Status of field quality and first trends at 1.9 K

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and the AT-MTM measurement and analysis teams.

Workshop on Field Quality Steering

of the Dipole Production, 20-21 March 2003.

Overview

- *General considerations*
- *Field quality at operating conditions.*
  - *Main field (field integral,magnetic length, field direction).*
  - *Multipoles at injection and collision.*
- *Field component errors.*
  - *Geometric errors at 1.9 K and warm/cold correlations.*
  - *Effect of the Lorentz force*
  - *Iron saturation.*
  - *Magnetization effect, cable coupling currents, decay/snap-back.*
- *Conclusions and perspectives.*

Scope of the testing at cold.

General considerations.

- *To guarantee that specifications are met.*
- *To complete the production control and late feed-back on parameters that can only be measured cold.*
  - *cold geometry (deformations during cool-down and under e.m. loads).*
  - *Saturation effect.*
  - *SC cable effects*
- *To provide relevant installation data.*
  - *quadrupole center, dipole direction*
- *To produce database for LHC magnetic reference (interface to LHC control system).*

Field errors must be known at operation time
to insure that control systems is within its limits.

Beam dynamic specifications.

General considerations.

☐ *Beam dynamic specifications are given in terms of :*

- *systematic: average of the averages per arc.*
- *random : sigma of the multipoles per arc (1/8 of the machine)*
- *uncertainty : sigma of the average per arc.*

☐ *(Hard) specifications at injection and nominal field were defined in the LHC project note 501 (2001) by S.Fartoukh and O.Brüning.*

☐ *Expected multipoles coming from the different errors sources were presented in a table issue in 1999 by the Field Quality Working Group and updated in August 2001.*

In this contribution : Integrated (critical) multipoles at injection or collision are compared to lower and upper limits of the systematic (+1 and/or+3 σ bounds).

Magnets tested at cold.

General considerations.

☐ *24 pre-series cryo-dipoles measured at 1.9 K+1019 under cold test.*

- 14 Alstom (100X), 4 Ansaldo (200X), 5 Noell (300X).

- Dipoles 2002 and 3004 : no magnetic measurements.

☐ *Striking features of magnet geometry:*

- 22 magnets with X-section 1 (non corrected for b_3 and b_5).

- 3 magnets with X-section 2 (1003, 1014,1019).

- 8 magnets with non nominal shims.

- 18 magnets with the 3rd end generation (extra end-spacer with reduced thickness).

(contribution of S.Russenchuck, M.Modena)

☐ *Magnetic measurement at 1.9 K*

- without beam screen.

- calculated contribution used : Δb_3 =-0.424 u, Δb_5=0.386 u, Δb_7= -0.244 u)

(simulation by M.Aleksa)

Cables in the magnets.

General considerations.

- *Rutherford cables:multi-strand compacted, keystoned.*

- Inner layer : 28 strands (∅=1.065 mm, Lp=18 mm), filament ∅ 7 µm.

- Outer layer : 36 strands (∅ =0.825 mm, Lp=15 mm), filament ∅ 6 µm.

- Max strand hysteresis spec: 30 mT (inner layer), 26 mT (outer layer) ± 4.5 %.

- Minimum inter-strand resistance spec: 15 µΩ.

(contribution of A.Verweij)

- *Strand manufacturers (B,C,D,E,G,K)*

- 14 magnets with the combinations 01B-02B.

- 2001, 3009 : 2 types of outer layer cables.

(data from the LHC –cable data -base)

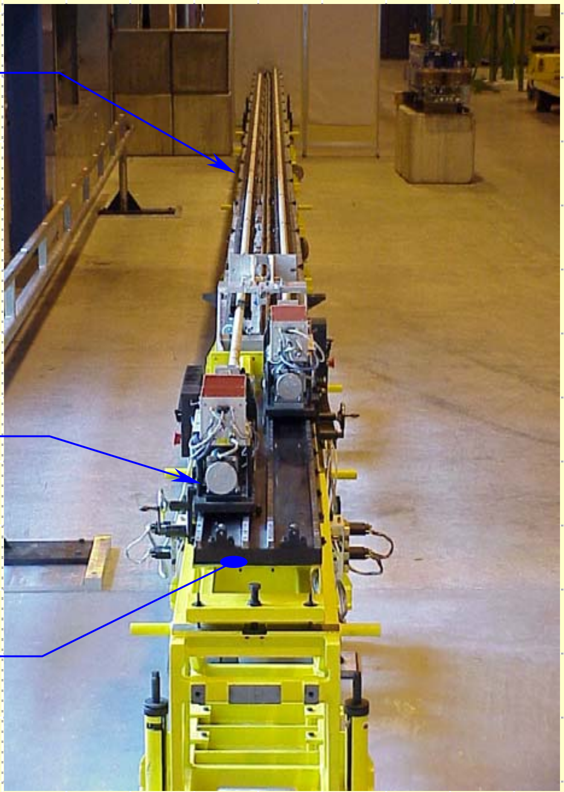
Equipment for measurements at cold (1).

General considerations.

15-m long twin rotating coils.

Twin coils

- *13 segments*
- *1.25 m module length*
- *16.25 m total length*



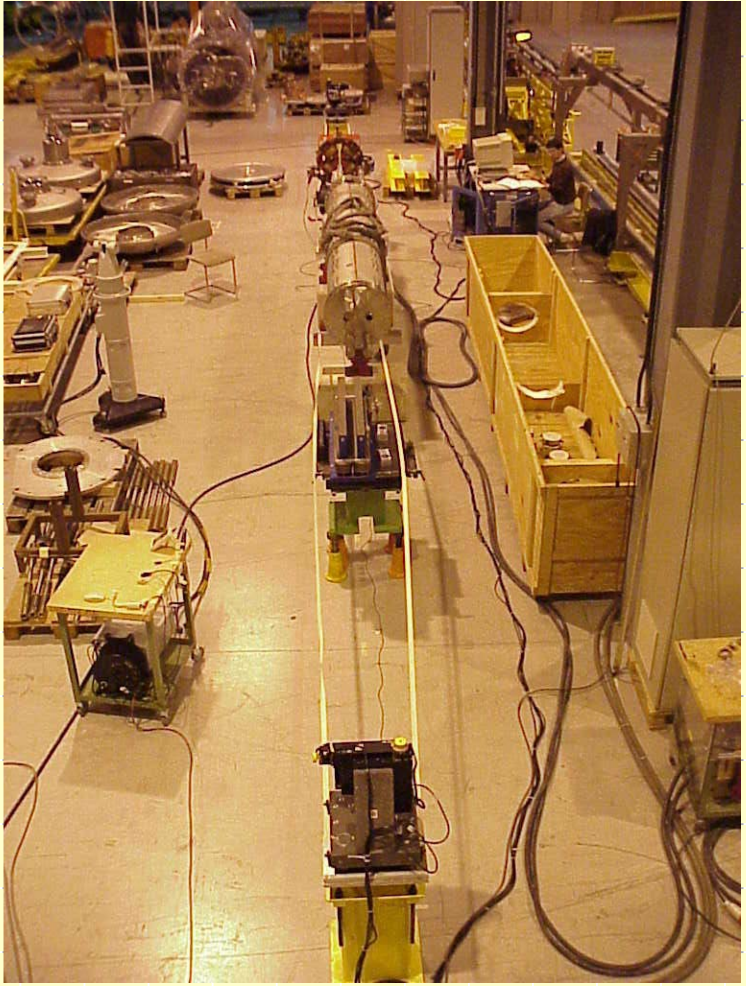
Stepping motor

Twin Rotating Unit

- *Highly efficient through simultaneous measurement of both apertures, full magnet length divided in 12 sectors.*
- *Accuracy:*
  - *- b1 ≈ 1×* 10^{-4} *(1 unit)*
  - *- harmonics ≈ 0.01-0.001 units @ 17 mm.*
- *Field angle: nominal accuracy ±0.2 mrad, however recently large uncertainty ±1 mrad due to mechanical calibration instability*

Equipment for measurements at cold (2).

