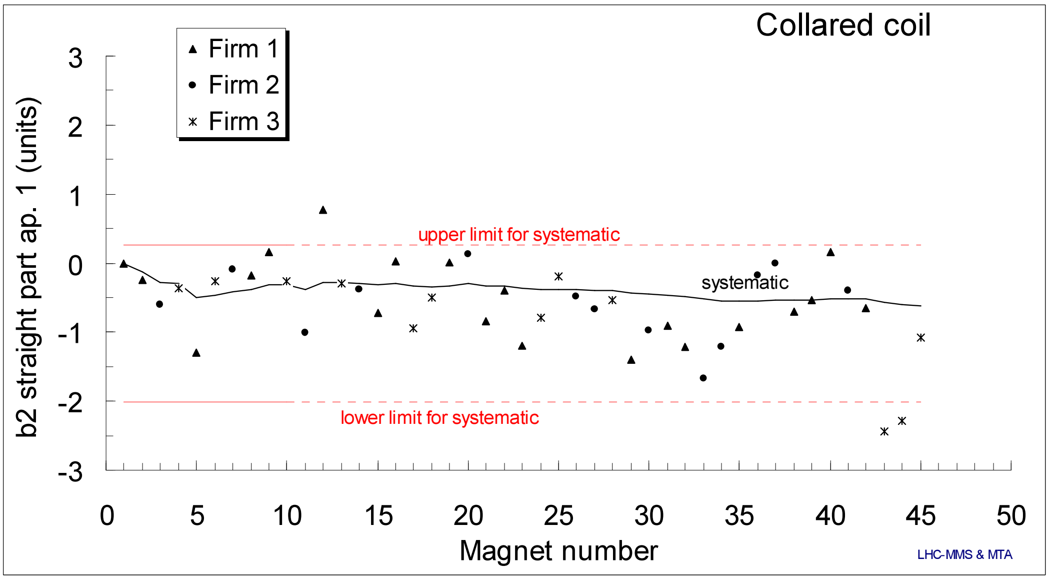

Fig. 14: Average b_2 in the straight part of the aperture 1 collared coils (dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

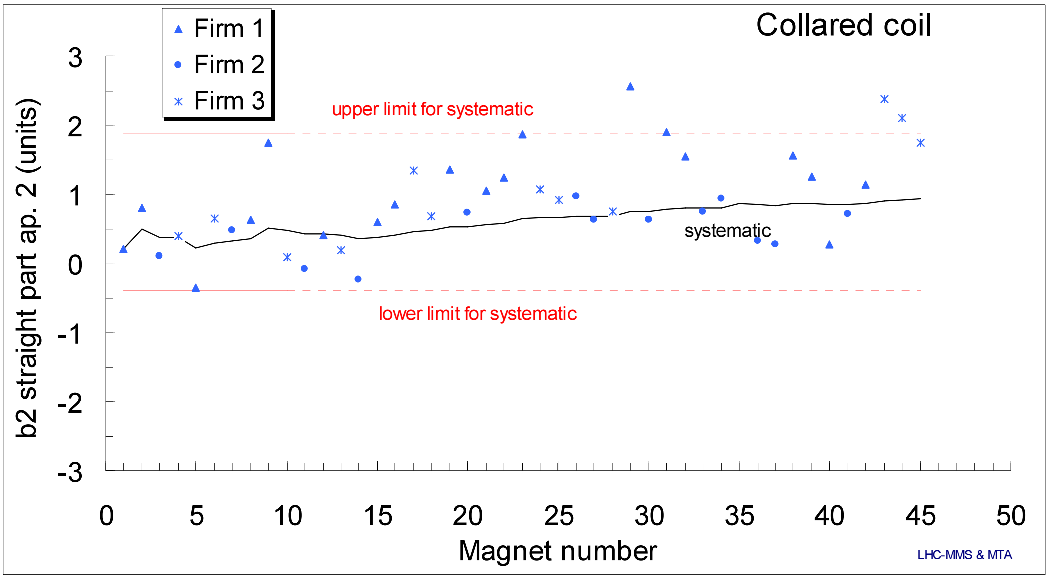

Fig. 15: Average b_2 in the straight part of the aperture 2 collared coils (dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

- The systematic per beam normal quadrupole is within specifications (see Fig. 16).

