Status and trends of field quality at 300° K and possible corrective actions

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AT-MAS-MA

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- What is large and what is tight
- Limits to field quality steering towards beam dynamics
  - Models versus measurements
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  - (Correlations from collared coil to operational conditions)
- Status of field quality (see also talks of S. Fartoukh and S. Sanfilippo)
  - Systematics
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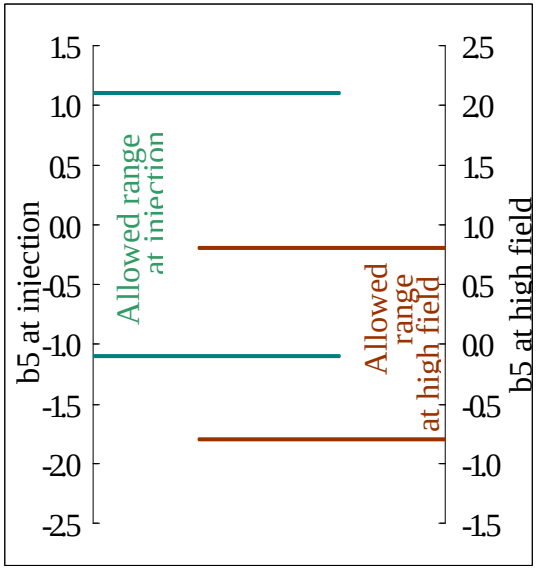
  - Random BdL
  - Systematic odd multipoles
- Conclusions

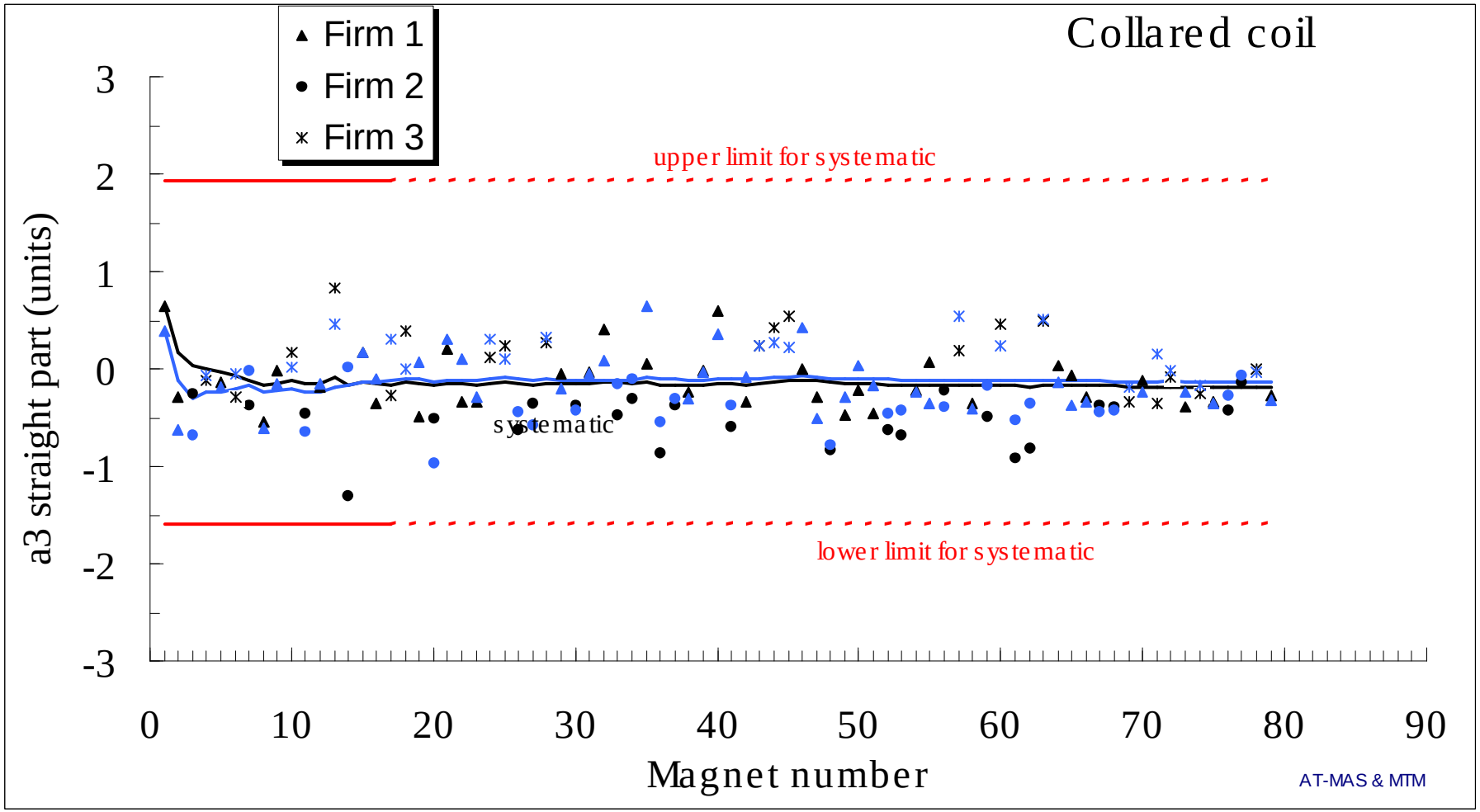
What is large and what is tight



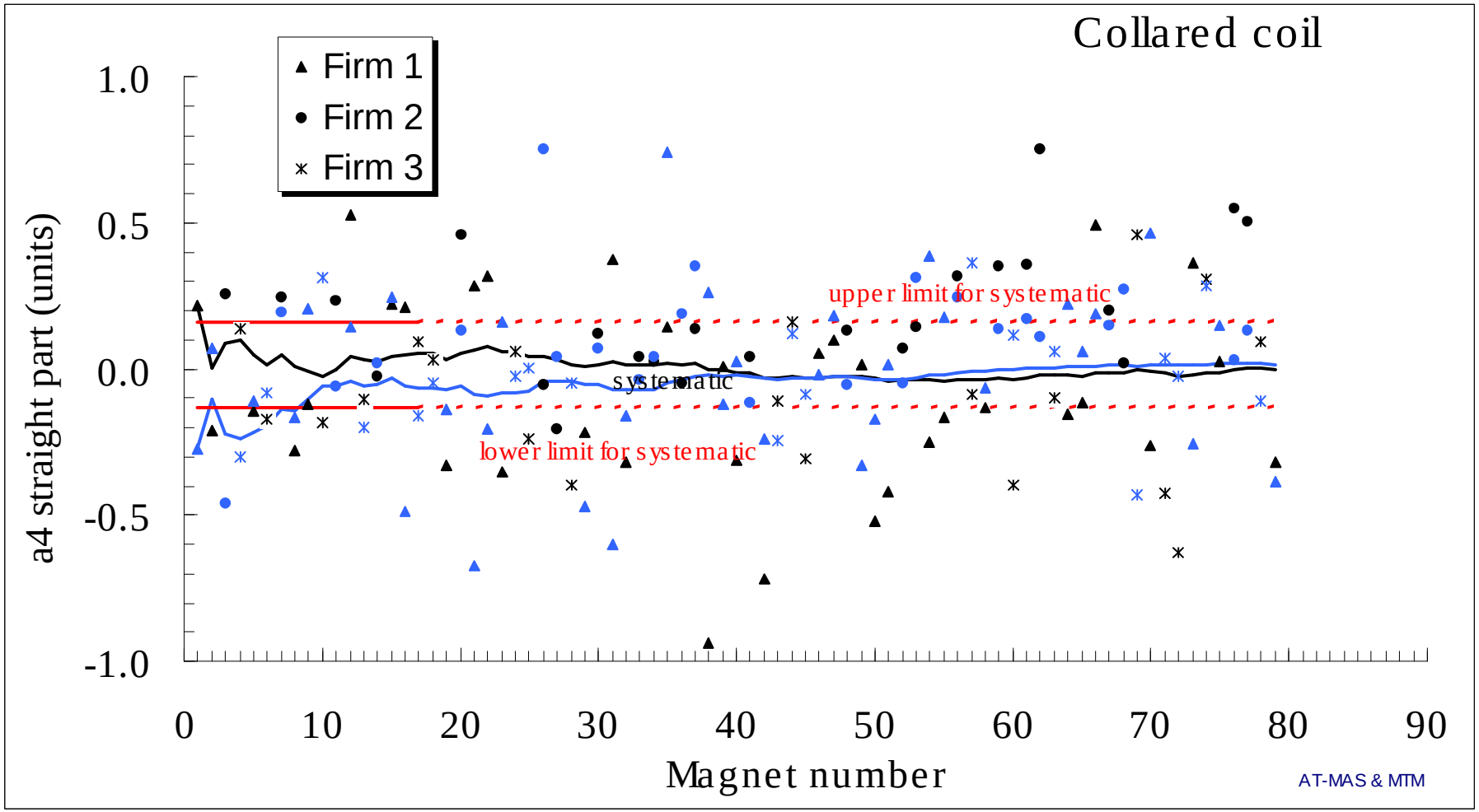
- Beam dynamics targets given as
  - Random – Uncertainty – Systematic
  - For random and uncertainty target values were agreed in FQWG (maximal values)
  - Ranges on systematics given by beam dyn. only [LHC Pr. Rep. 501] (iteration needed ?)
- Which are the tighter constraints ? On systematics
  - We compare the range allowed for systematics to the natural sigma [measured random,1 σ]
  - a_4 and b_5 ranges are very tight (control needed at 0.05 units !)

	random (measured)	syst. half range (beam dynamics)	
b3	1.50	3.50	easy
b5	0.45	0.35	hard
b7	0.17	0.24	so-so
b2	0.70	1.10	so-so
b4	0.11	0.37	easy
a2	1.30	1.00	hard
a3	0.40	1.70	easy
a4	0.30	0.14	hard

An easy case: a_3



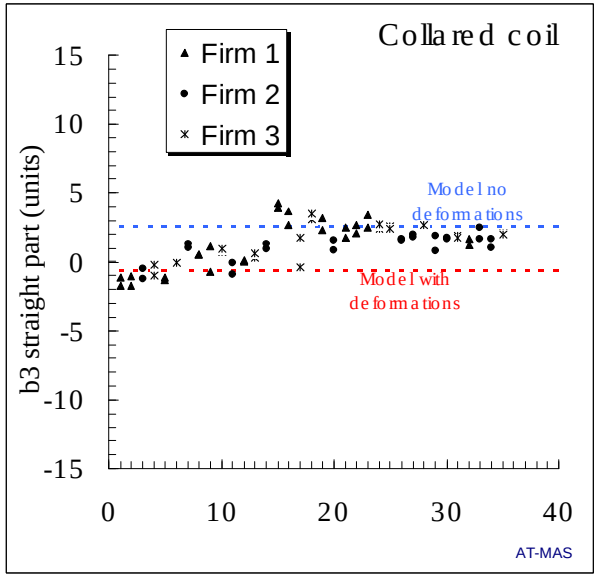
A hard case: a_4

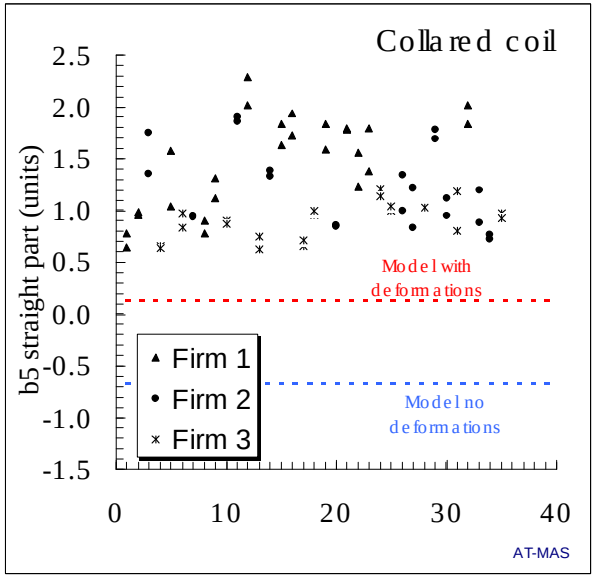


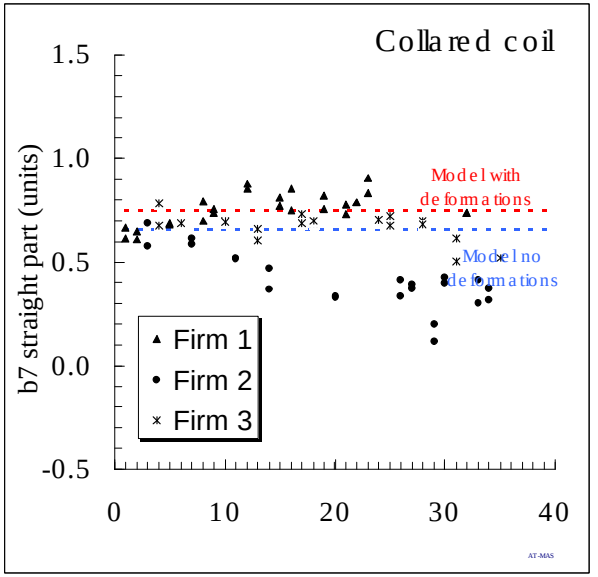
Limits to FQ steering: model vs measurements

- Geometric, absolute: estimate of b_3 b_5 b_7 in collared coil discrepancy is 1-2 times the sigma (2 units of b_3, 1 of b_5)
  - Models are not enough predictive to get field quality within beam dynamics spec (ex. allowed range for b_5 is 0.7 units)
  - The effect of coil deformations is relevant for b5
  - Iteration on coil design is needed