General considerations.

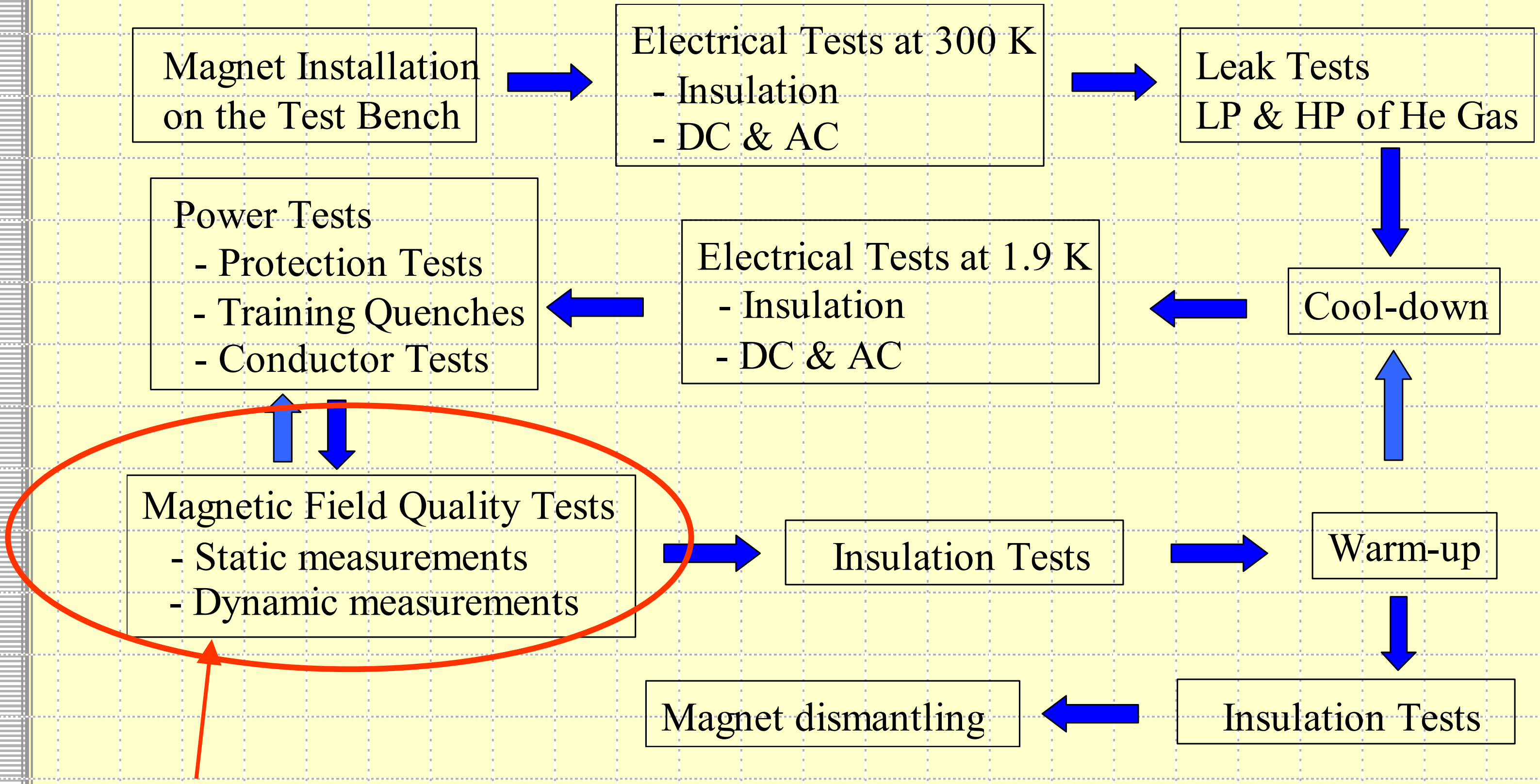


Single Stretched Wire system. (SSW).

- fully automatic system supplied by FERMILAB
- ∅0.1 mm tension-controlled single CuBe stretched-wire
- 2 × LEICA-referenced precision translation stages
- basic working mode used: DC flux sweeping in the vertical and horizontal directions → **integrated** field angle is computed from the ratio (no access to local values)
- Measurement precision ±0.2 mrad.

Magnetic measurements in the test flow diagram.

General considerations.



Magnet Installation
on the Test Bench

Electrical Tests at 300 K
- Insulation
- DC & AC

Leak Tests
LP & HP of He Gas

Cool-down

Electrical Tests at 1.9 K
- Insulation
- DC & AC

Power Tests
- Protection Tests
- Training Quenches
- Conductor Tests

Magnetic Field Quality Tests
- Static measurements
- Dynamic measurements

Insulation Tests

Warm-up

Insulation Tests

Magnet dismantling

- Combined with power tests.

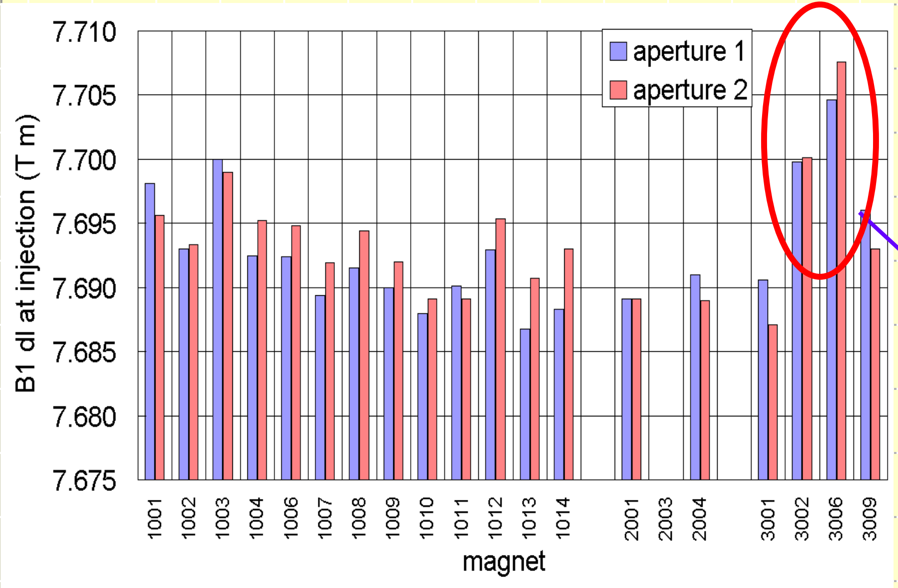
- Performed after the magnet is trained up to 9 T.

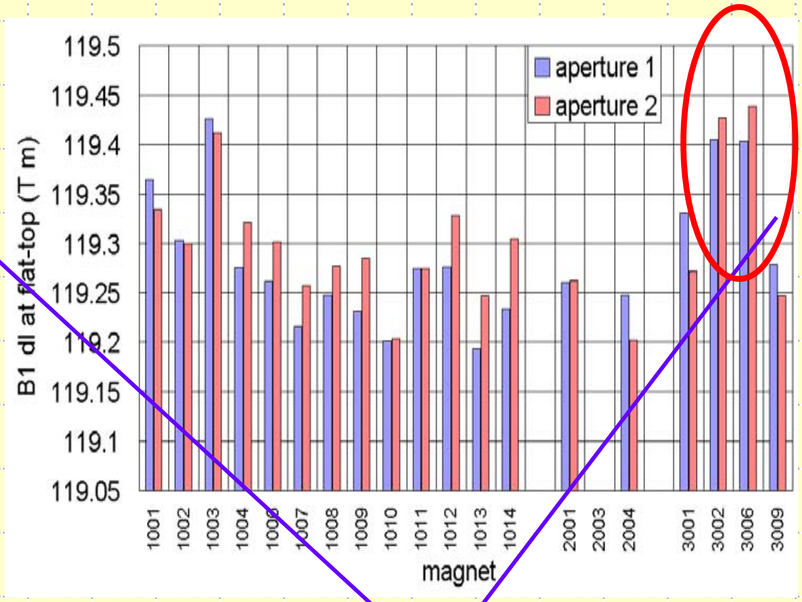
Status of the field quality at operating conditions .