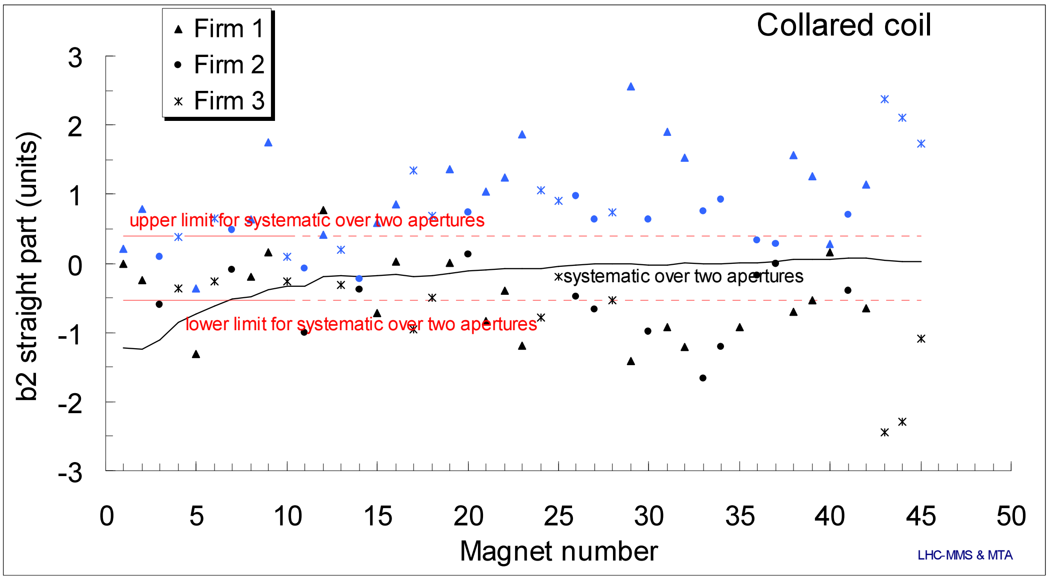

Fig. 16: Average b_2 in the straight part of collared coils (dots), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

6.2 Normal octupole

- The systematic per aperture is within specifications in both apertures (see Figs. 17 and 18).
- The systematic per beam is also within specifications (see Fig. 19).

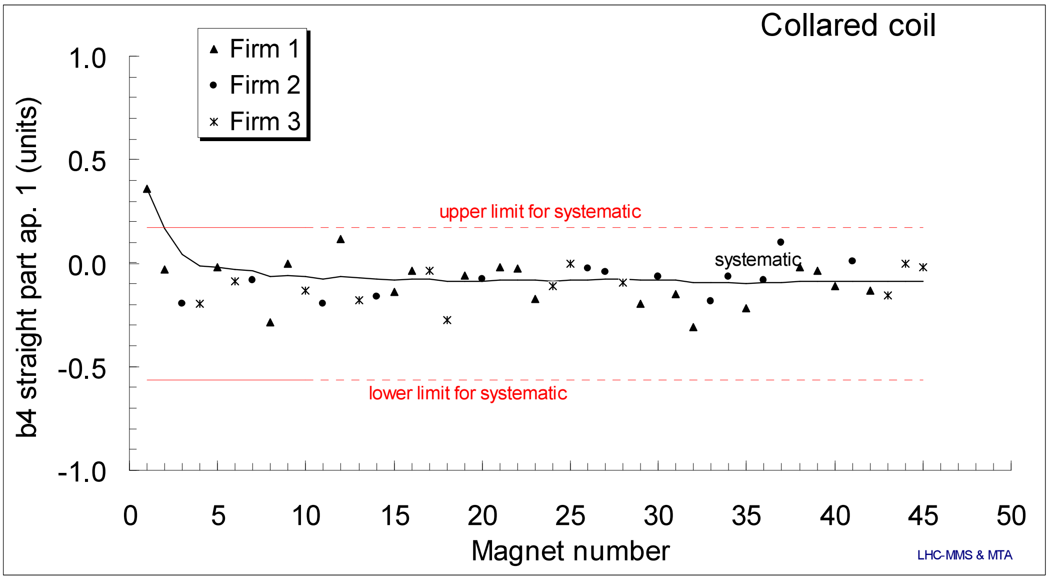

Fig. 17: Average b_4 in the straight part of the aperture 1 collared coils (dots), best estimate for systematic per aperture (black line), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