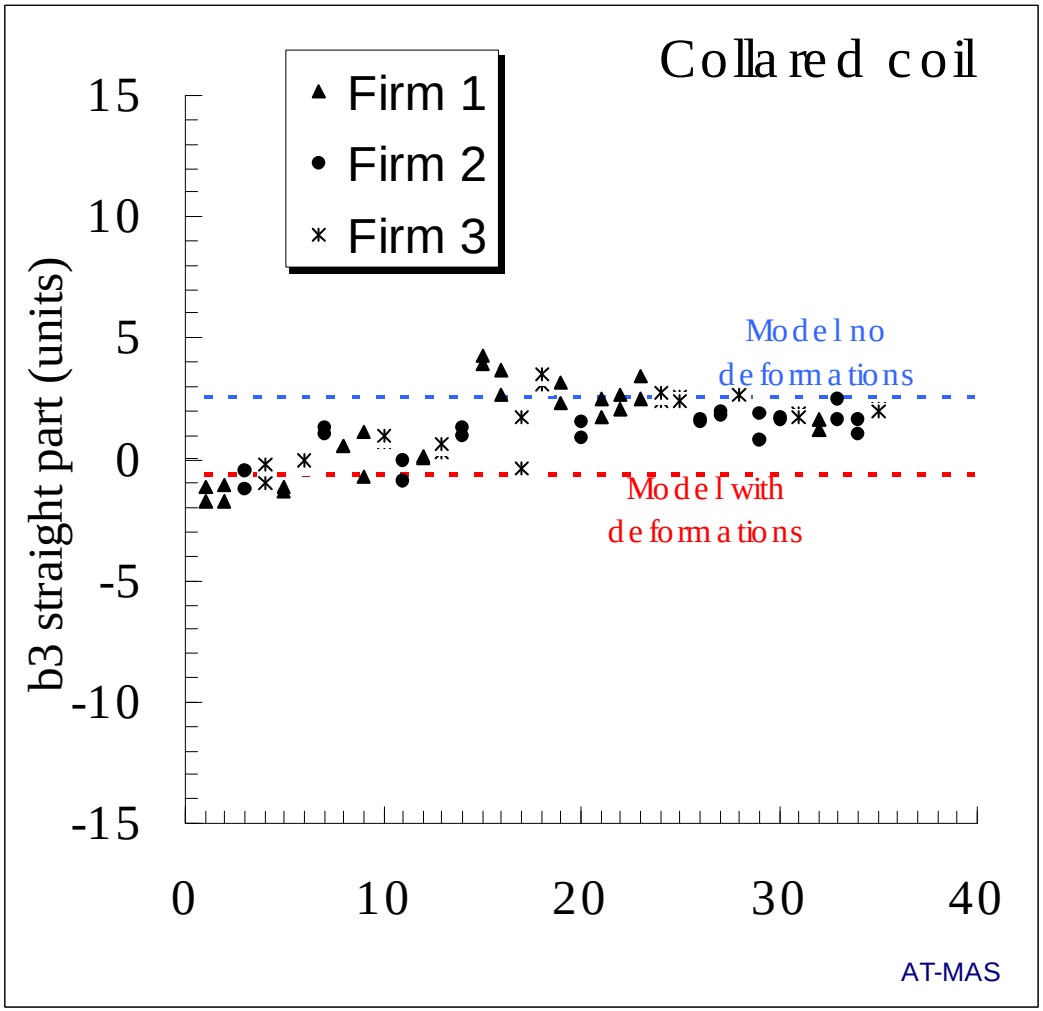
Data of X-section 1





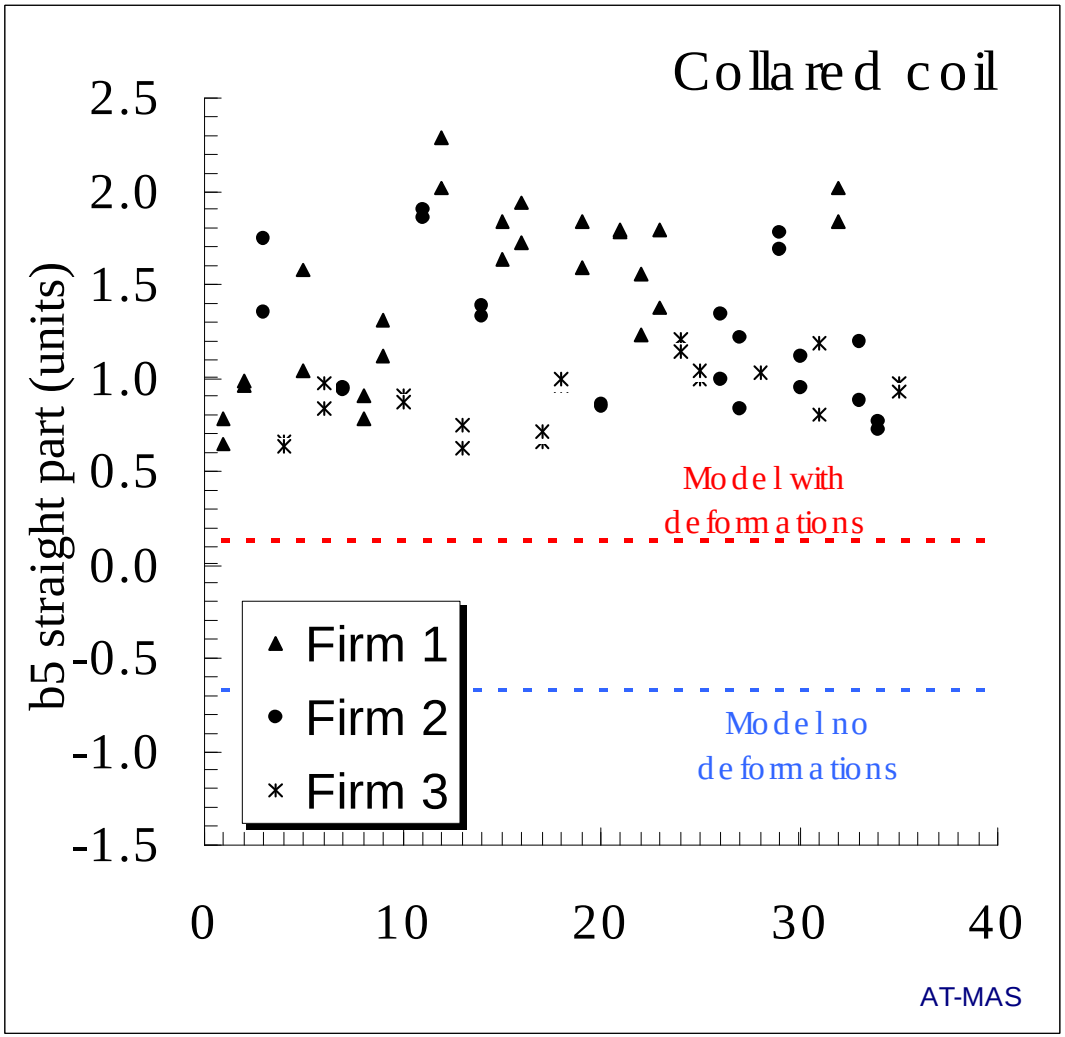


Limits to FQ steering: model vs measurements



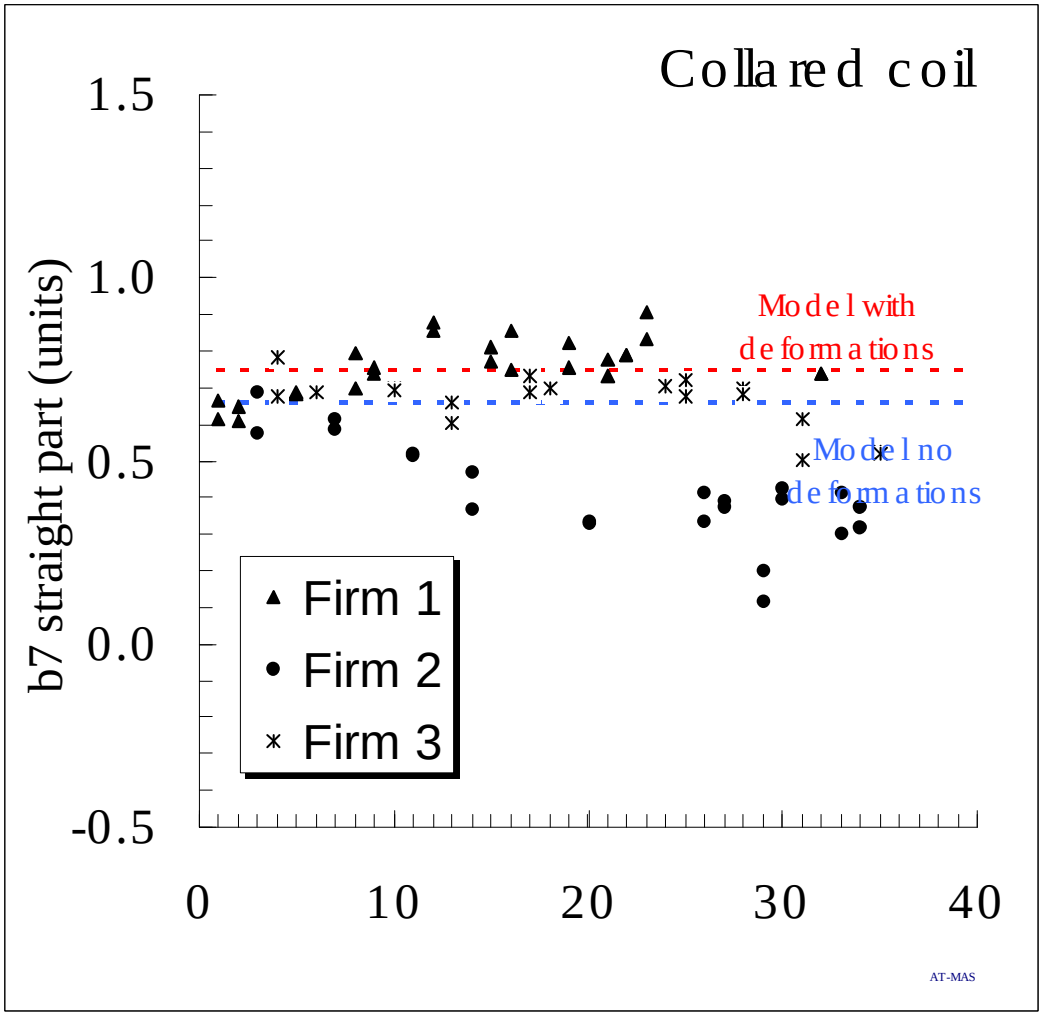
Data of X-section 1

Limits to FQ steering: model vs measurements



Data of X-section 1

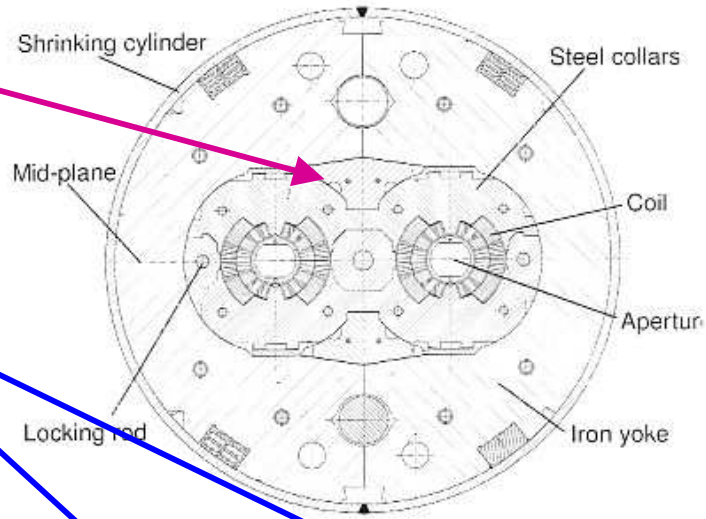
Limits to FQ steering: model vs measurements

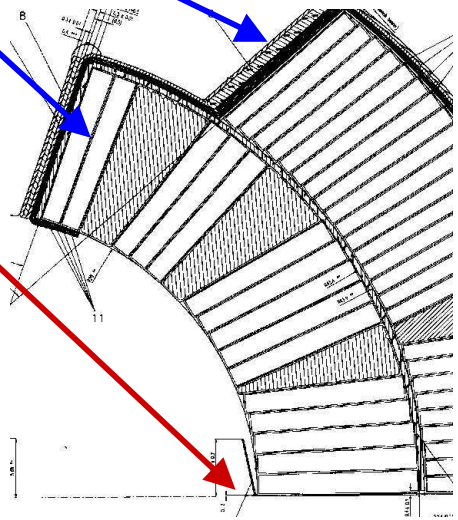


Data of X-section 1

Limits to FQ steering: model vs measurements

- Geometric, relative: what we did
  - estimate of dependence b_2 b_4 on insert shape: [S. Redaelli et al, LHC-Project-Report **467,** EPAC 2002]
  - estimate of dependence of b_3 b_5 b_7 on polar shims [P. Ferracin, W. Scandale, D. Tommasini, E. Todesco, PRSTAB **5** (2002)]
  - estimate of dependence of b_3 b_5 b_7 on midplane insulation [H. Kummer, D. Tommasini, et al. in progress]
    - Different models give different sensitivities up to 10%, depending on hypothesis to squeeze the coil [L. Bottura, A. Devred, E. Todesco, ...]
- In all cases agreement between model and experiment is within 20%
  - Corrective actions are expected to work at 80% to 120%

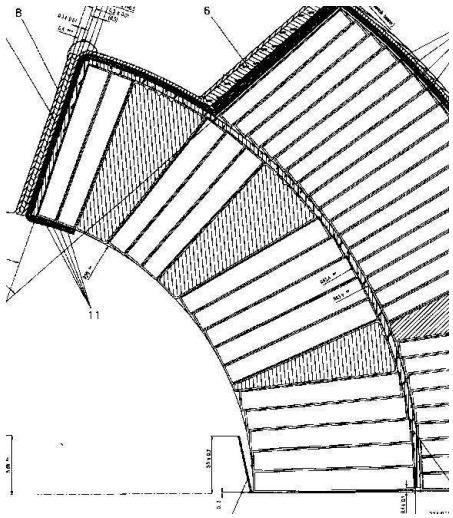




Limits to FQ steering: model vs measurements

- The midplane insulation experiment
  - Adding 0.05 mm and 0.10 mm more on midplane inner layer
    - Change of prestress – test on linearity
  - Adding 0.05 mm more on midplane outer layer
  - Adding 0.05 mm more on midplane and reducing of 0.05 mm in the pole (inner layer only)
  - Sensitivities to be divided by 1.18 at 1.9 K (iron yoke missing)