Dipole integrated strength (B1 dl).

Field Quality at operating conditions.

		injection	*flat-top*
average	*(T m)*	*7.693*	*119.30*
sigma	*(units)*	*6.14*	*5.66*
Nom.val.	*(Tm)*	*7.655*	*119.08*



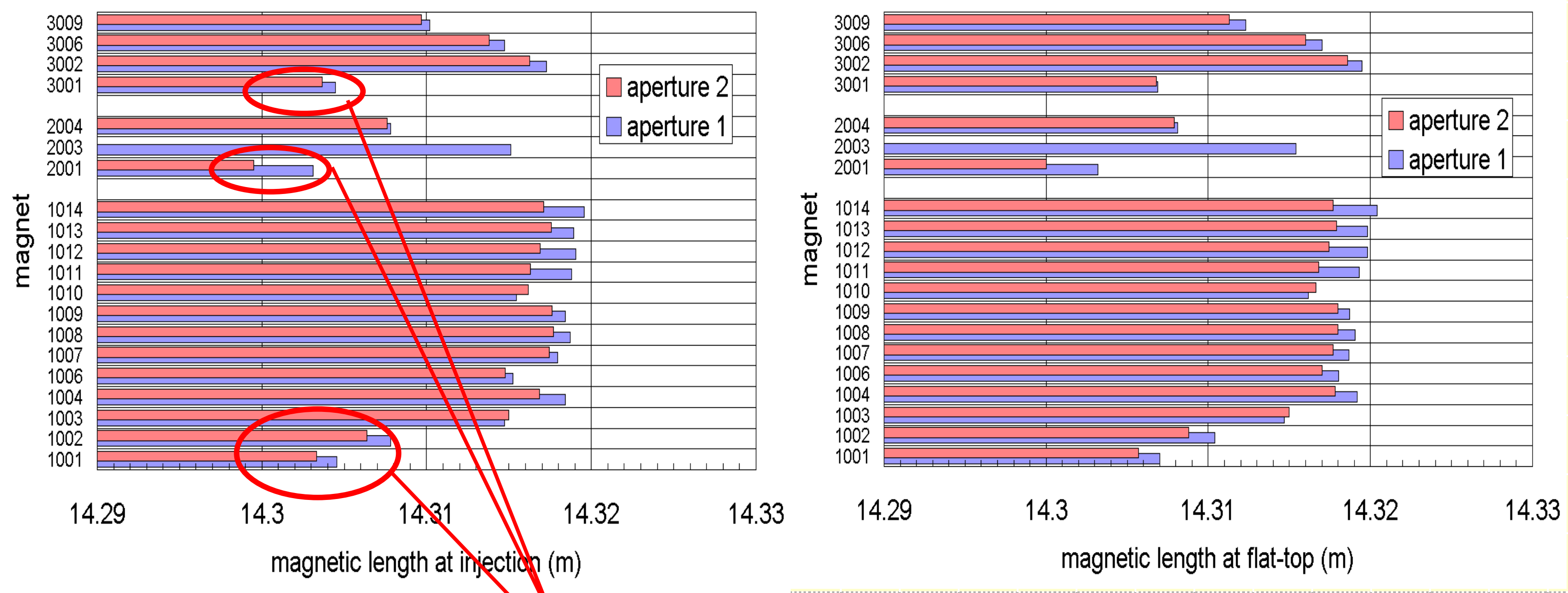


300X dipoles have Bdl above the average. → Sorting?

Magnetic length.

Field Quality at operating conditions.

		injection	*flat-top*
average	*(m)*	*14.314*	*14.315*
sigma	*(mm)*	*5.7*	*5.4*
Nom.Val	*(m)*	*14.300*	*14.300*



different spacers in the magnet ends

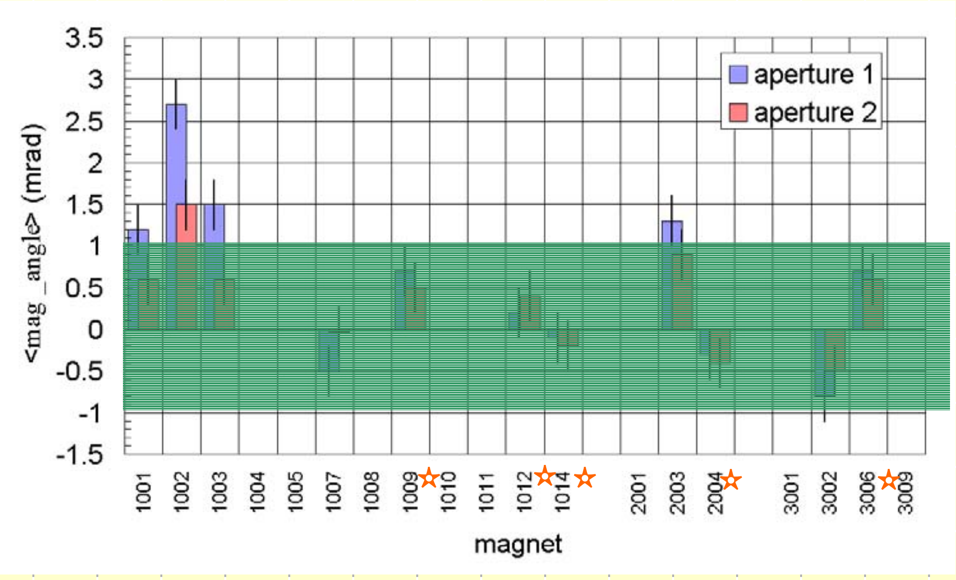
Dipole field direction.

Field Quality at operating conditions.

		flat-top
average	*(mrad)*	*0.5 ±1.0*
sigma	*(mrad)*	*0.8*
Tolerances	*(mrad)*	*±1*

estimate of measurement error with long shaft.

Mag_angle:field direction with respect to magnet mid-plane as used for the installation.