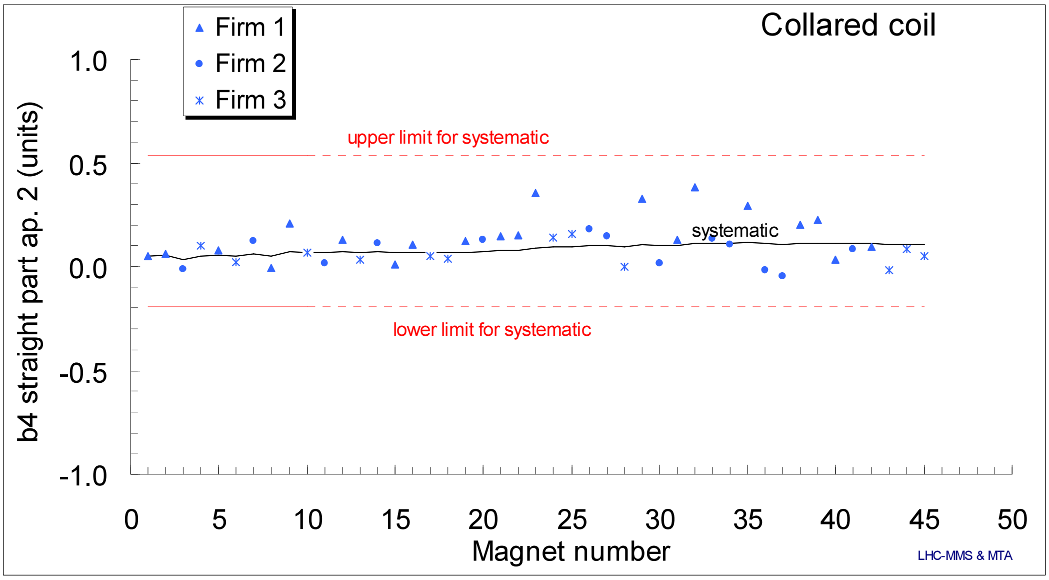

Fig. 18: Average b_4 in the straight part of the aperture 2 collared coils (dots), best estimate for systematic per aperture (black line) and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

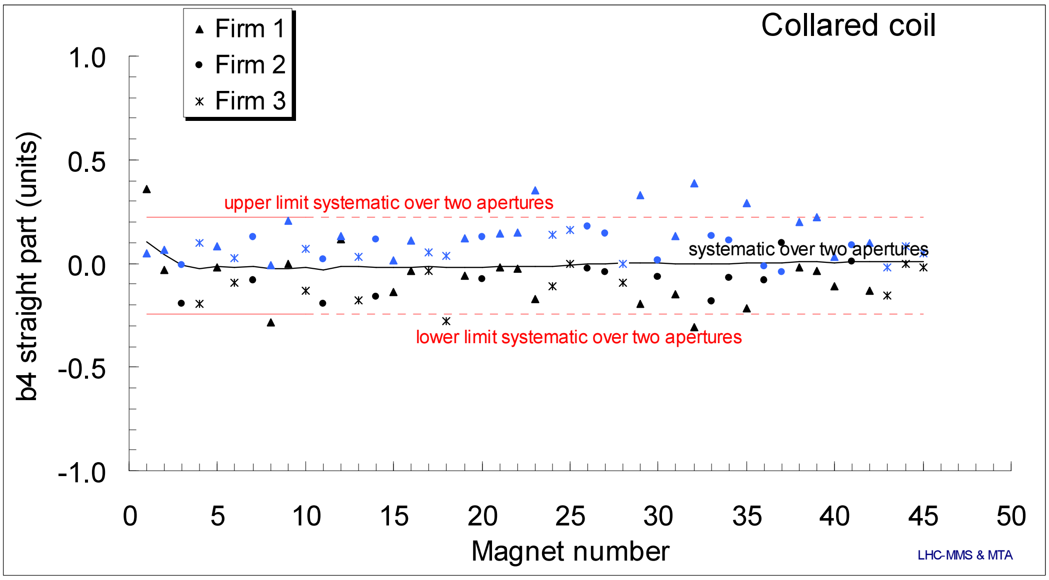

Fig. 19: Average b_4 in the straight part of collared coils (dots), best estimate for systematic per beam (black line) and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

7. Systematic odd multipoles

7.1 Normal sextupole

- Data from Noell collared coil with the new X-section confirm previous results from Alstom and Ansaldo (see Figs. 20 and 21).
- The cross section correction shifted down the normal sextupole from around 2.2 units (excluding the data from collared coil 1 to 15 that experienced an upward trend) to –1.8 units, in agreement with simulations (-3.9 units).
- Due to the positive trend, our estimate for systematic in X-section 2 is 0.7 units out of the limit (see fig. 21). The associated error is 0.6 units (95% confidence level, see Fig. 10).
- The low systematic difference between firms observed in X-section 1 seems to be preserved in X-section 2; Alstom collared coils feature a lower b_3 with respect to Noell and Ansaldo.
- Cryodipoles with the new X-section should feature 3.5 units of b_3 at high field; this is outside the specification but within the hard limit of 4.2 units given by chromaticity correctors.