Pole in	Midpl in	Midpl ou		b3	b5	b7
0.00	0.05	0.00	Model	-1.8	-0.54	-0.15
			Measured	-1.9	-0.42	-0.13
0.00	0.10	0.00	Model	-3.6	-1.07	-0.30
			Measured	-3.8	-0.87	-0.27
0.00	0.00	0.05	Model	-0.7	-0.10	-0.01
			Measured	-0.5	-0.10	0.00
-0.05	0.05	0.00	Model	-2.9	-0.36	-0.23
			Measured	-2.4	-0.32	-0.18

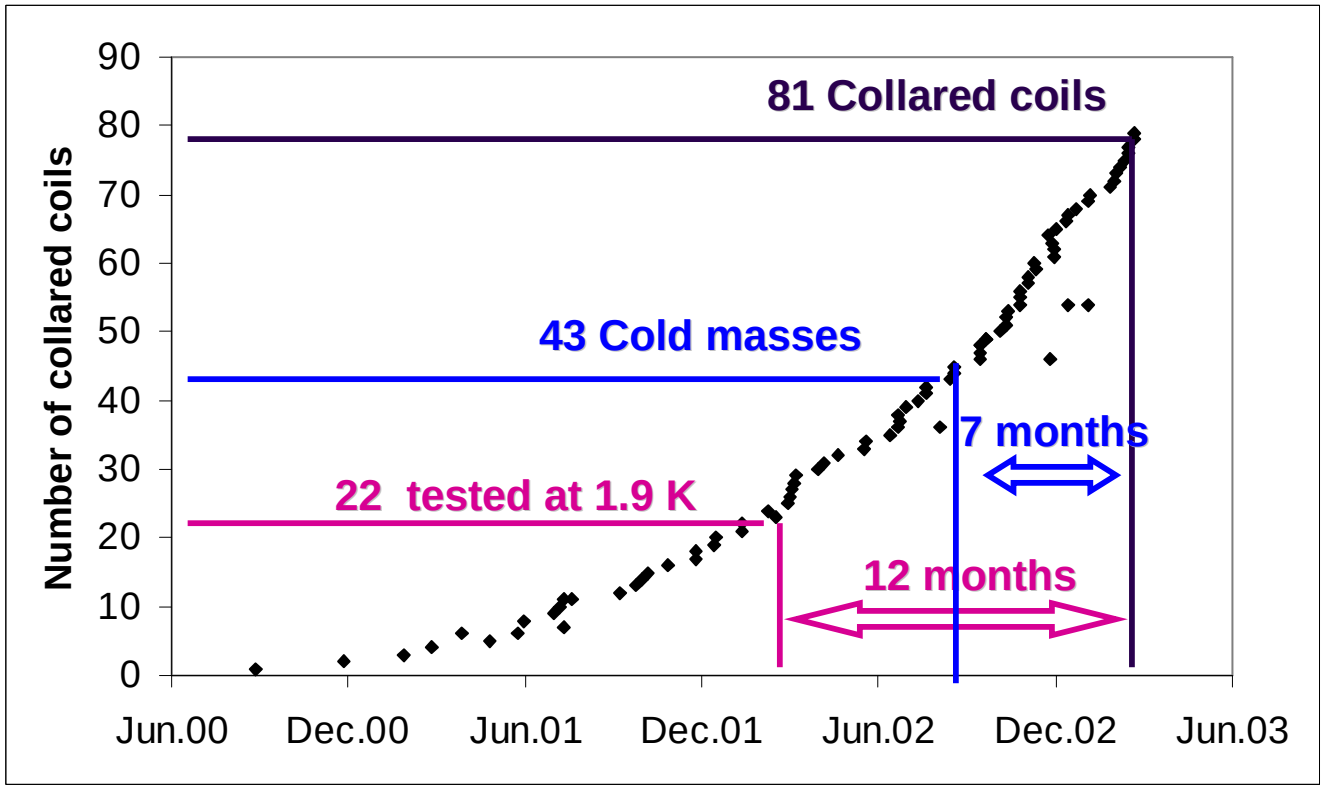


Limits to FQ steering: reproducibility

- What is the FQ reproducibility of a collared coil made with the same components ?
  - Experience from short models at CERN (range of variation):
    - $\Delta b_3 = \pm 0.2$ units $\Delta b_5 = \pm 0.05$ units $\Delta b_7 = \pm 0.01$ units
    - This is the best reproducibility one can obtain
    - No systematic effect
    - It is of the order of 1/10 of the natural random component
  - Experience from pre-series at manufacturer: some systematic effect (range of variation)
    - $\Delta b_3 = -0.6 \pm 0.2$ units $\Delta b_5 = +0.5 \pm 0.2$ units $\Delta b_7 = -0.13 \pm 0.12$ units
    - Statistics: 6 apertures in two manufacturers, collared two times
    - Large effect on b_5
    - Effect of the virgin state ?
    - What about a third decollaring ? (wait for 2002 data)

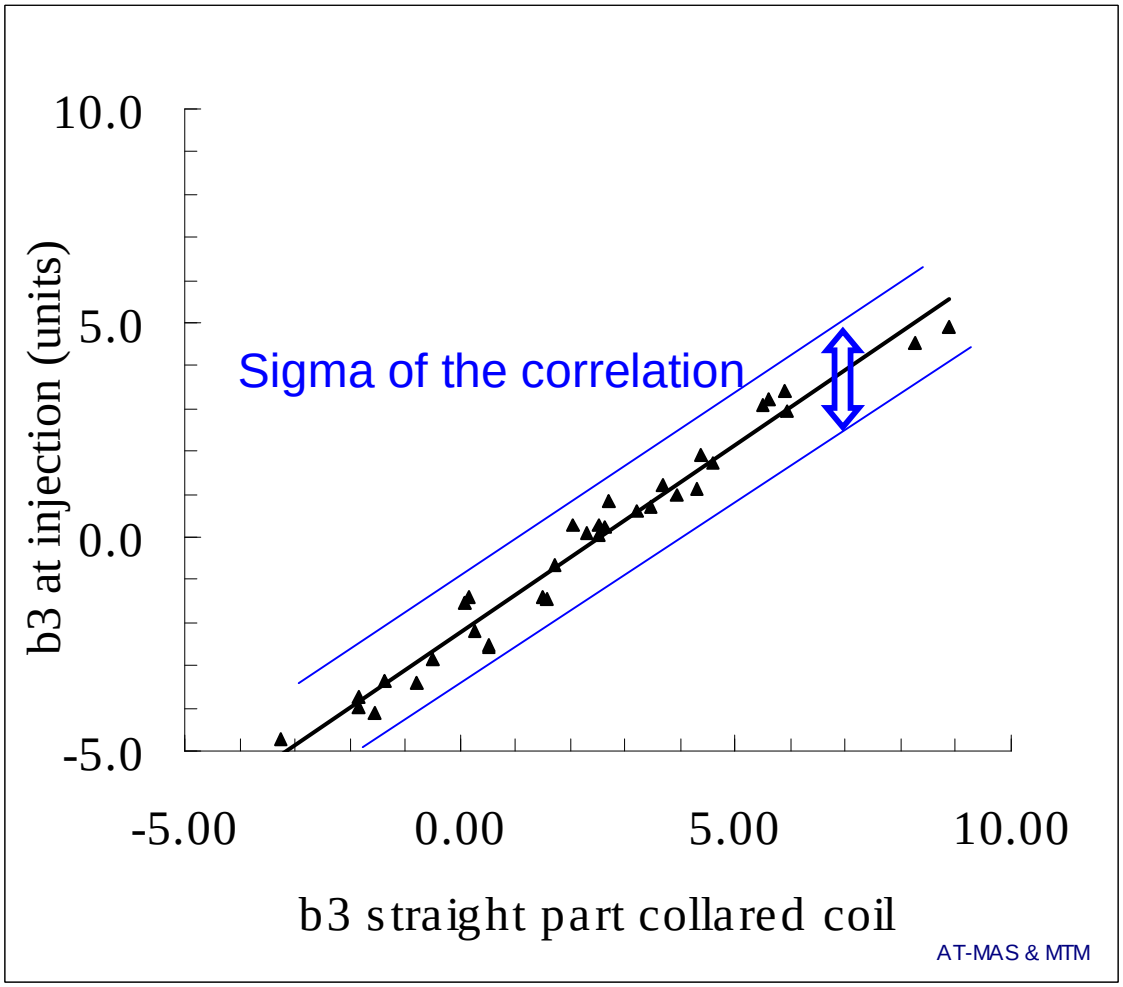
Limits to field quality steering: production snapshot

- 81 collared coils, 43 cold masses, 22 (18) cryomagnets
  - 7 months is the now the minimum delay between collared coil and test at cold (obtained for 1014) [expected to reduce to 2-3 months]



Limits to FQ steering: correlations (based on 17 dipoles)

- How good correlations are ? [see Sanfilippo talk]



Limits to FQ steering: correlations (based on 17 dipoles)

- How good correlations are ? (referred to beam dynamics)
  - In general they are very good (yoking, persistent currents, saturation, Lorentz forces are well under control)
  - a_4 at injection is bad, some concern for b_5, a_2, and others

	sigma correlations to high field	sigma correlations to injection	Half allowed range (beam dyn.)
Mag. Len.	4.2	4.0	15.0
C1/I	3.4	4.1	15.0
Bdl	5.1	5.4	24.0
b2	0.37	0.23	1.00
a2	0.29	0.46	1.10
b3	0.25	0.47	3.50
a3	0.09	0.07	1.70
b4	0.06	0.07	0.36
a4	0.06	0.16	0.15
b5	0.12	0.14	0.34
a5	0.02	0.02	0.47
b7	0.02	0.03	0.23

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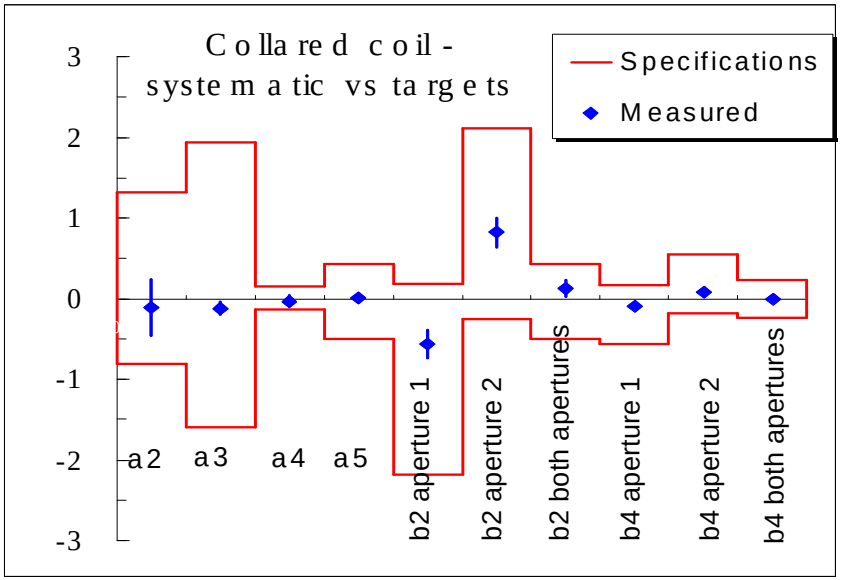
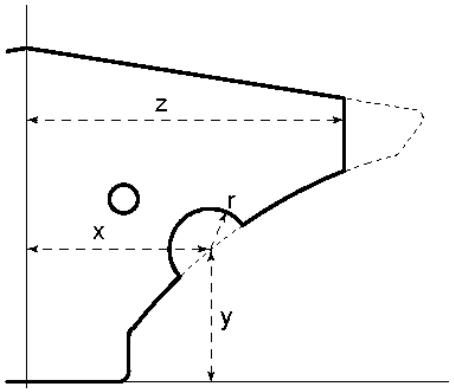
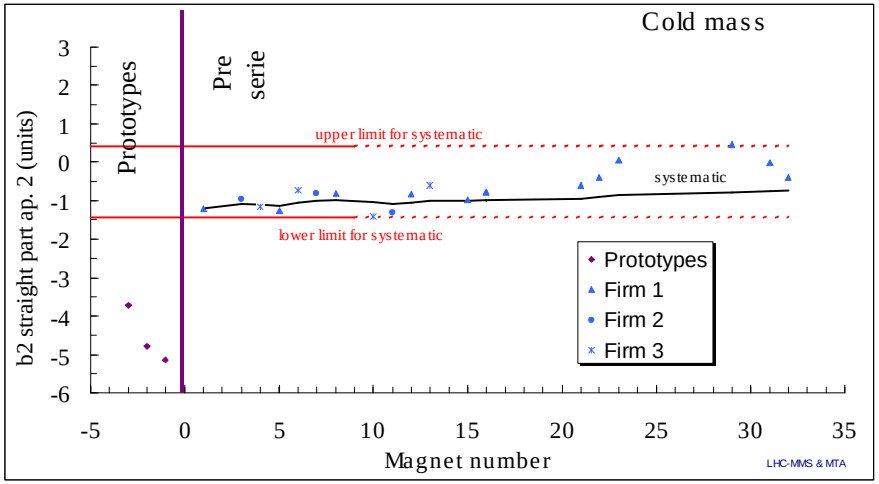
Field quality status: non-allowed systematics

- Everything is ok
  - two sigma error bars (on the average) are shown
  - a_4 is tight
  - Corrective action based on insert reshaping to minimize b_2 and b_4 in pre-series has been effective [S. Redaelli et al, LHC-Project-Report **467,** EPAC 2002]