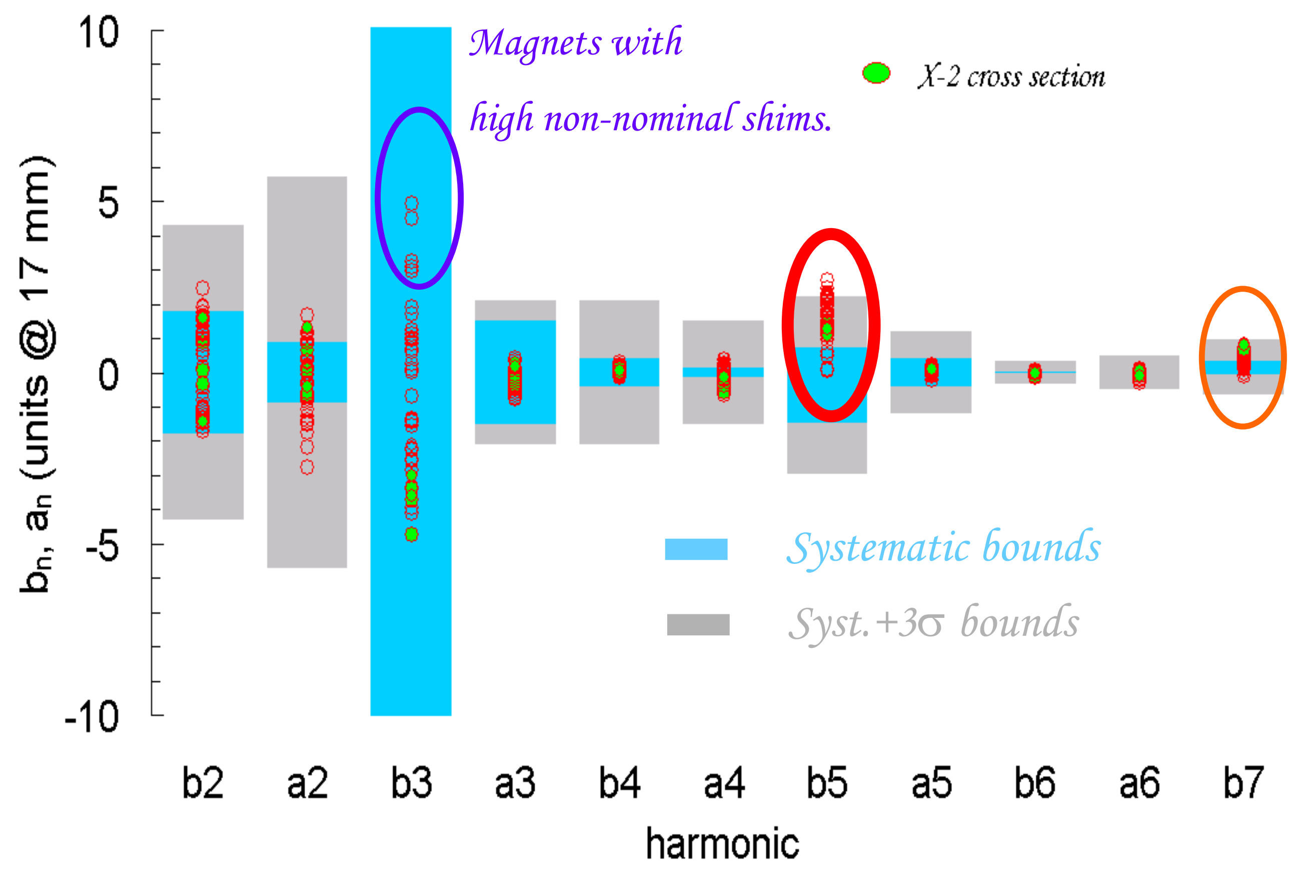


Tolerances

* *Measured with SSW*

Magnets measured with SSW are within the tolerances.

Field quality at injection.



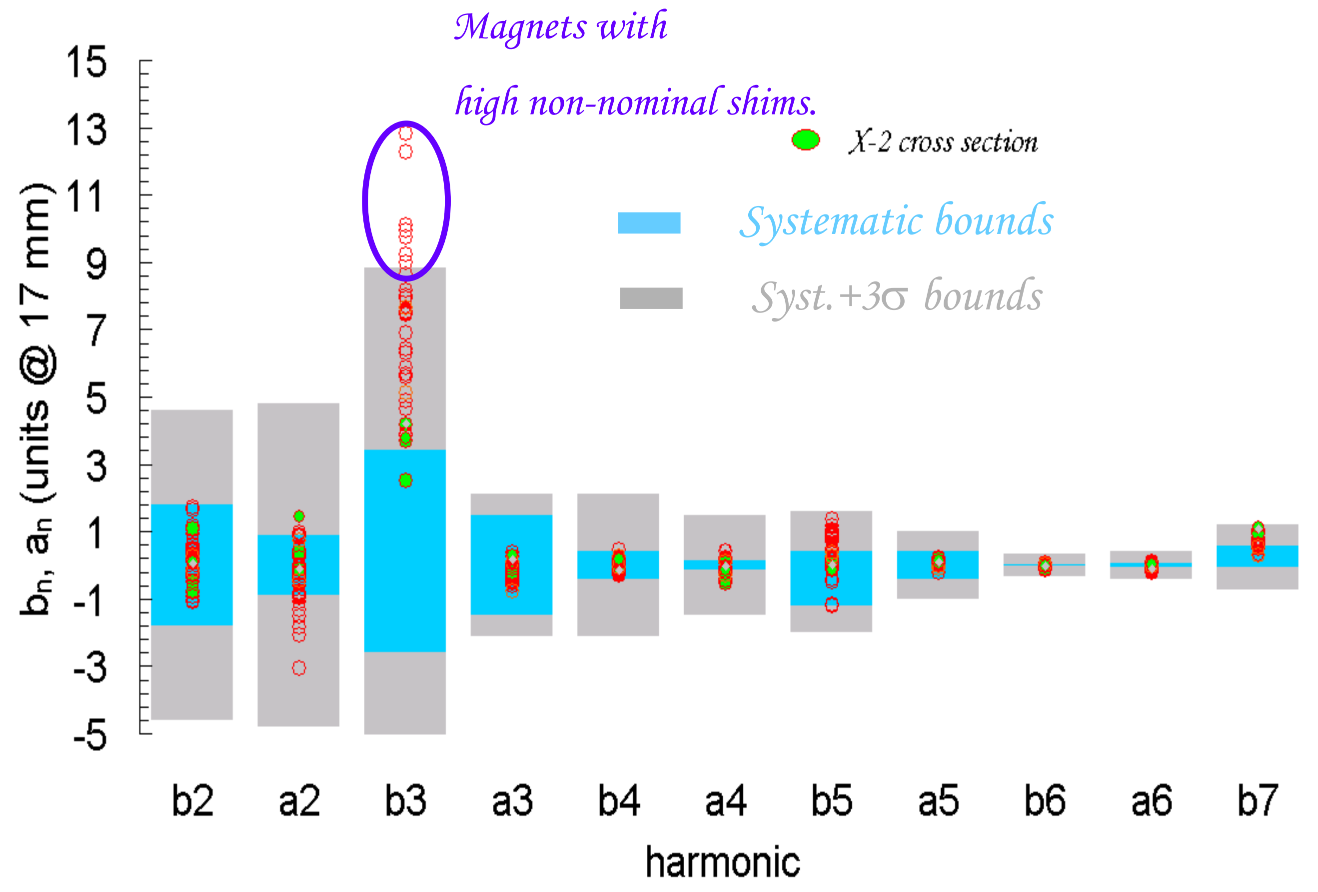
beam frame

	average (units)	sigma (units)
b1		
a1		
b2	0.16	1.27
a2	-0.28	1.00
b3	-0.47	2.48
a3	-0.22	0.29
b4	0.01	0.10
a4	-0.06	0.26
b5	1.57	0.59
a5	0.06	0.09
b6	0.00	0.04
a6	-0.02	0.09
b7	0.35	0.21

b_5 and b_7 out of specs: see geometric errors.

b_3 random should decrease to about 1.4 units.

Field quality at flat-top (7 TeV)



beam frame

	average (units)	sigma (units)
b1		
a1		
b2	0.16	0.66
a2	-0.30	0.02
b3	6.98	2.35
a3	-0.24	0.28
b4	0.01	0.22
a4	-0.05	0.24
b5	0.31	0.55
a5	0.07	0.09
b6	0.00	0.04
a6	-0.02	0.07
b7	0.71	0.19

X-section 1 : b_3 and b_5 out of specs (see geometric errors).

X- section 2 :Gap with specs reduced . b_7 is outside the limits.