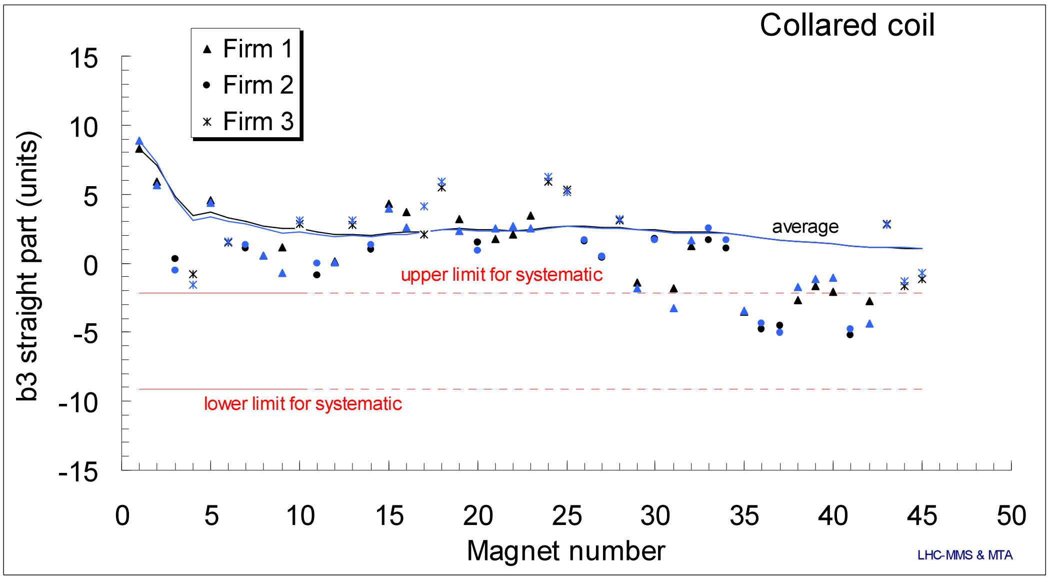

Fig. 20: Average b_3 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

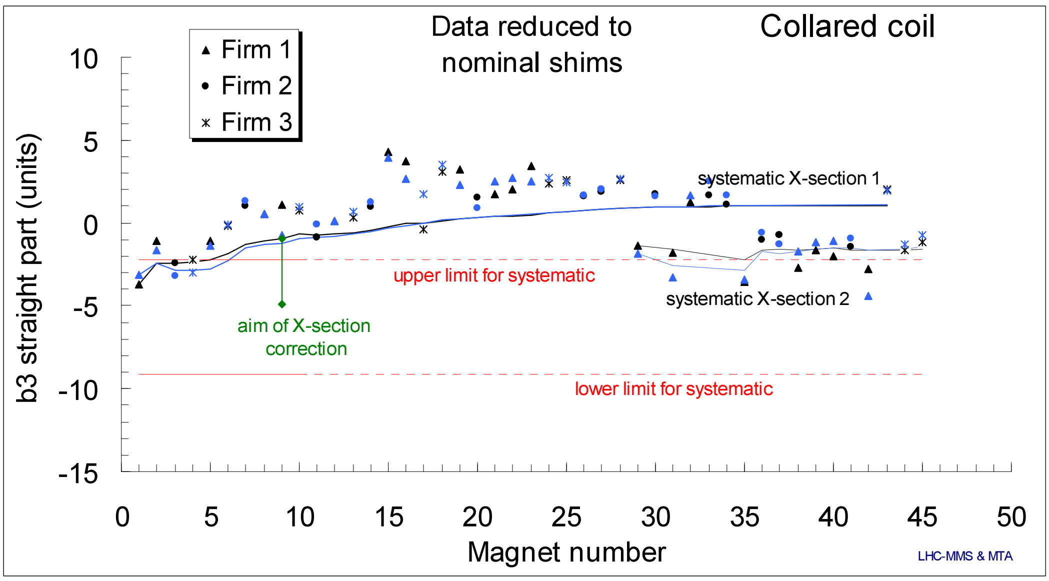

Fig. 21: Average b_3 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles. Data reduced at nominal shims and separated according to X-section type.

7.2 Normal decapole

- Alstom 21 (collared coils 42nd in Figs. 22 and 23) features a very high b_5 (around 0.7 units more than previous collared coils 38th –40th).
- Measured b_5 in new X-section Noell collared coils is larger than expected: the average is close to Alstom values, whilst in the previous X-section it was much lower, being close to Ansaldo (see Fig. 23, collared coils 44th and 45th).
- Best estimate for systematic b_5 in new X-section is 0.25 units larger than the upper allowed limit. Part of this difference is due to a positive trend of 0.2 units experienced from collared coil 9th (where the correction was defined) to 20th. The remaining 0.35 units are due to a measured effect of the correction (-1.0 units) lower than expected (-1.35 units). We still have a large error associated to the estimate of the new X-section systematic: ±0.24 units(at 95% confidence level), i.e. nearly the width of the allowed range (see Fig. 10).