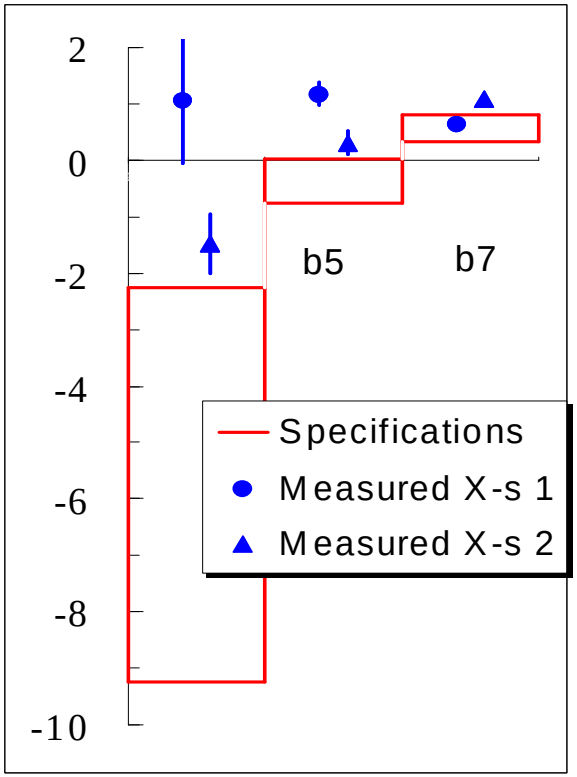






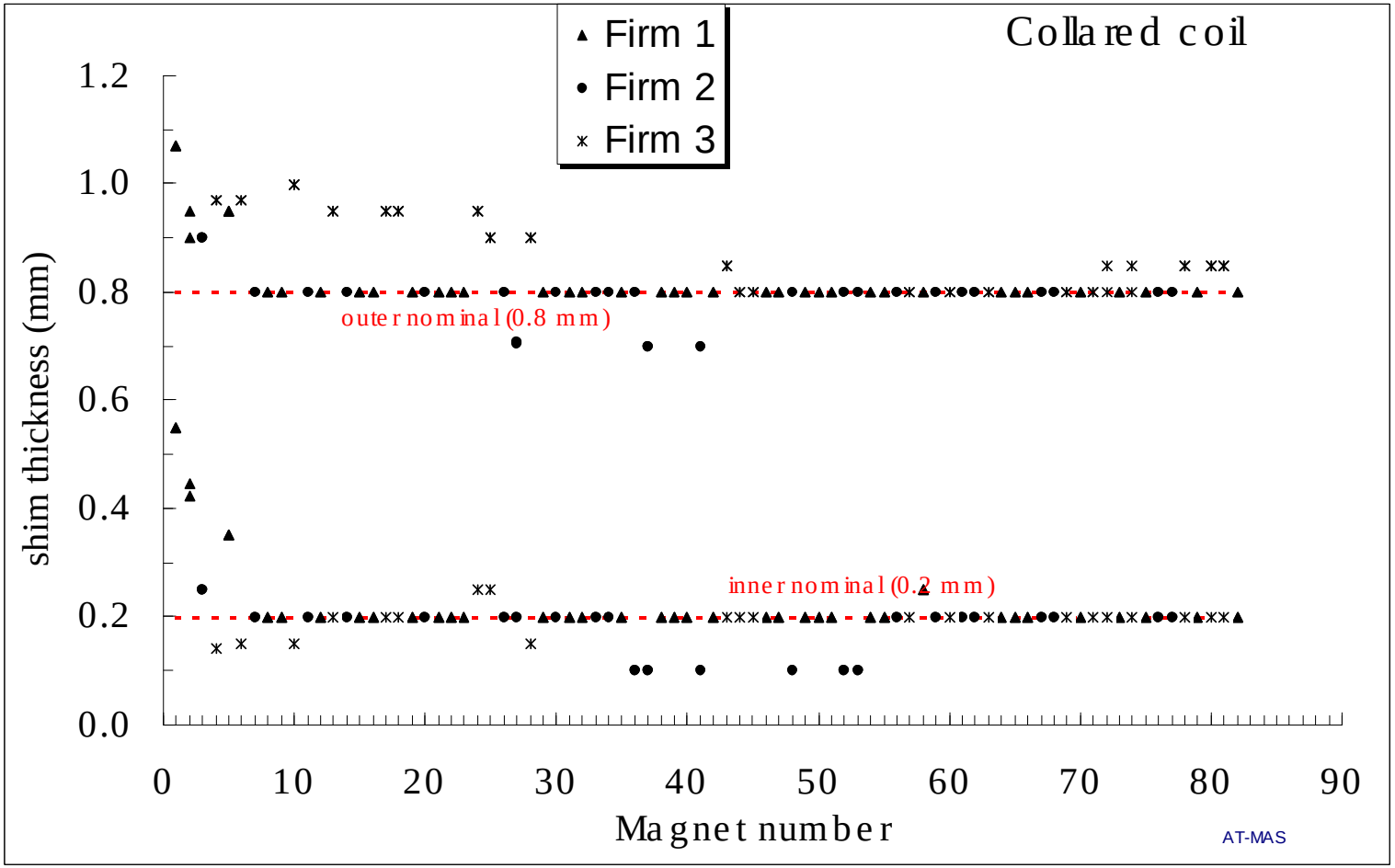
Field quality status: allowed systematics

- X-section 1: b_3 and b_5 were out of target of 3 and 1 units
  - Correction of the internal copper wedges after 9 collared coils
- Relevant improvements:
  - b_3 b_5 b_7 at less than 1 u from targets
  - b_3 within ultimate limit (4.35 u)
  - b_5 at injection much better
- LHC would work with these values
  - with previous X-section severe limitations
- One could have minor limitations
  - b_5 at injection of 1.40 units
  - b_7 at injection of 0.33 units
  - Beam dynamics simulations are in progress (talk by S. Fartoukh)
- A drift could be very harmful (especially for b_3)

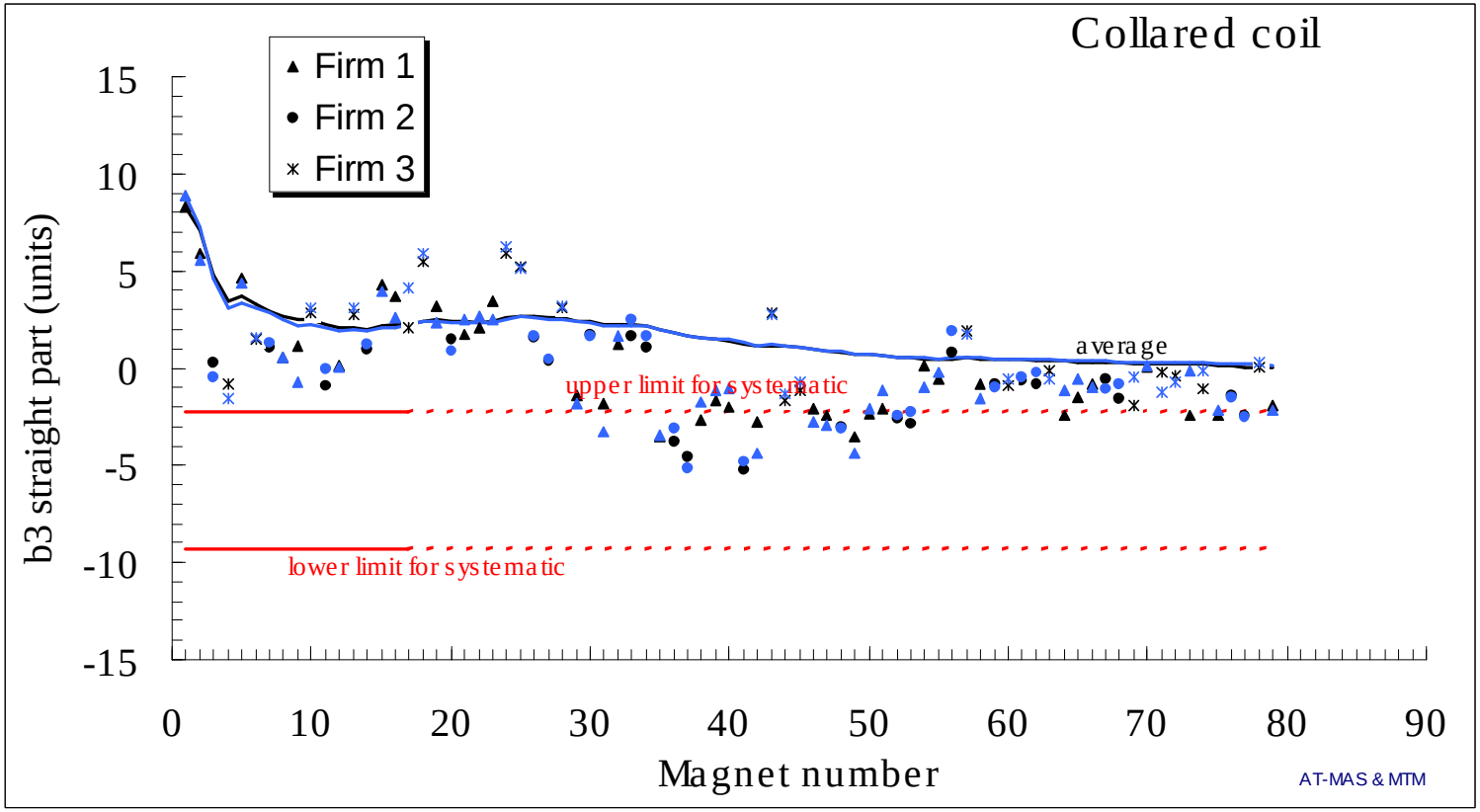


Polar Shims: nominal within 0.05 mm in the last 25 c.c.