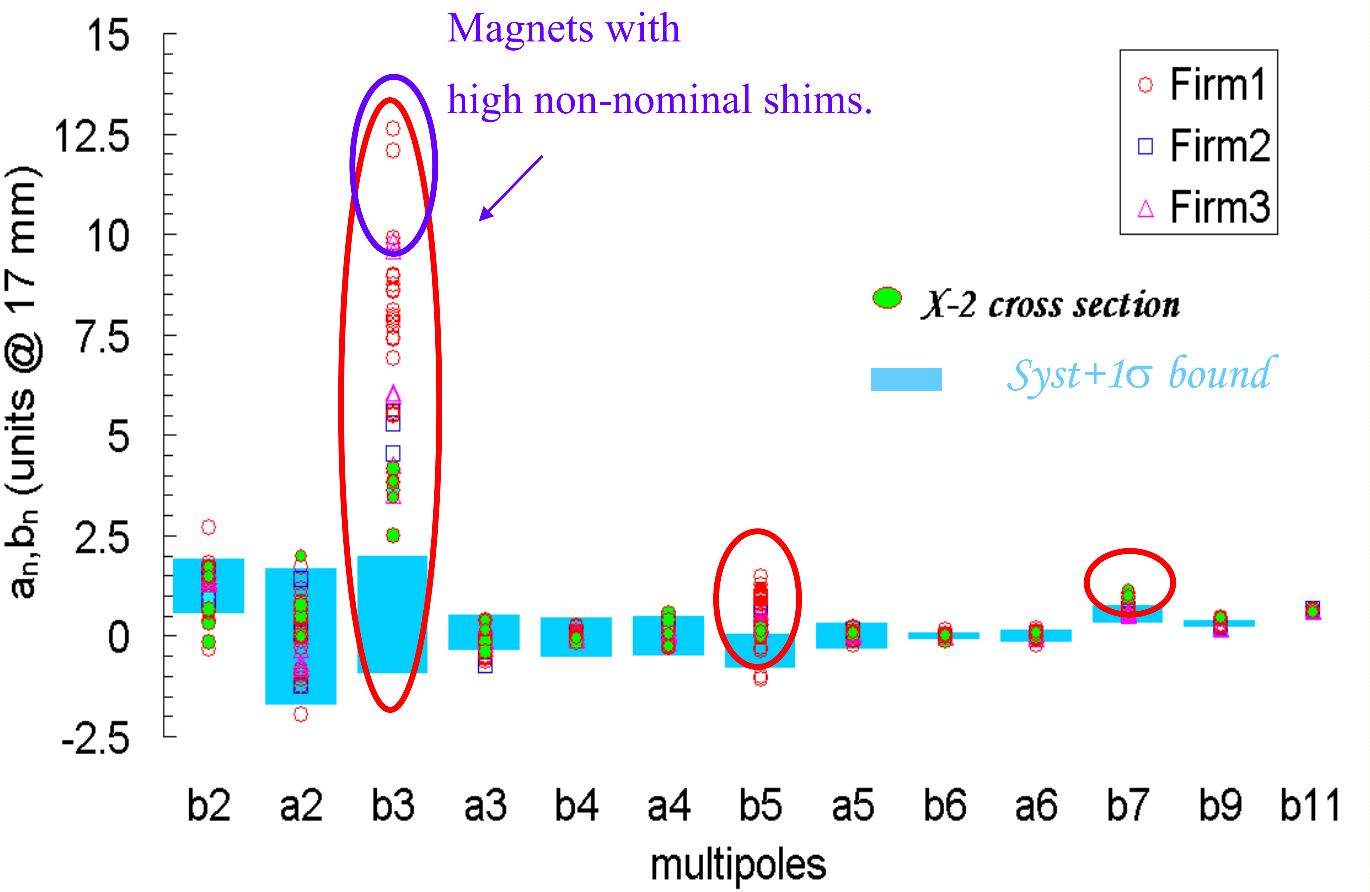
Study of the field component errors.

- *cold geometry (deformations during cool-down and under e.m. loads).*
- *Saturation effect at high field.*
- *SC cable effects at injection :*

  (magnetization, ramp rate induced harmonics, decay/snapback.)

Geometric field errors.

Field component errors.



Magnets with

high non-nominal shims.

Field frame

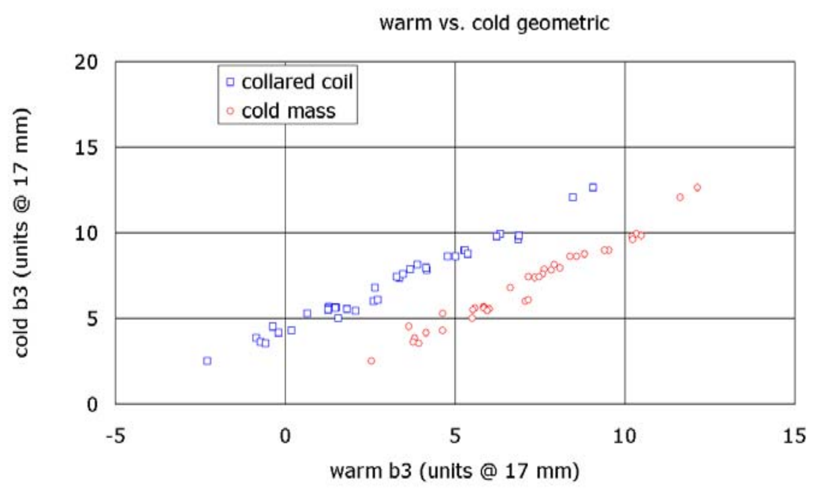
	average (units)	sigma (units)
b1		
a1		
b2	1.18	0.57
a2	-0.08	0.95
b3	6.82	2.36
a3	-0.23	0.29
b4	0.00	0.09
a4	0.08	0.24
b5	0.43	0.54
a5	0.07	0.09
b6	-0.01	0.04
a6	0.01	0.07
b7	0.71	0.18
a7	0.03	0.02

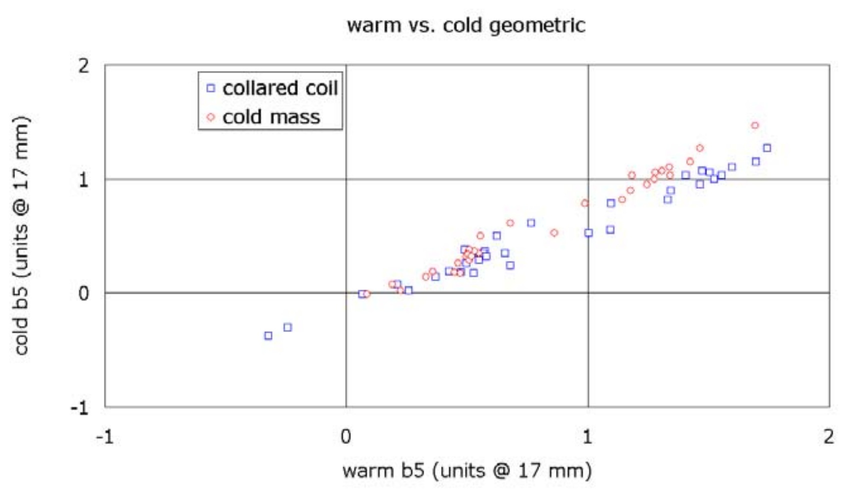
X-section 1+high shims: b_3, b_5 out of specs (by 6 units and 0.5 units).