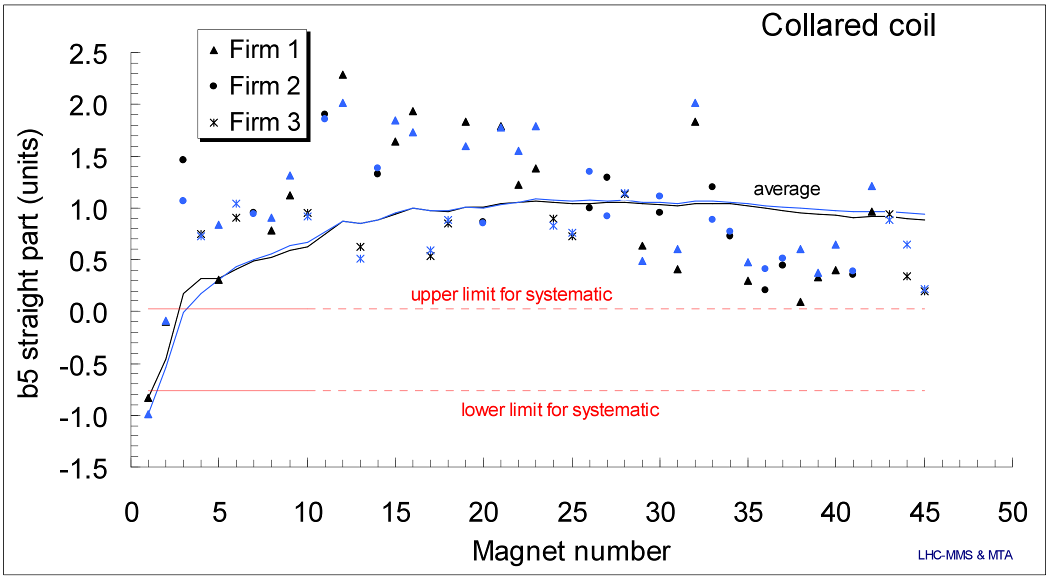

Fig. 22: Average b5 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

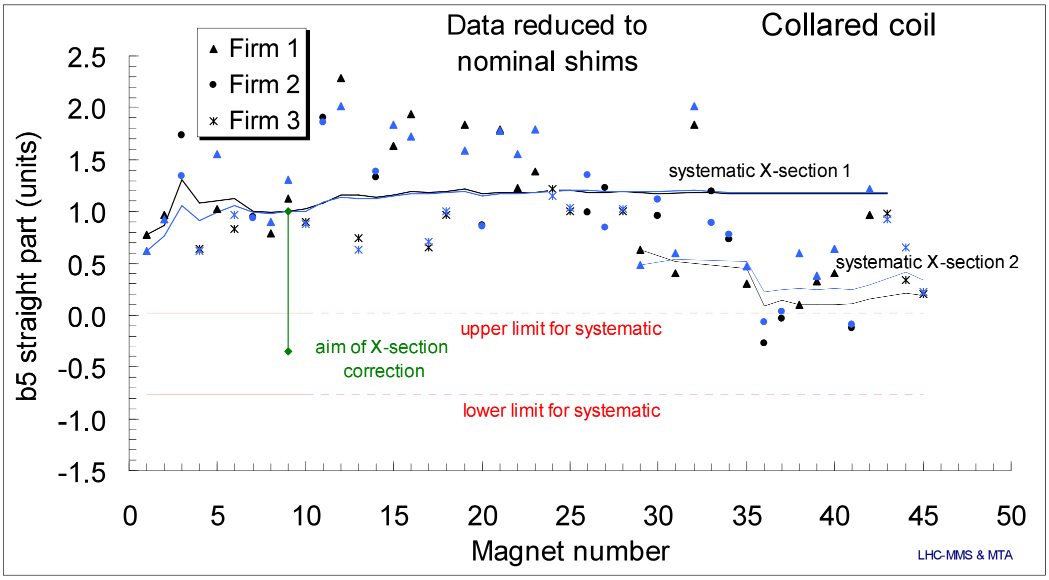

Fig. 23: Average b5 in the straight part of the collared coils (dots), best estimate for systematic (blue line), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

7.3 Normal 14-th pole

- Alstom 19 (collared coils 40th in Figs. 24 and 25) features a very high b_7 (around 0.2 units more than previous Alstom collared coils 29th –39th).
- Noel data confirm previous trends: new X-section collared coils have a systematic b_7 of around 1.1 units, i.e. 0.3 units more than the upper limit. The associated error is small (0.04 units at 95% confidence level, see Fig. 10).
- The b_7 has been increased by the cross-section correction of about 0.48 units against a foreseen value of 0.18 units, i.e. 0.3 units more than expected. This feature is under investigation. In particular, the very low value of b_7 observed in Ansaldo for the first X-section has been not found in the second one.