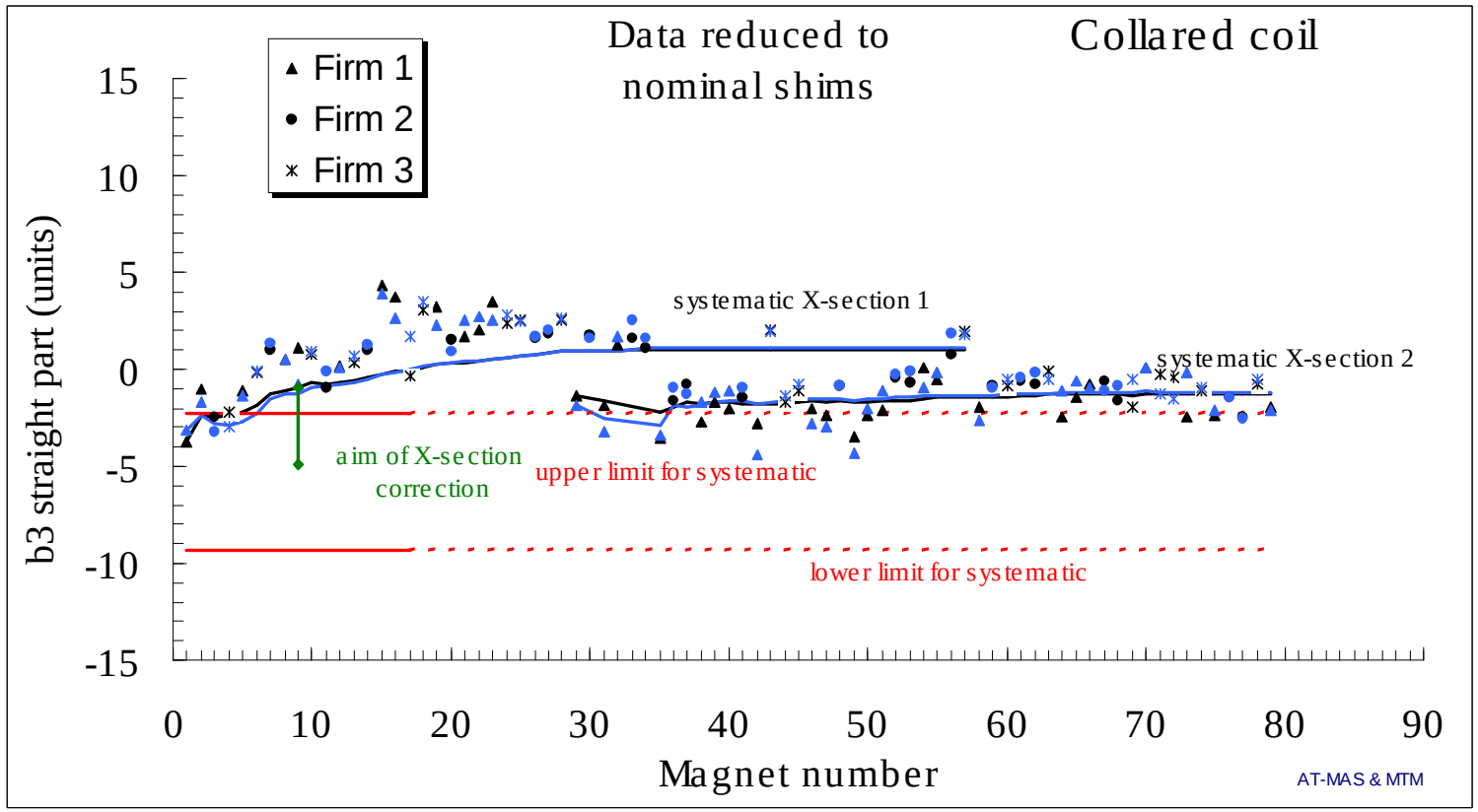
- Negligible effect on field quality



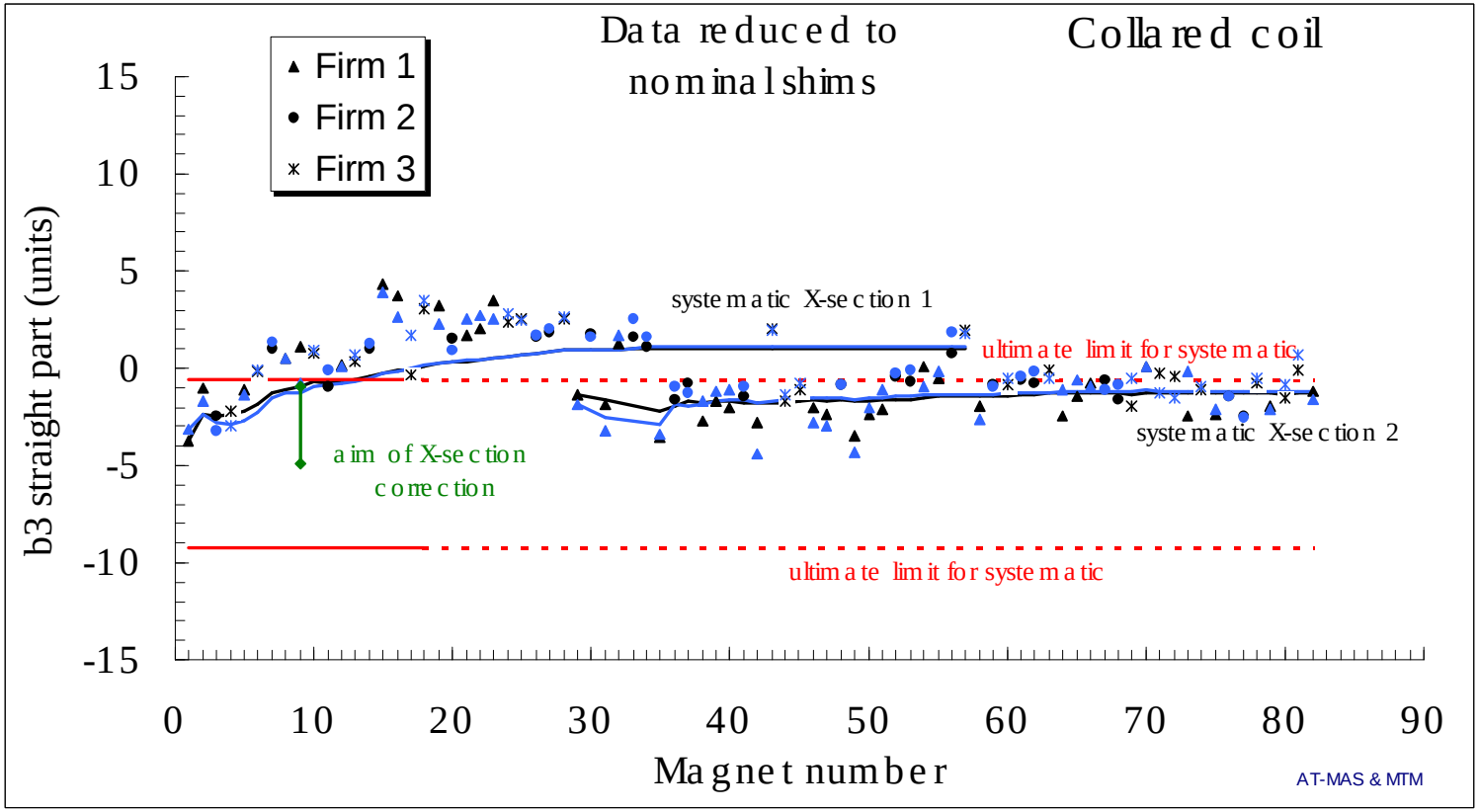
Systematic b_3 (raw data)



- Systematic b_3 is 1.0 unit larger than target range
  - Allowed range wide with respect to random part
  - Negligible differences between firms
  - X-section correction worked at 85% - a drift of around 3 units in part given by copper wedges dimensions [B. Bellesia et al, in press]

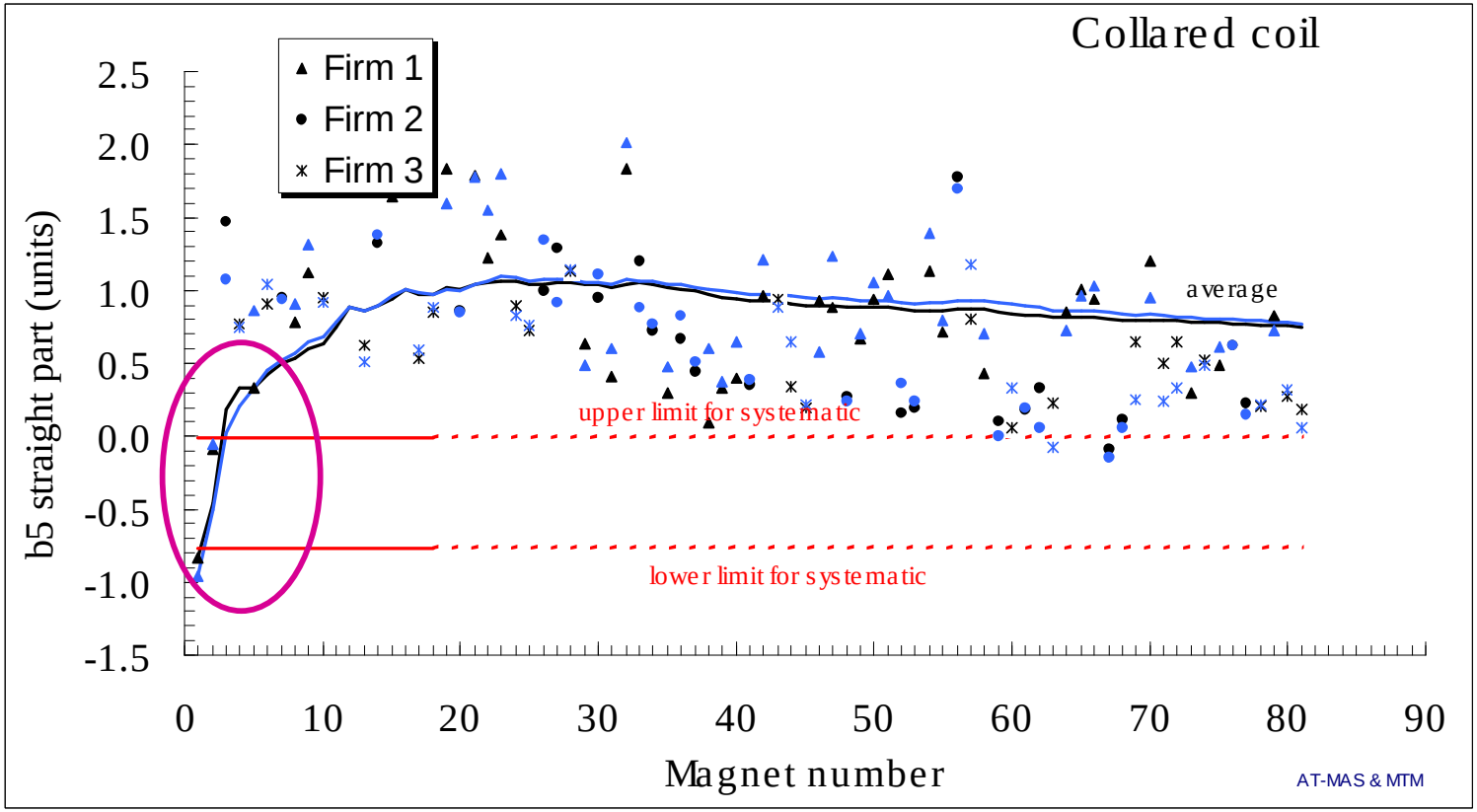


- Systematic b_3 is within ultimate limit
  - (should we trust Clint ?)

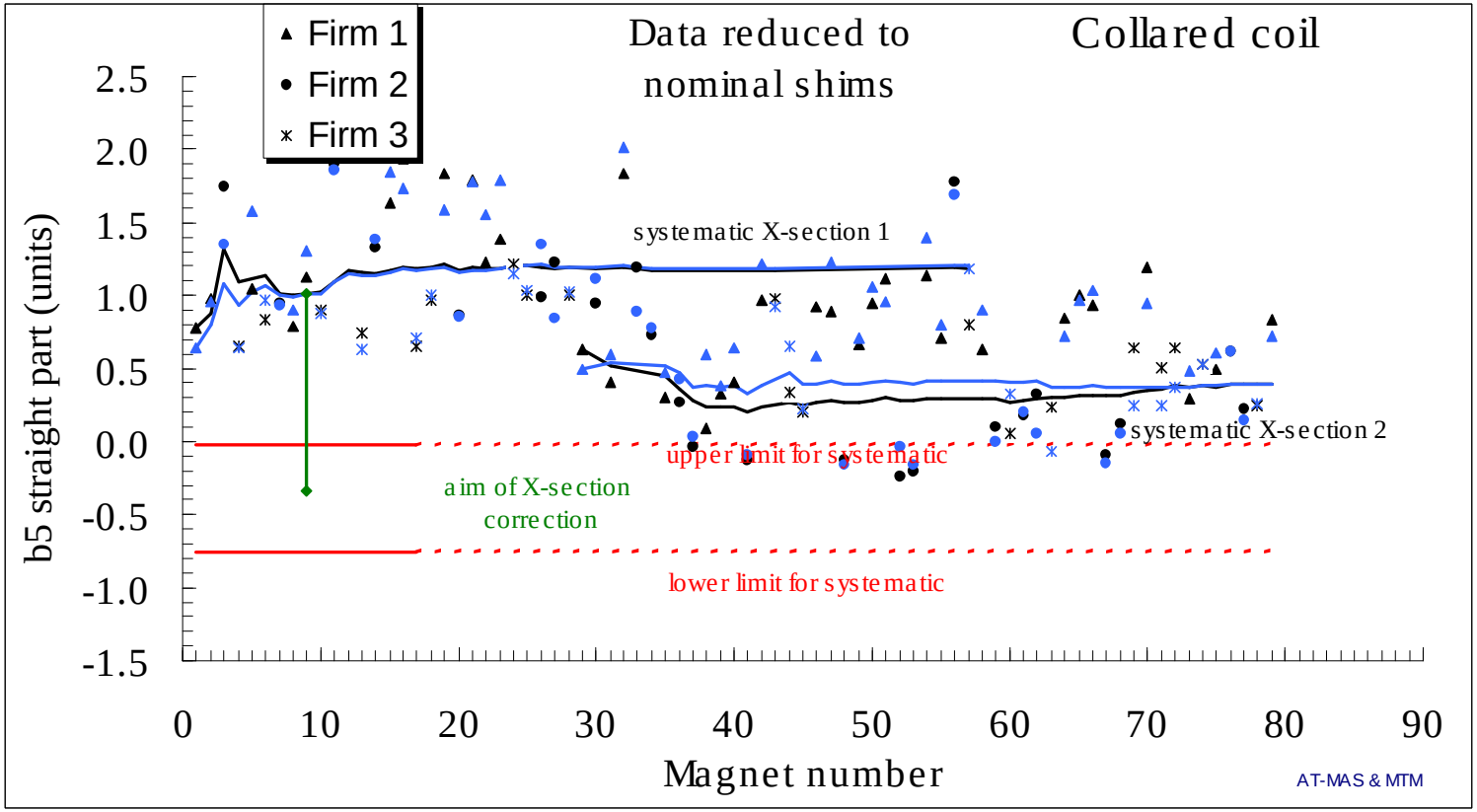


Systematic b_5 (raw data)

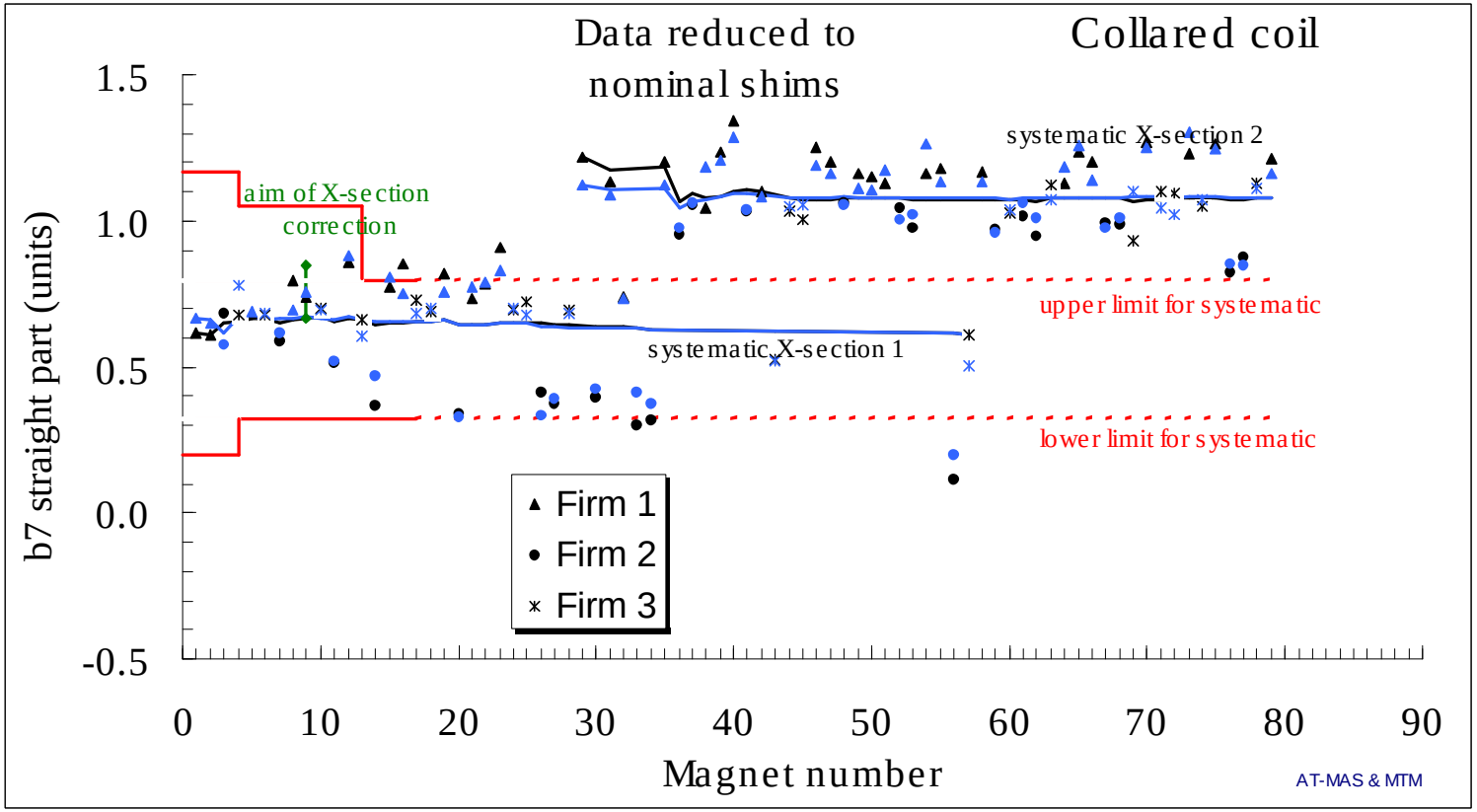
- The correction based on raw data would have been underestimated of 0.5 units (shim non-nominalities up to 0.3 mm in 1001-1003)