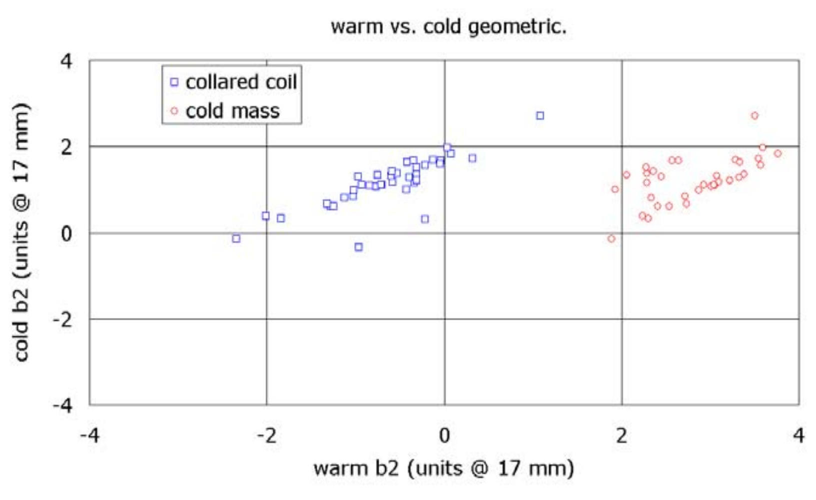
X-section 2 :Gap with specs reduced . b_7 becomes out of the window.

Warm/cold correlations.

Field component errors.







Courtesy of E.Todesco, V.Remondino.

Warm/cold correlations summary.

Field component errors.

Order n	σ warm/cold b_n	δ offset b_n	σ warm/cold a_n	δ offset a_n
2	0.48	- 1.53	0.18	0.02
3	0.40	-0.19	0.11	-0.10
4	0.03	-0.01	0.05	-0.01
5	0.10	-0.22	0.03	-0.01

(wrt ideal corr.line.)

(for cold mass)

Warm data :Courtesy of E.Todesco, V. Remondino.

Good correlation between warm and cold measurements.

Discrepancy in b_2 (heads) under investigation.

Knowledge only through warm measurements may be not enough for operation ?

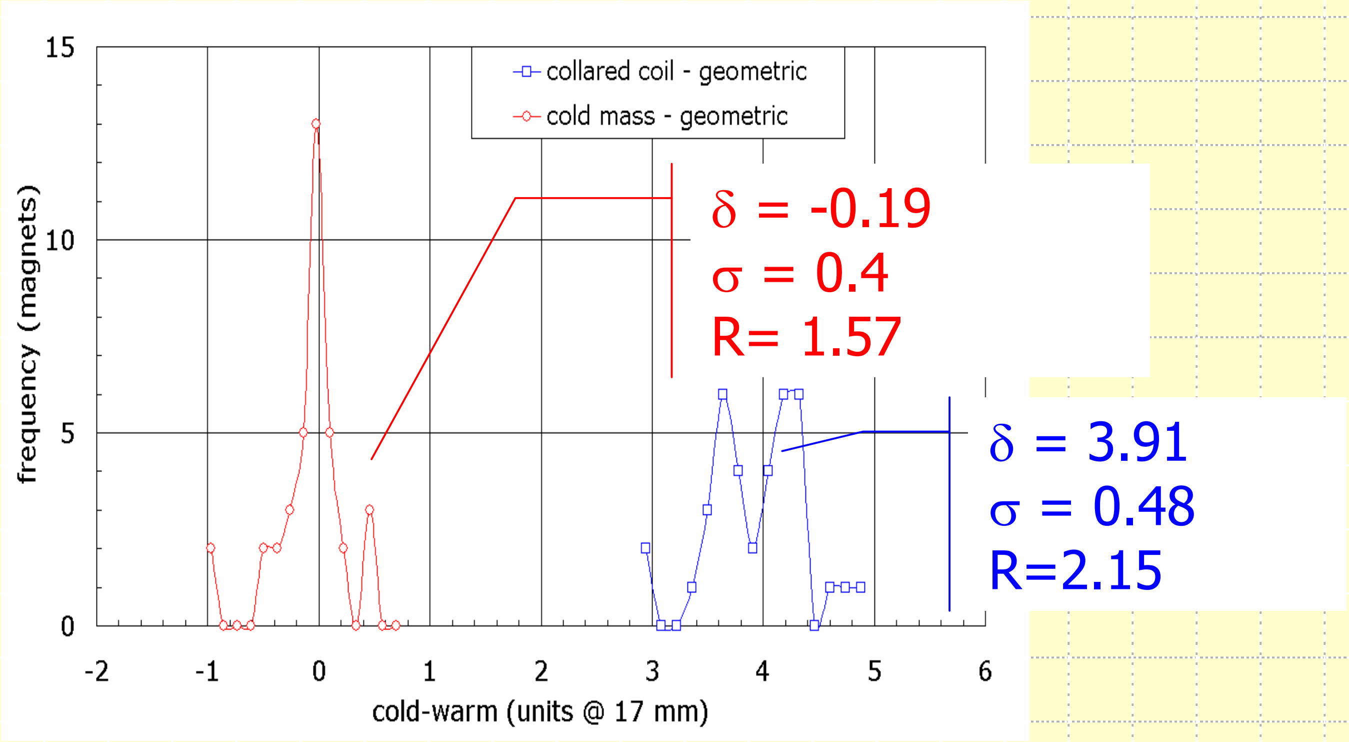
NB : $\Delta\ b_3 = 0.4$ unit $\Rightarrow \Delta\ \xi = 20$ units, $\Delta\ b_5 = 0.2$ unit $\Rightarrow 1\ \sigma$ on D.A.

Warm/cold distribution.

Field component errors.

Histogram of:

$\Delta = b_3^{geometric} - b_3^{collared\text{-}coil}$ $\Delta = b_3^{geometric} - b_3^{cold\text{-}mass}$