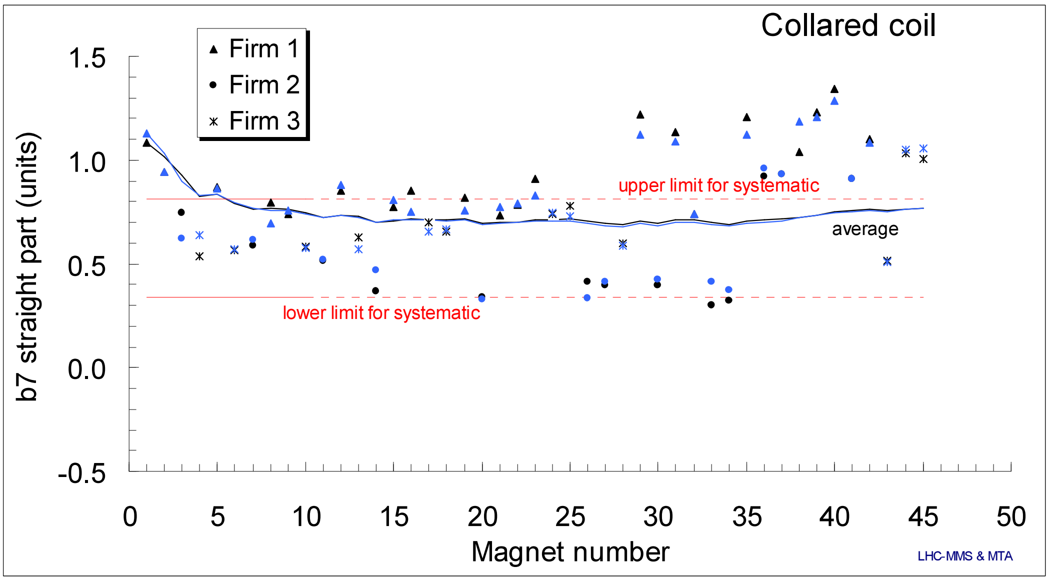

Fig. 24: Average b_7 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles.

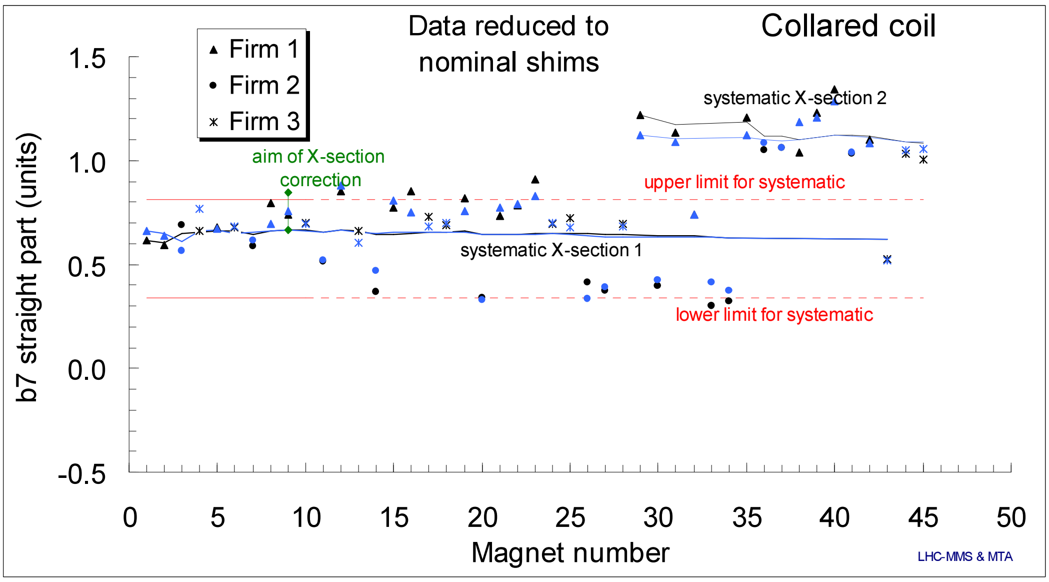

Fig. 25: Average b_7 in the straight part of the collared coils (dots), best estimate for systematic (solid lines), and beam dynamics limits for the systematic (red line) based on correlations with 10 cryodipoles. Data are reduced to nominal shims and separated according to different cross-sections.

8. Random multipoles

- Random per manufacturer and global random (i.e., the standard deviation of the distribution of all magnets) are shown in Figs. 26 and 27.
- Raw data (see Fig. 26) show an out of tolerance for b_3 and b_5. This is mainly due to the change of cross-section that shifted down these multipoles of 3 units and 1 unit respectively. The other parameters are within specifications, also in the hypothesis of a complete mixing.
- When data are reduced to nominal shims and split according to the cross-section type, one observes a random b_3 out of tolerance in the old X-section: this is due to the upward trend (see Section 7.1, Fig. 21). This is the only out of tolerance in the old X-section.