- Systematic b_5 is 0.40 units larger than target range
  - Narrow band (0.7 units) with respect to random (0.45 units)
  - Correction worked at 70% - Large differences between firms (1 u.)
  - Very sensitive on deformations – Worst agreement for sensitivities

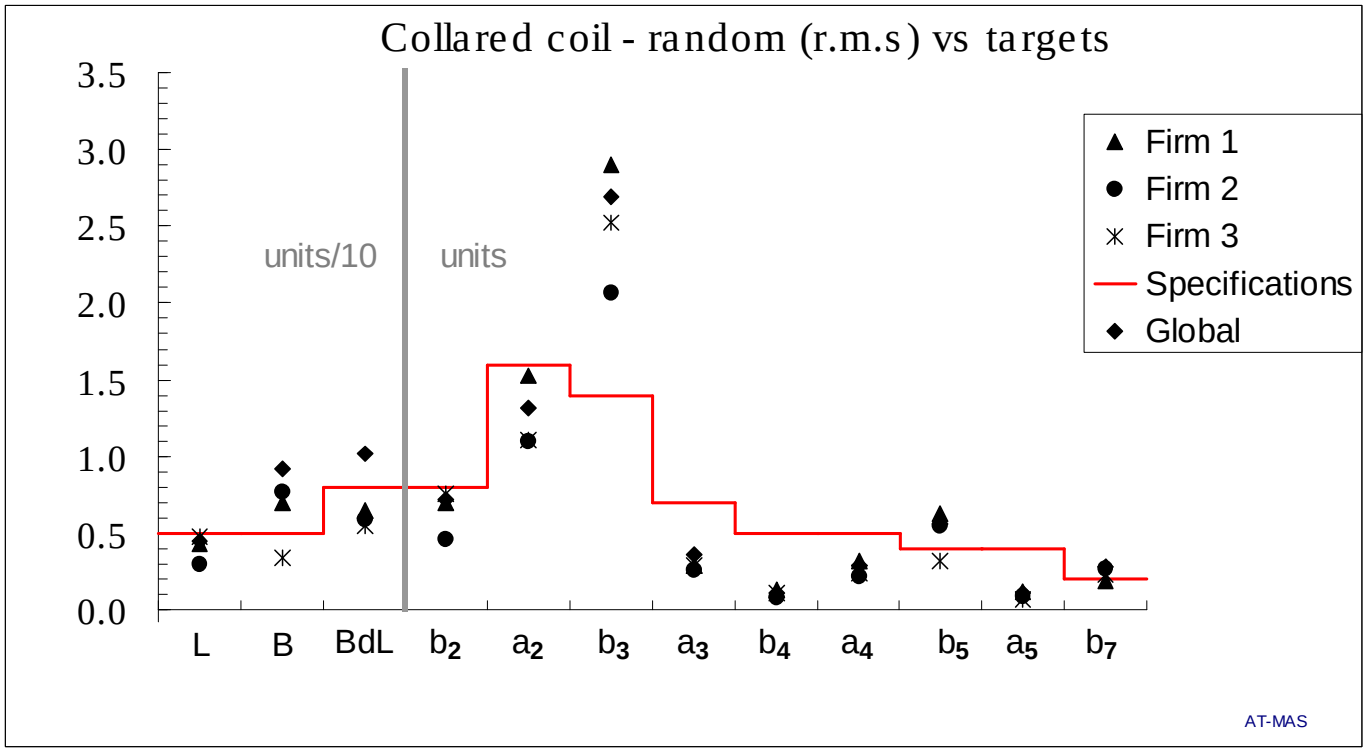


- Systematic b_7 is 0.28 units larger then target range
  - Large differences between firms reduced in the new X-section
  - Correction effect on cc: 0.47 instead of 0.18 - not explained
  - Negative drift in Firm 2 ? (as in X-section 1)



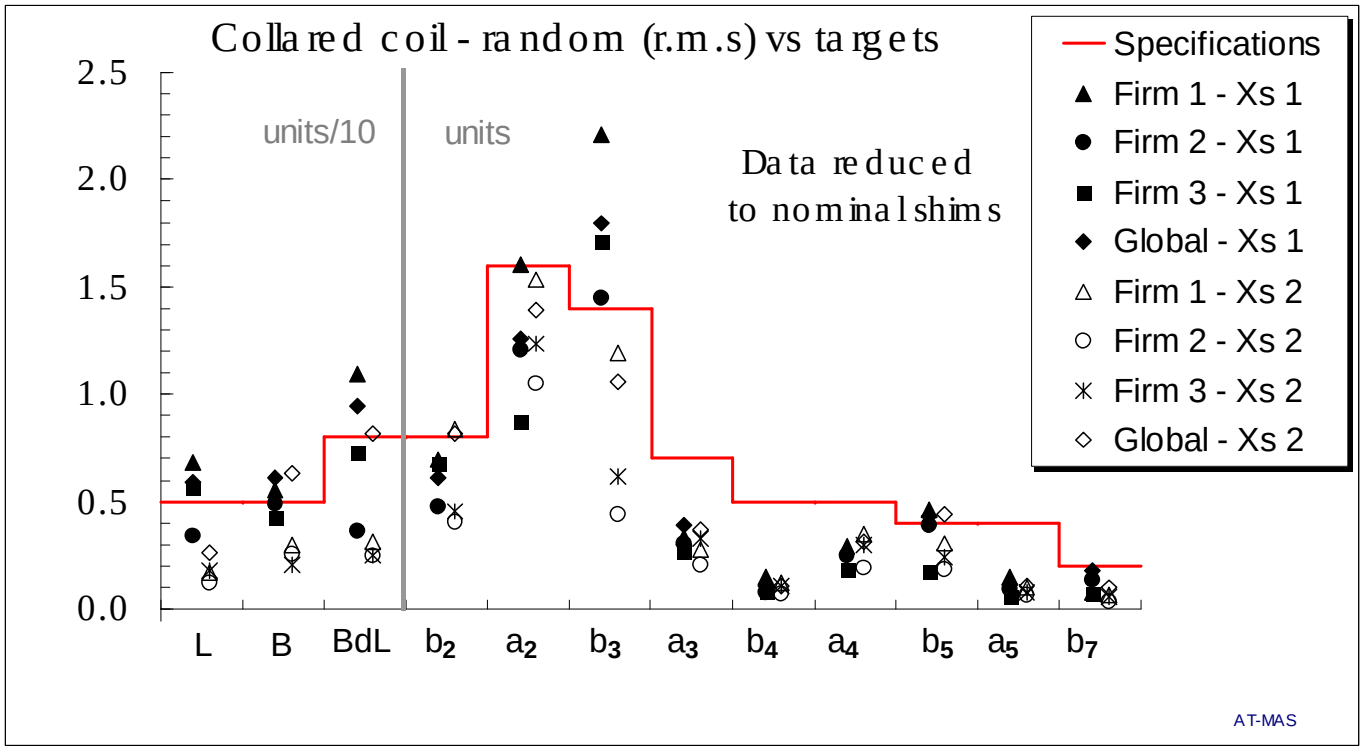
Field quality status: randoms

- Random b_3 (and b_5) out of target (non-nominal shims, X-section change)
  - This effect will be reduced (production now is more stable)



Field quality status: randoms per X-section

- The collared coil is the main source of randoms: all other effects (persistent, decay ...) are much smaller [L. Bottura talk]
  - Global random < spec – mixing firms in different arcs seems ok



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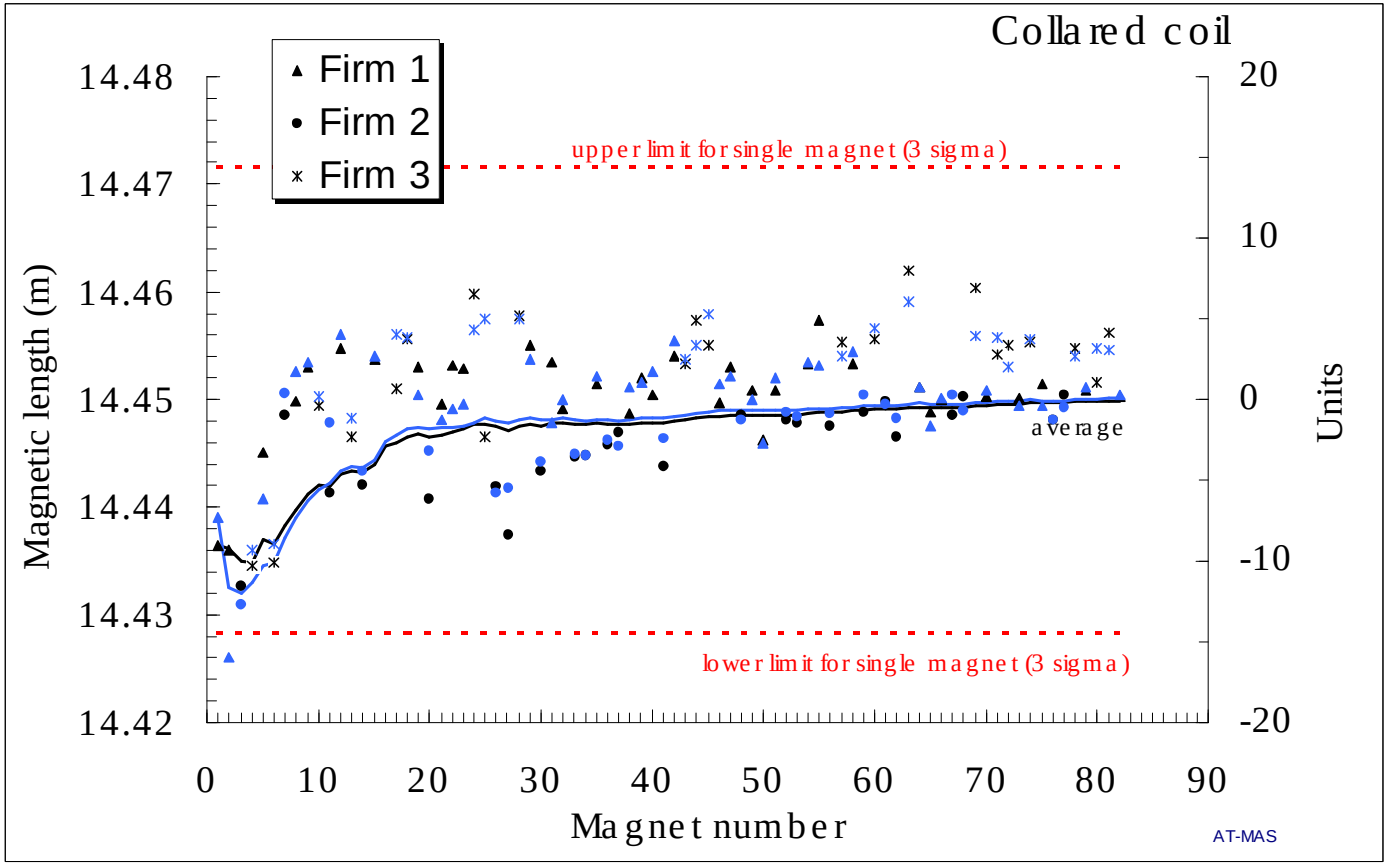
Corrective actions: integrated main field

- Steering of magnetic length
  - Magnetic length has a very low spread (3 units)
  - It can be used to steer BdL