δ = -0.19
σ = 0.4
R= 1.57

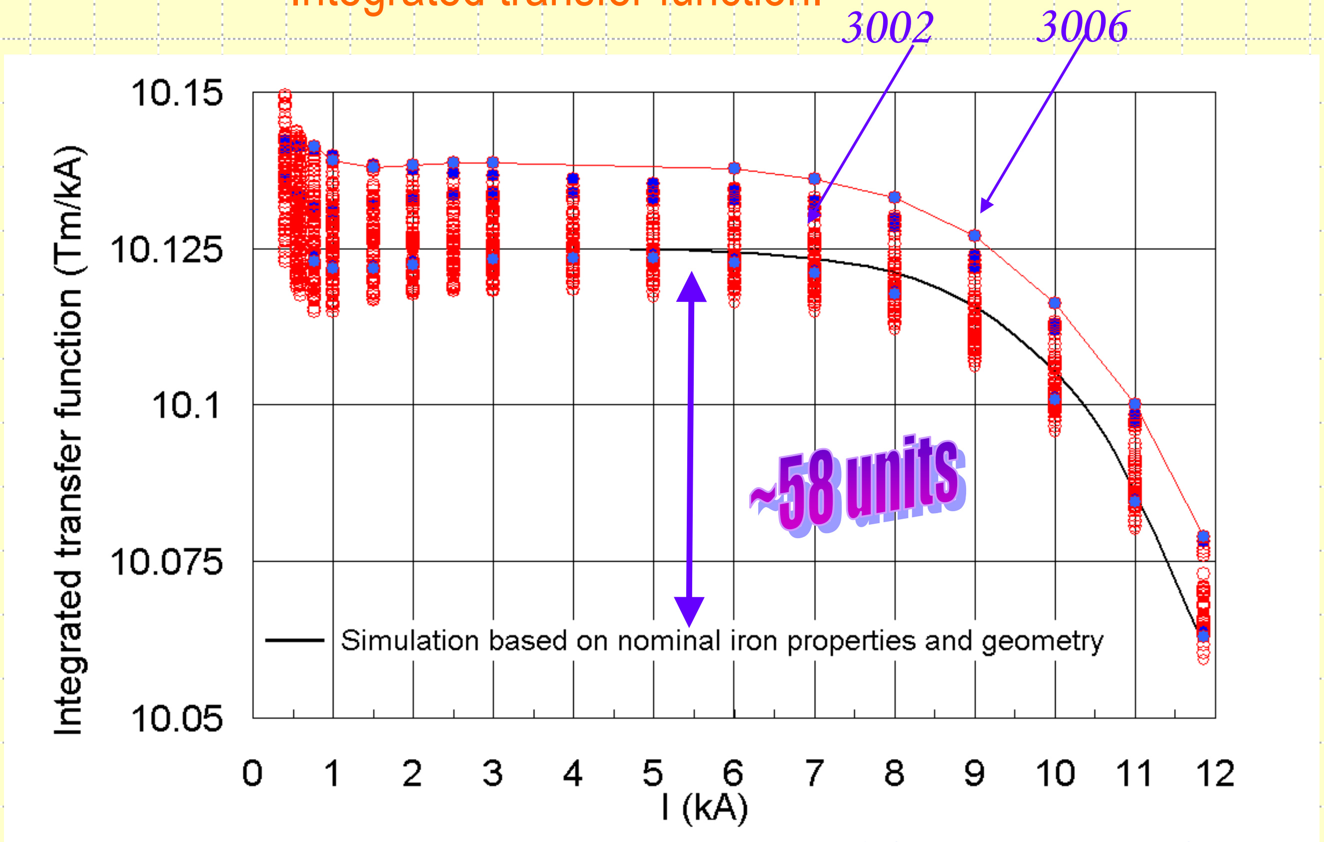
δ = 3.91
σ = 0.48
R=2.15

The distribution of warm-cold difference is not gaussian .

Distribution is not fully stable yet.

Saturation summary (1).

Integrated transfer function.

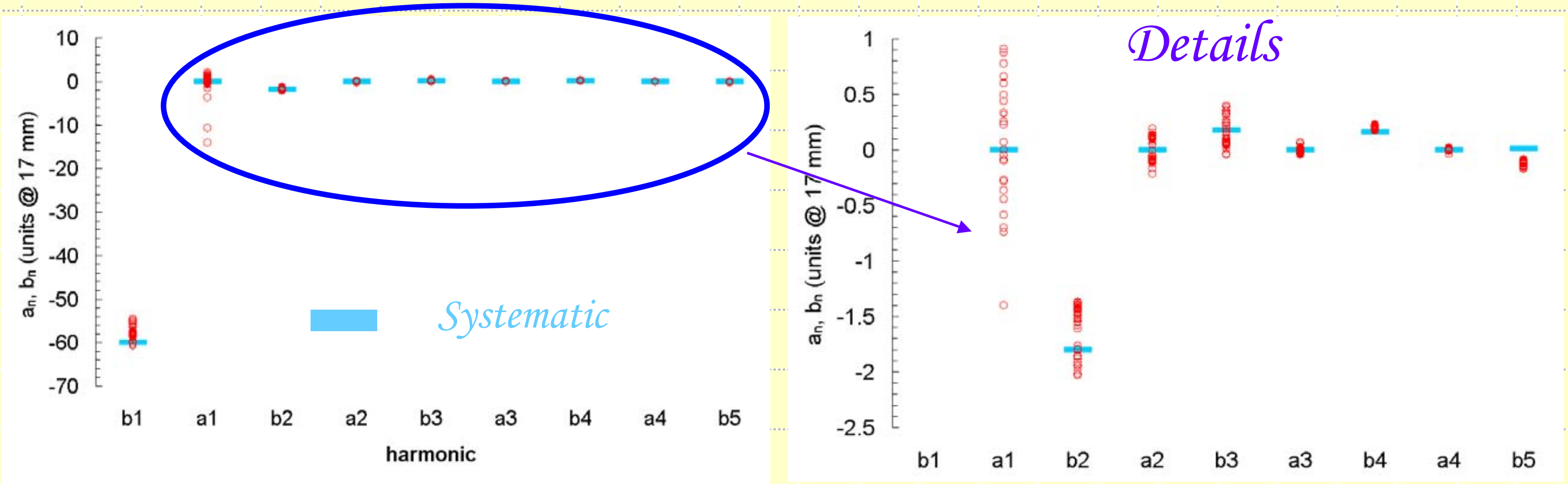


Model: courtesy M.Aleksa

High field behavior of the TF well described by the saturation of the iron.

Saturation summary (2).

Field Component errors.

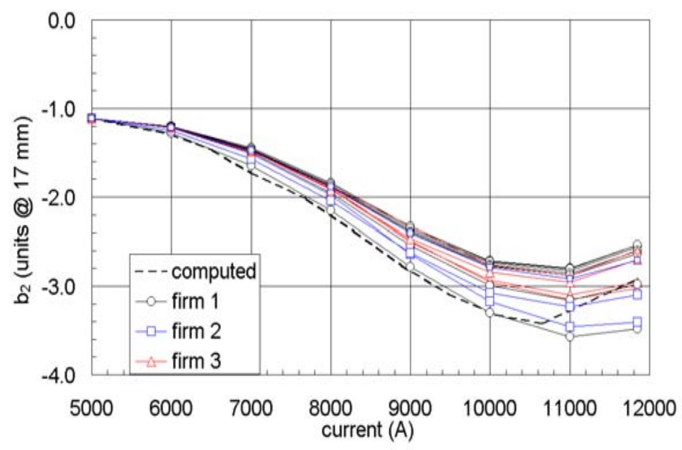


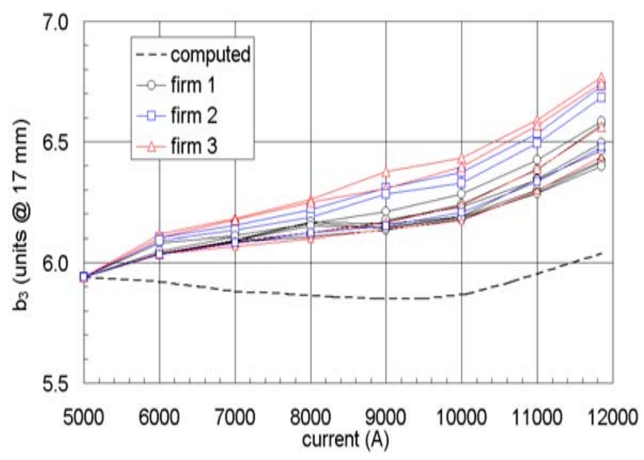
Field frame

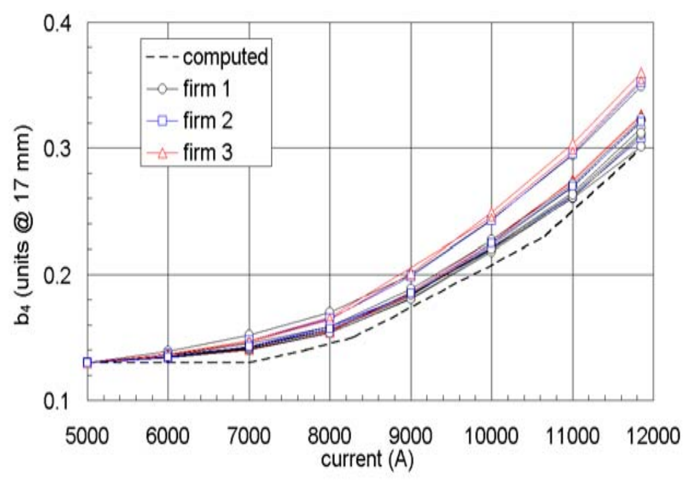
		b1	a1	b2	a2	b3	a3	b4	a4	b5
average	(units)	-57.23	-0.58	-1.60	0.00	0.16	0.00	0.19	0.00	-0.12
sigma	(units)	1.50	3.18	0.22	0.11	0.12	0.02	0.01	0.01	0.02

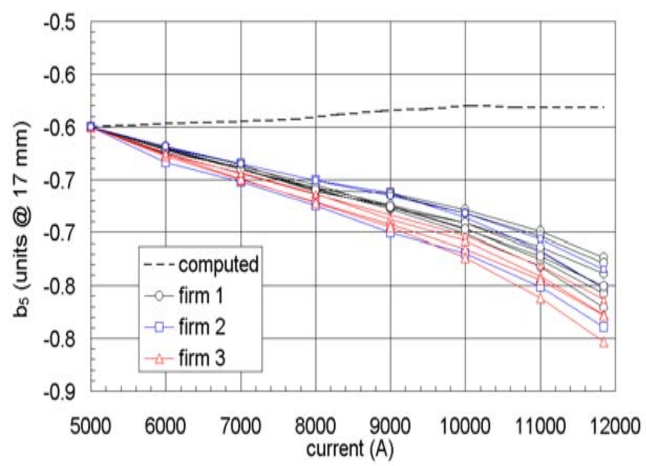
Measurements in accordance with the estimates but Unforeseen saturation effect for b_5.