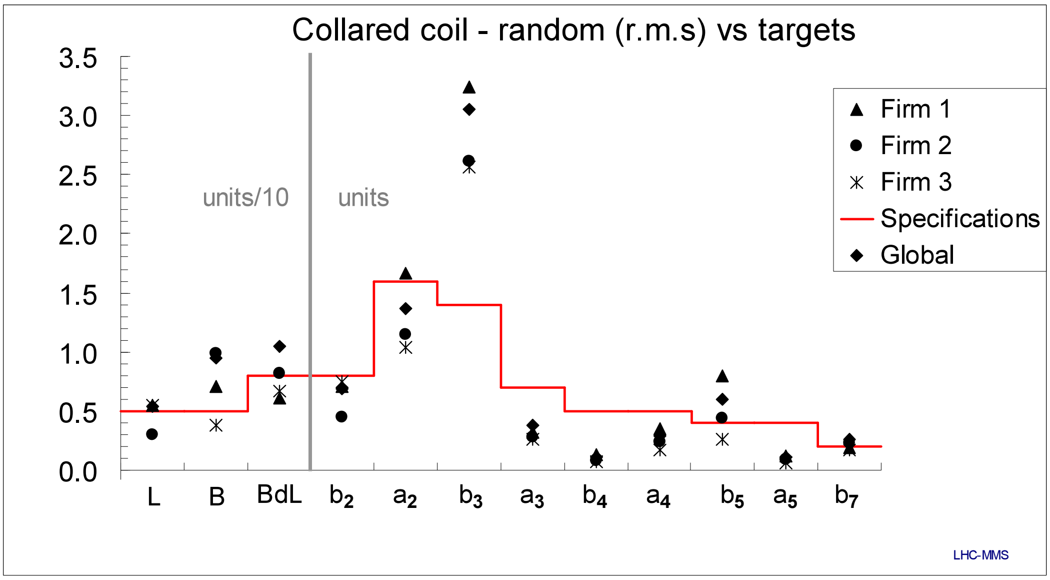

Fig. 26: Random component in the measured collared coils

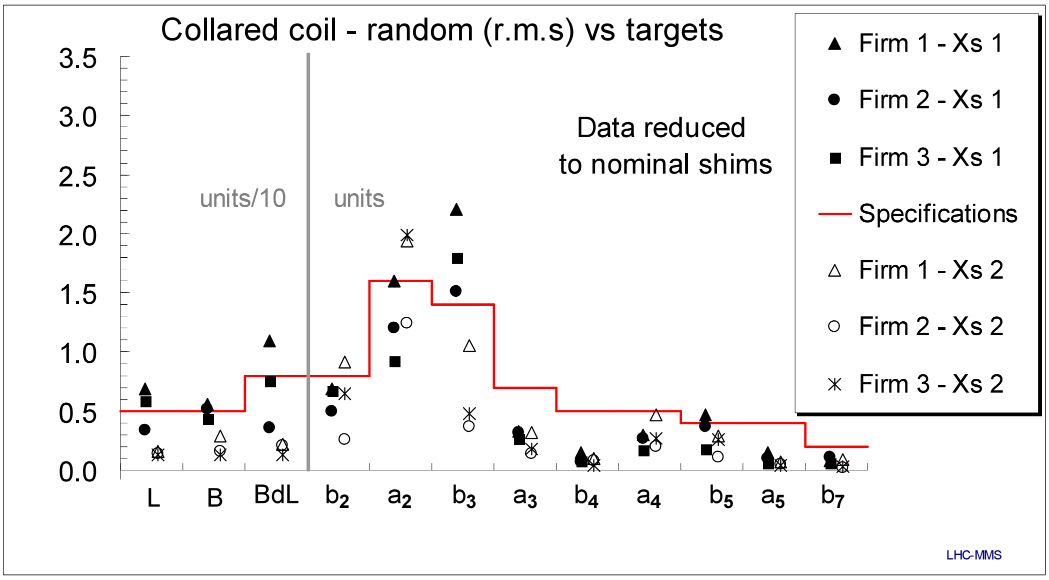

Fig. 27: Random component in the measured collared coils. Data reduced to nominal shims and split according to different cross-sections.

- The statistics for the new cross-section is still very poor and therefore some features could change when more data will be available; with the present set of data we make the following preliminary considerations:

- Collared coils with the new cross-section feature a very stable integrated main field BdL and odd multipoles (see Fig. 27).
  - Firm 1 has a large random b_2, mainly due to the very high value measured in Alstom 13 (collared coil 29th in Fig. 16).
  - Firm 1 and Firm 3 have a large random a_2 (see Figs. 27 and 11).
- All the random components are expected to decrease by around 20% in the cold mass, due to the main field increase. Therefore, out of tolerances in a_2 and b_2 are likely to disappear in the cold mass.

9. Holding point results

Table II: results of the holding point for the measured collared coils

	Magnet name		Collared coil measure	Data at CERN	Answer to MMS-MD	Answer To manufact.	Result	Comments
39rd	HCMB__A001	1000018	03/07/02	04/07/02	05/07/02	05/07/02	Ok	Coil waviness almost normal
40th	HCMB__A001	1000019	17/07/02	18/07/02	18/07/02	24/07/02	Ok-w	Strong coil waviness in aperture 1 (50 microns) – b7 higher than in previous ones
41th	HCMB__A001	2000014	24/07/02	24/07/02	24/07/02	25/07/02	Corr. Act.	Same as 2000013 and 12: more laminations will be added in the cold mass to recover good TF
42th	HCMB__A001	1000021	24/07/02	24/07/02	24/07/02	25/07/02	OK	
43th	HCMB__A001	3000011	19/08/02	20/08/02	21/08/02	22/08/02	Ok-w	Rather large value of b2 in both apertures
36th	HCMB__A001	2000013	08/08/02	08/08/02	08/08/02	12/08/02	HOLD	Re-collared with 0.1 mm more shim in the outer layer – Effect on multipoles different from what expected in c1, b5, b7
44th	HCMB__A001	3000012	20/08/02	22/08/02	24/08/02	26/08/02	Ok-w	Rather large value of b2 in both apertures
45th	HCMB__A001	3000013	23/08/02	23/08/02	24/08/02	26/08/02	Ok	