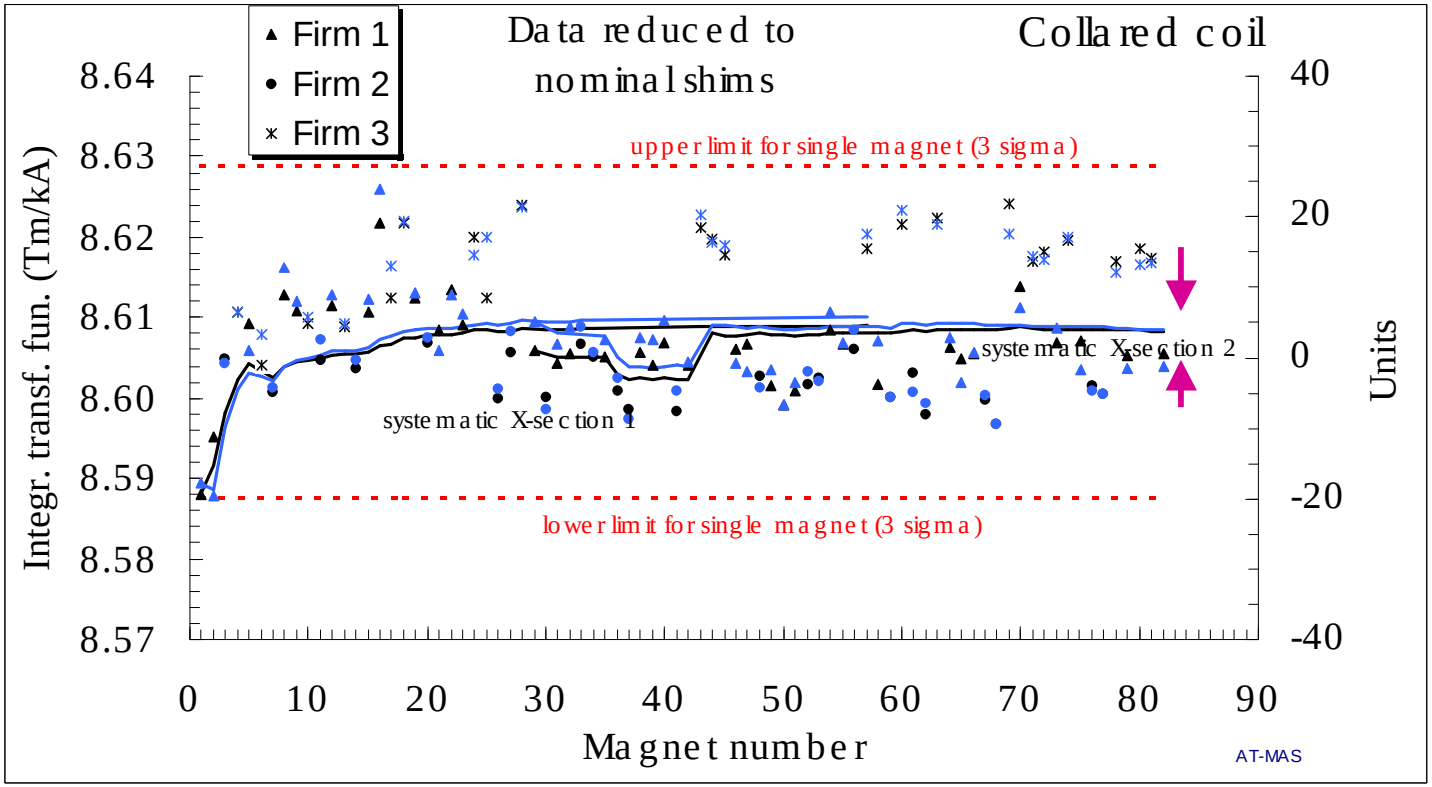


Corrective actions: integrated main field

- Addition of iron laminations
  - Foreseen in the specification
  - Add 100 mm max (to avoid ramp splice)
  - Take out 100 mm or more (... but expensive – nested laminations)
- Maximal effect
  - In prototype design: no nested laminations in the end, ±100 mm of laminations ⇒ ± 100*0.18 = ± 18 mm more in magnetic length (± 13 units)
  - With nested laminations (very effective b2 optimization in heads), substituting nested with iron increases field of 10% only, therefore ±100 mm of laminations ⇒ ±100*0.10 = ±10 mm more in magnetic length (±7 units)
  - We have now a very limited effect (14 units can be recovered at maximum)

Corrective actions: integrated main field

- Now: 17 units difference between Firm 3 and Firm1-2
  - Origin of the difference under analysis
  - Correction with magnetic length: 50 mm more in Firm 1-2, 100 mm less in Firm 3 (10 units recoverable, almost cost neutral)



Corrective actions: odd normal multipoles

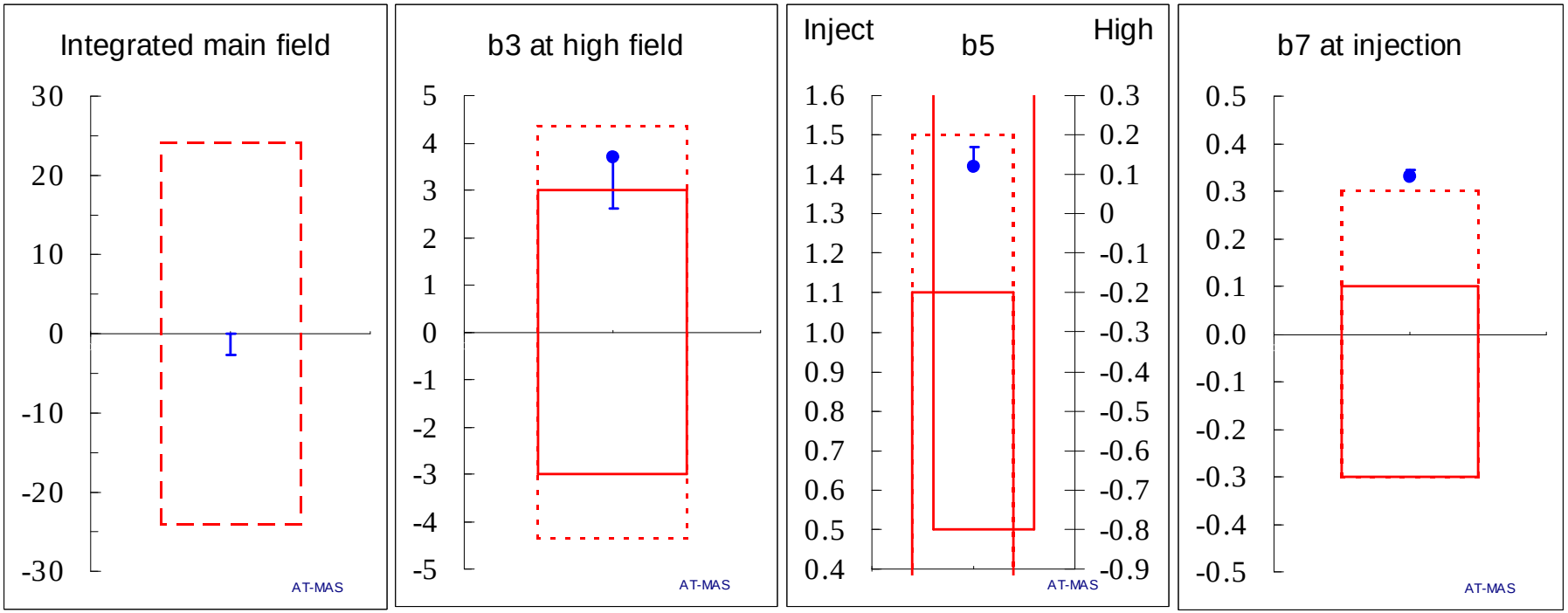
- Present situation
  - b_3 of 3.8 units at high field (optimal* 3 units, mortal 4.35 units, lower limit –3 units): around –2 unit needed
  - b_5 of 1.40 units at injection (optimal* 0.5 units): around –0.9 units needed
  - b_7 of 0.33 units at injection (optimal* 0.0 units, bad at 0.4-0.5 units): -0.33 units needed

*S. Fartoukh, priv. commun., 20.03.2003

- First handle: polar shims
  - The spec. on prestress (±15 MPa) allows to change shims of ±0.12 mm, if coil size is under control
  - Shims are quantized in 0.05 mm, in the spec we have ±0.10 mm
  - One could push up to 0.15 mm (±18 MPa, considered not critical)
  - Problem: if coil size is not measured any more ....
  - Very fast action

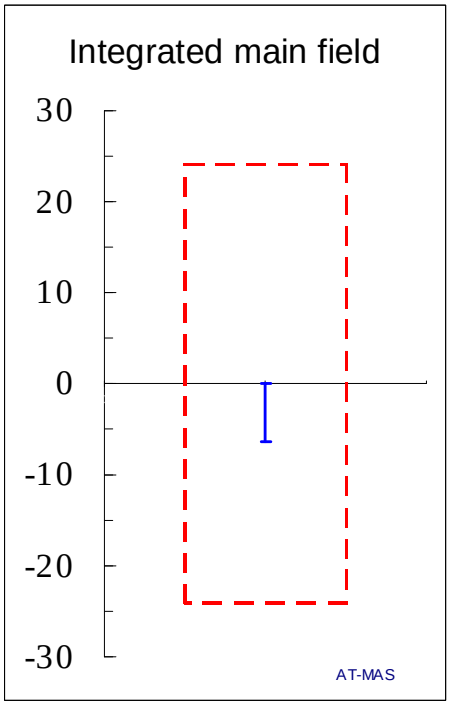
Corrective actions: odd normal multipoles

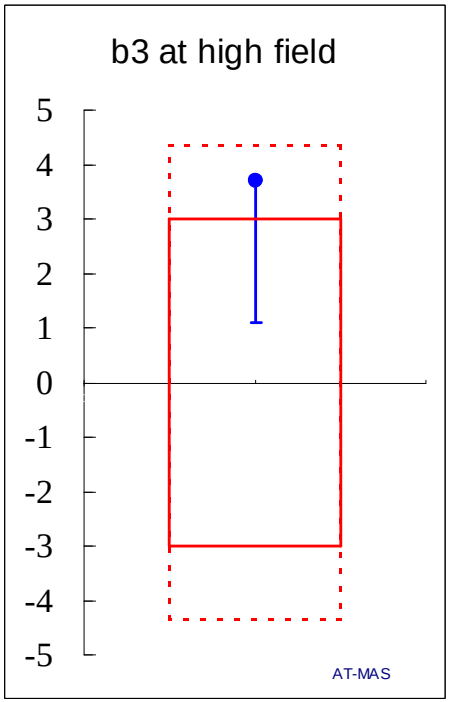
- Solution 1: 0.1 mm change of outer polar shim to steer b_3
  - Some influence on Δb_3=–1.2 units (enough ?)
  - Negligible influence on b_5 and b_7 (less than 0.1 units)
  - Negligible influence on main field (-3 units)

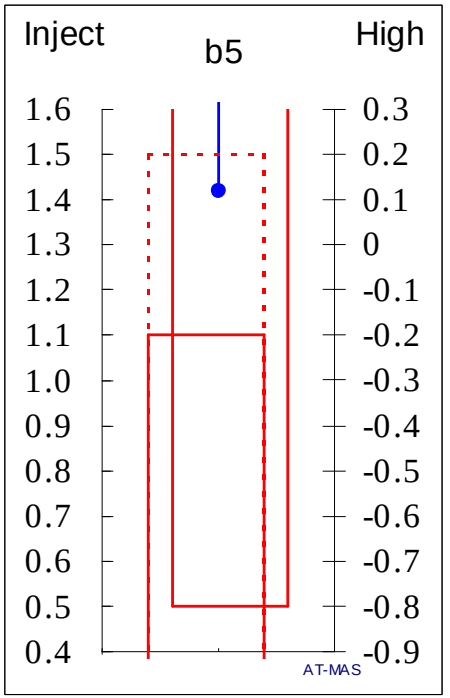


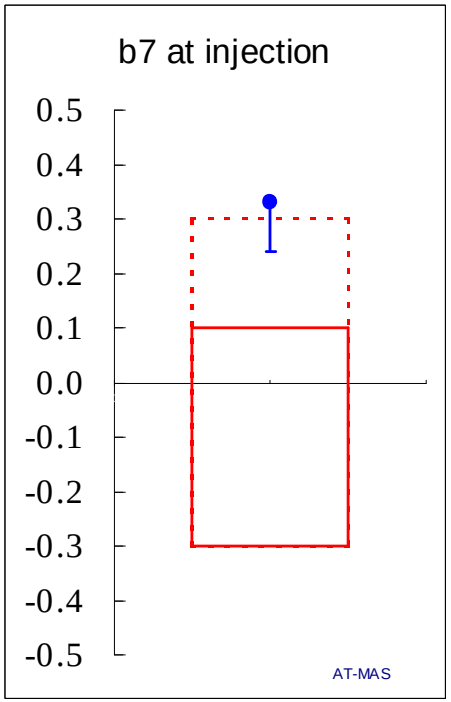
Corrective actions: odd normal multipoles

- Solution 2: change of both polar shims to steer b_3
  - A change of –0.1 mm in inner and outer polar shims: larger effect on b_3 –2.6 units (probably enough to steer b_3 along production)
  - Influence on b_5: +0.3 units (bad, wrong direction)
  - Some influence on main field (6.5 units)



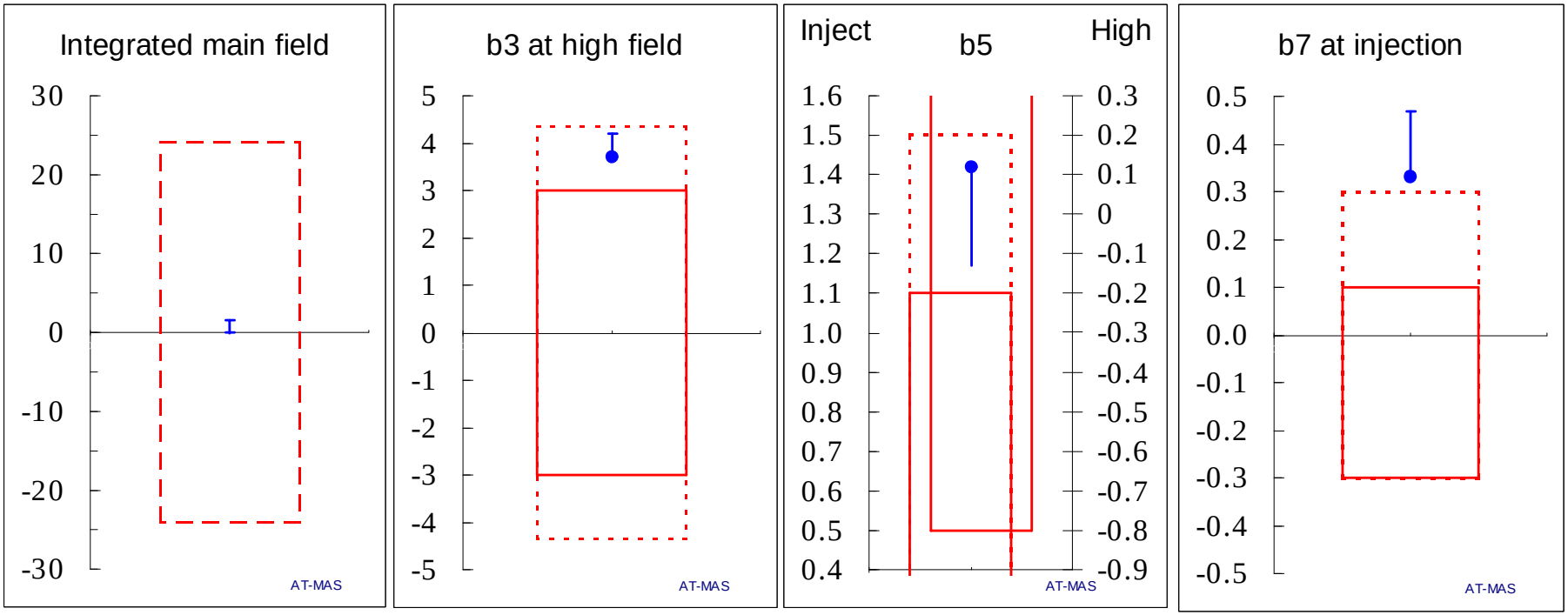






Corrective actions: odd normal multipoles

- Solution 3: change of both polar shims to steer b_5
  - A change of +0.1 mm in inner and -0.1 mm in outer polar shims:
  - Influence on b_5: -0.25 units (not so large)
  - Negligible influence on main field (1.5 units)
  - Negligible influence on b_3 (0.5 unit), some on b_7 (0.15 unit)