- A corrective action will be taken on Ansaldo 14. It has been agreed to add magnetic laminations to recover an integrated main field within tolerances.
- Ansaldo 2000013 that has been collared and measured in June 2002 has been de-collared for electric problems and a thicker shim on the external layer has been inserted (0.1 mm more). The effect on field quality is different from what expected from simulations (see Table III), especially for main field and b_5. The collared coil has been not approved and investigations are in progress. The following steps will be taken:
  - All collared coils that will be de-collared for any reason, in any firm, will be measured before and after the de-collaring to have more statistics.
  - Components and assembly procedures of Ansaldo 2000013 will be analysed

Table III: Effect of a shim change of 0.1 mm on the outer layer: model, measurements on HCMB__A001-02000013, and discrepancy with respect to model

	ΔC_1	Δb_3	Δb_5	Δb_7
Model	4.0	1.6	-0.08	-0.02
02000013 Aperture 1	7.4	1.0	0.46	-0.11
02000013 Aperture 2	8.7	1.2	0.42	-0.13
02000013 Average	8.0	1.1	0.44	-0.12
02000013 Av.-model	4.0	-0.5	0.52	-0.10

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Appendix A

In Figs. 2 to 25, collared coils are identified by a progressive number. The link between this number and the official name is given in the following table.

Table III: relation between magnet numbers used in Figs. 2-25 and official names

1st	1000001	21st	1000010	41st	2000014
2nd	1000002	22nd	1000011	42nd	1000021
3rd	2000001	23rd	1000012	43rd	3000011
4th	3000001	24th	3000007	44th	3000012
5th	1000003	25th	3000008	45th	3000013
6th	3000002	26th	2000008		
7th	2000003	27th	2000007		
8th	1000004	28th	3000009		
9th	1000005	29th	1000013		
10th	3000003	30th	2000006		
11th	2000002	31st	1000014		
12th	1000006	32nd	1000015		
13th	3000004	33rd	2000010		
14th	2000005	34th	2000009		
15th	1000007	35th	1000016		
16th	1000008	36th	2000013		
17th	3000005	37th	2000012		
18th	3000006	38th	1000017		
19th	1000009	39th	1000018		
20th	2000004	40th	1000019		

Appendix B. Control chart for magnetic length and main field

Control limits for the magnetic length (see Fig. 3) are put at 3 times the specified sigma from the measured average. No target is assumed for the average magnetic length. The same approach is followed for the control limits of the main field in the straight part (see Figs. 4-7): they are put at 3 times the specified sigma from the measured average, and no target is assumed for the average main field. We recall that beam dynamics specifications are given in terms of the sigma of the integrated main field. Therefore, the only chart relevant for beam dynamics is in Fig. 5 and 7. We assume an equal share of the integrated main field spread (8 units) between magnetic length and main field (5 units each), in the hypothesis of a Gaussian sum of the spreads.

Appendix C. Control chart for the systematic

Best estimates for systematic shown in Figs. 9-25 are defined as the average of the averages of each manufacturer. This definition takes into account for the quotas of dipoles assigned to manufacturers (one third each).

Control limits for the systematic are given using the following formula for working out correlations between collared coil data b_n^{cc} and multipoles at injection b_n^i or at high field b_n^h

$$b_n^h = (b_n^{cc}/k) + b_n^{oh} \qquad b_n^i = (b_n^{cc}/k) + b_n^{oi}$$

where $k = B_1^{cc}/B_1^{cm} = 1.18$ is the multipole rescaling induced by the 18% increase of the main field due to the yoke as derived from magnetic measurements.

Appendix D. Remarks on the cross-section correction

We recall the aim of the cross-section correction:

$$\Delta B_1 = 0 \quad \Delta b_3 = 3.3 \quad \Delta b_5 = 1.15 \quad \Delta b_7 = 0.15$$

These shifts are expected in the cold mass, whilst in the collared coil they are scaled by the factor k = 1.18 (see Appendix C). Therefore in the collared coil we aimed at

$$\Delta B_1 = 0 \quad \Delta b_3 = 3.9 \quad \Delta b_5 = 1.36 \quad \Delta b_7 = 0.18.$$

The cross-section correction has been based on the best estimates of the systematics in the collared coil, on the correlations to measurements at 1.9 K, and on the beam dynamics acceptance ranges. Correlations also used data of prototypes (if homogeneous with pre-series) to increase statistics. Figs. 21 and 23 show that the cross-section correction carried out at collared coil 9 aimed at centring the allowed ranges for b_3 and b_5.

For the b_7 the situation is different (see Fig. 25). This is due to some change in correlations, and to a change of the b_7 acceptance ranges that has been carried out after the definition of the new X-section. We recall that due to the intense tracking campaign carried out in 2001, the tolerance for b_7 at injection has been reduced from [-0.4,0.4] as presented in Villars, LHC Days, March 2001, to [-0.3,0.3] in June 2001 to the final value of [-0.3,0.1] in the LHC Project Report 501 published in August 2001. The cross-section correction computed in June 2001 has been based on the range [-0.3,0.3].