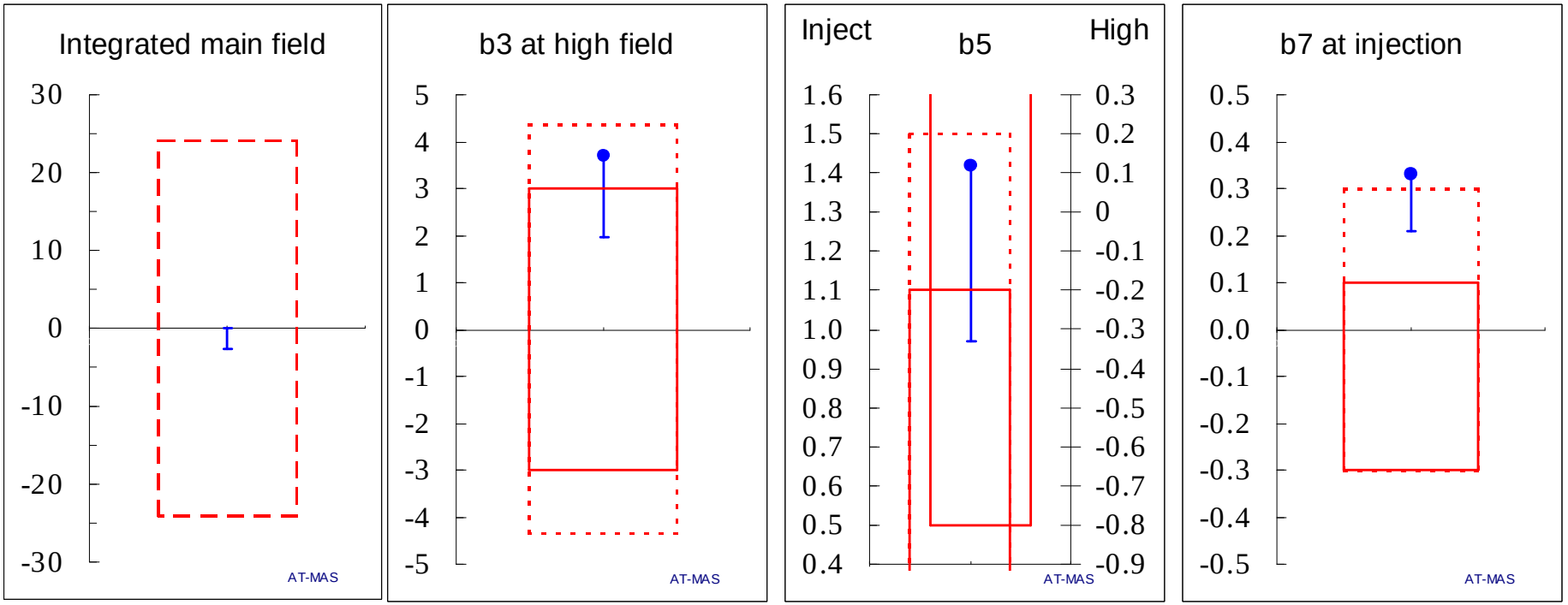
Corrective actions: odd normal multipoles

- Second handle: midplane insulation (and polar shims)
  - In ¼ of aperture, on the midplane we have
    - 0.125 mm U-shaped insulation in the midplane on both layers
    - 0.025 mm sticky apical U-shaped insulation on the outer layer
  - One can only increase this electrical protection
  - This increase pushes down b_3, b_5 and b_7
  - This action involves a substitution of material in the baseline
  - Simplest action: change the U in both layers
  - Quantization: 0.025 mm per ¼ of aperture (to be verified)
  - One can compensate with a reduction of polar shims
  - Strong impact on multipoles
    - Positive: small changes needed
    - Negative: more sensitive to dimensions of components

Corrective actions: odd normal multipoles

- Solution 4: 0.10 mm more in midplane (inner&outer layer)
  - Small pre-stress variation of 6 MPa (±15 MPa is the specification)
  - Δb_3=–1.8 units – this bring b_3 at around 2 units at high field
  - Δb_5=–0.45 units
  - Δb_7=–0.12 units

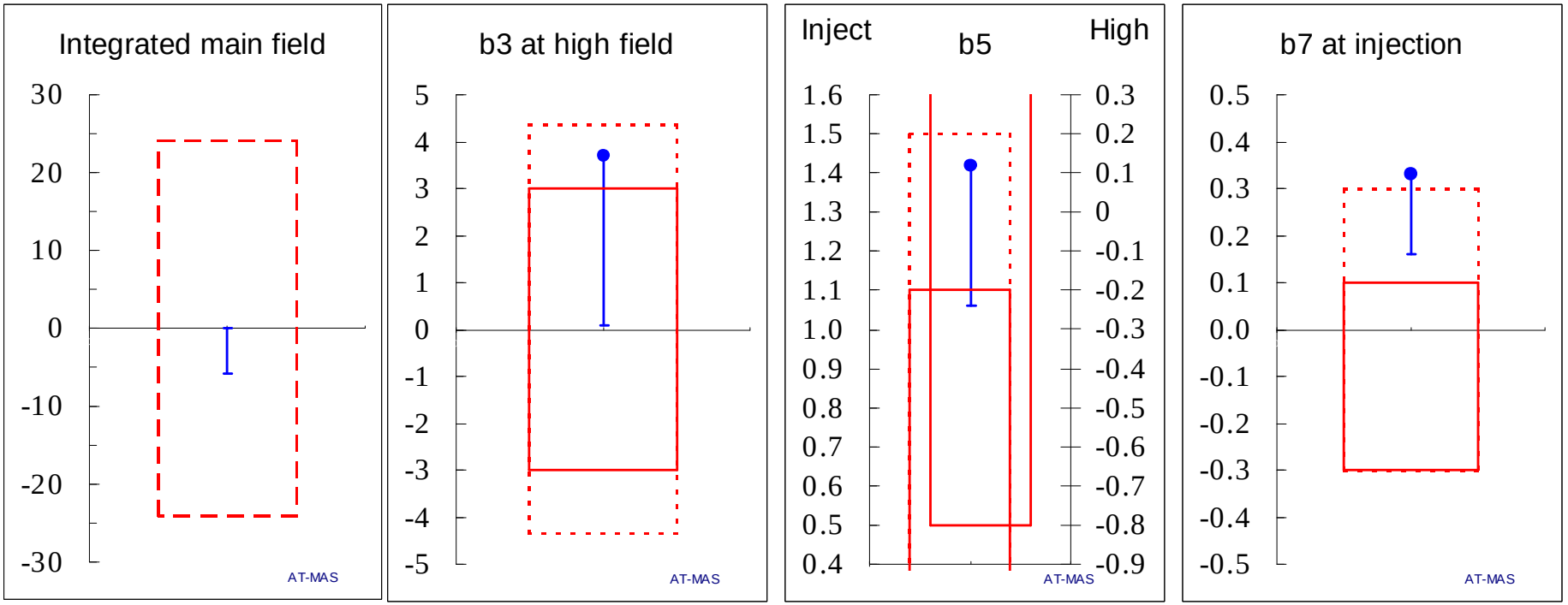
margin on b_3 and b_5, better b_7



Corrective actions: odd normal multipoles

- Solution 5: midplane 0.10 mm more, poles 0.05 mm less
  - Same pre-stress – Some variation of BdL (6 units)
  - Δb_3=–3.6 units – this bring b_3 at around 0 units at high field
  - Δb_5=–0.36 units – at the limit at injection
  - Δb_7=–0.17 units

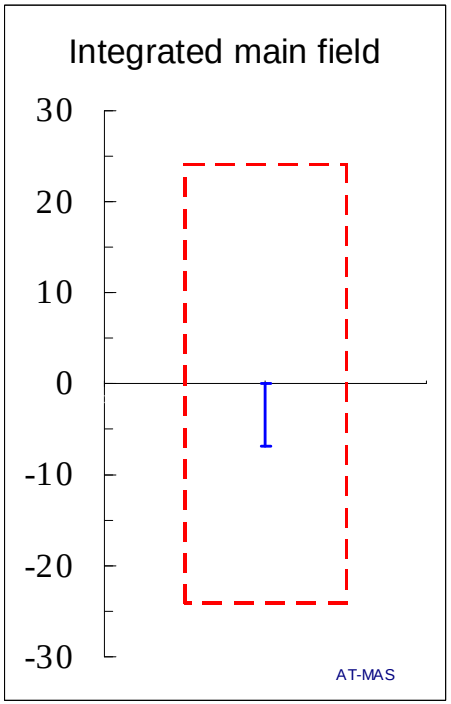
very safe on b_3, better b_7, hang on b_5

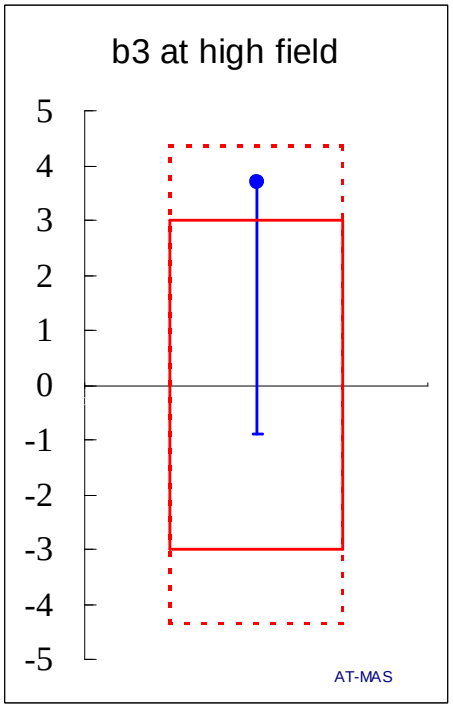


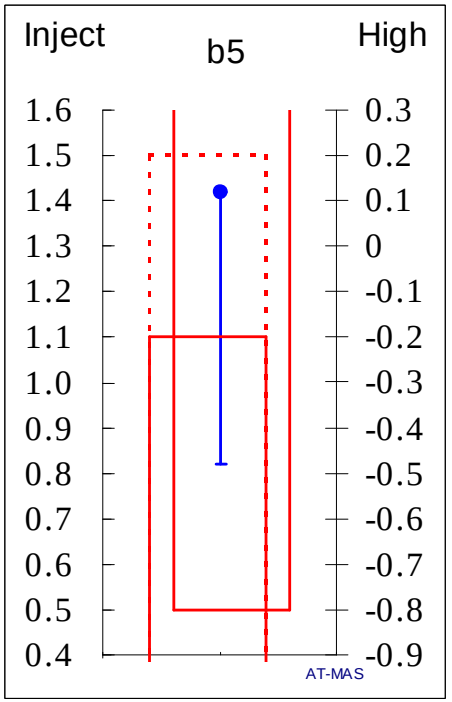
Corrective actions: odd normal multipoles

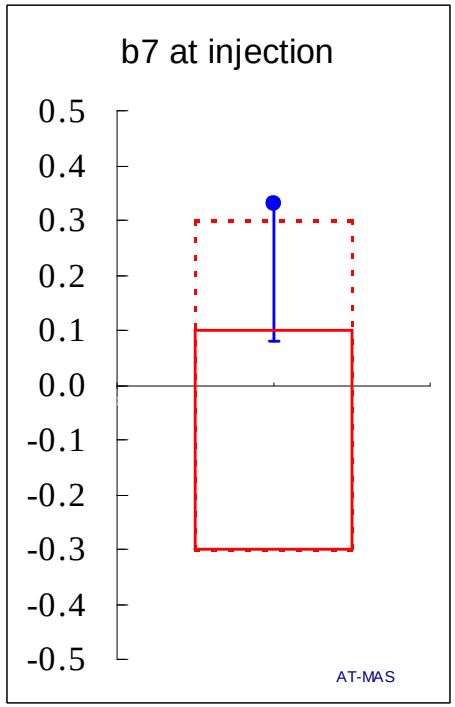
- Solution 6: midplane 0.15 mm more, poles 0.05 mm less
  - Negligible pre-stress variation (3 MPa) – some effect on BdL
  - Δb_3=–4.6 units
  - Δb_5=–0.60 units
  - Δb_7=–0.25 units

everything within our draconian targets









Corrective actions: odd normal multipoles

- Third handle: copper wedges
  - Same collar shape
  - Same midplane insulation
  - Work in progress (C. Vollinger)

Conclusions

- Beam dynamics specifications are very tight for a_4, b_5
- Limits to field quality steering towards beam dyn. limits
  - Model: corrective actions expected to work within ±20%
  - Correlations: bad for a_4, fair for magnetic lenght, a_2, b_5
- Present status
  - (Randoms), systematics skew and even normal within specs
  - Systematics odd normal may need actions with present specs
  - Mixing seems possible and is now the baseline
- Corrective actions
  - BdL: use laminations
  - Odd multipoles: polar shims or midplane insulation

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too late ....

S. Francisco, January 2003