Harmonics at high field







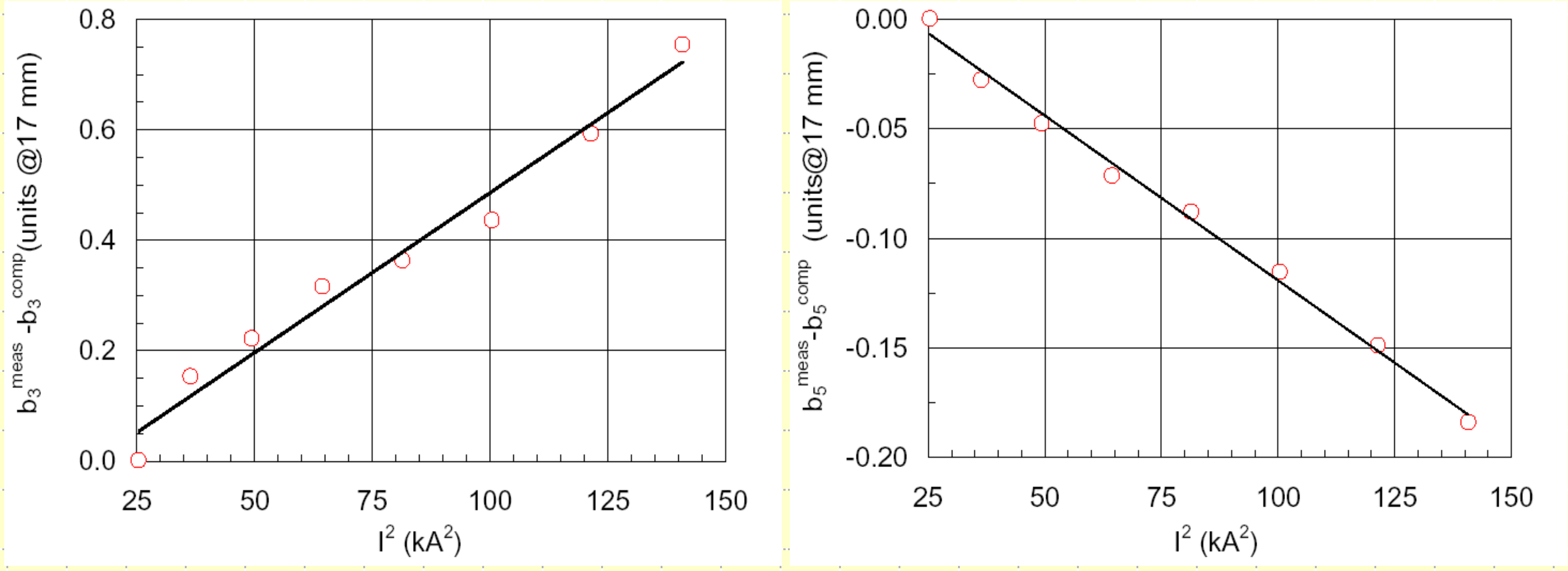


Field computation program ROXIE with analytical BEM-FEM coupling methods by S.Russenchuck, M.Aleksa.

Very good agreement exp/model for b_2 and b_4.

Coil movements at high field

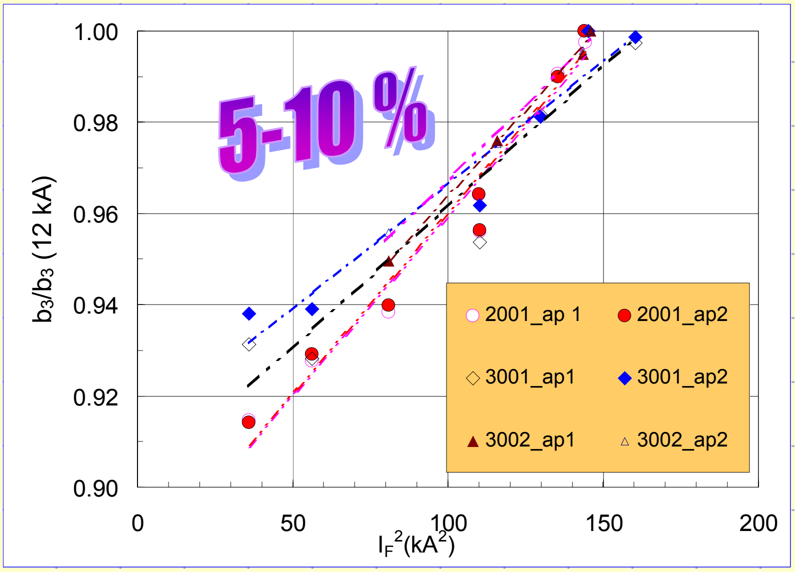
difference between measured b_3 and b_5 and multipoles expected at high field variation, averaged over the complete magnet population.

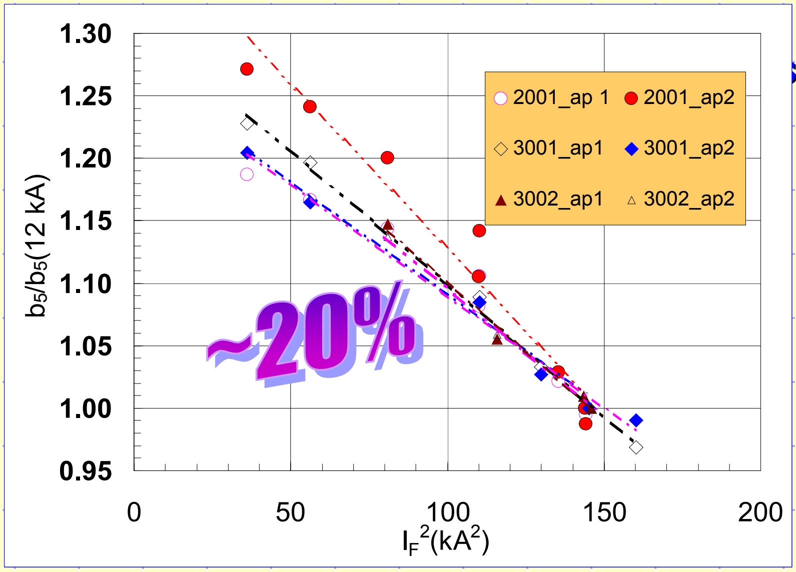


Coil movements at high field, initially thought to be negligible,
will give a small but visible, systematic effect.
Effect to be taken into account in the warm/cold correlation.

Evolution of the geometric multipoles b_n^{geo} during the training of the magnet .

Δb_n^{geo} between 6-12 kA (Unit)	Δb_2	Δb_3	Δb_5	Δb_7
Average	-0.12	0.3	-0.15	0.02
σ	0.05	0.14	0.05	0.01



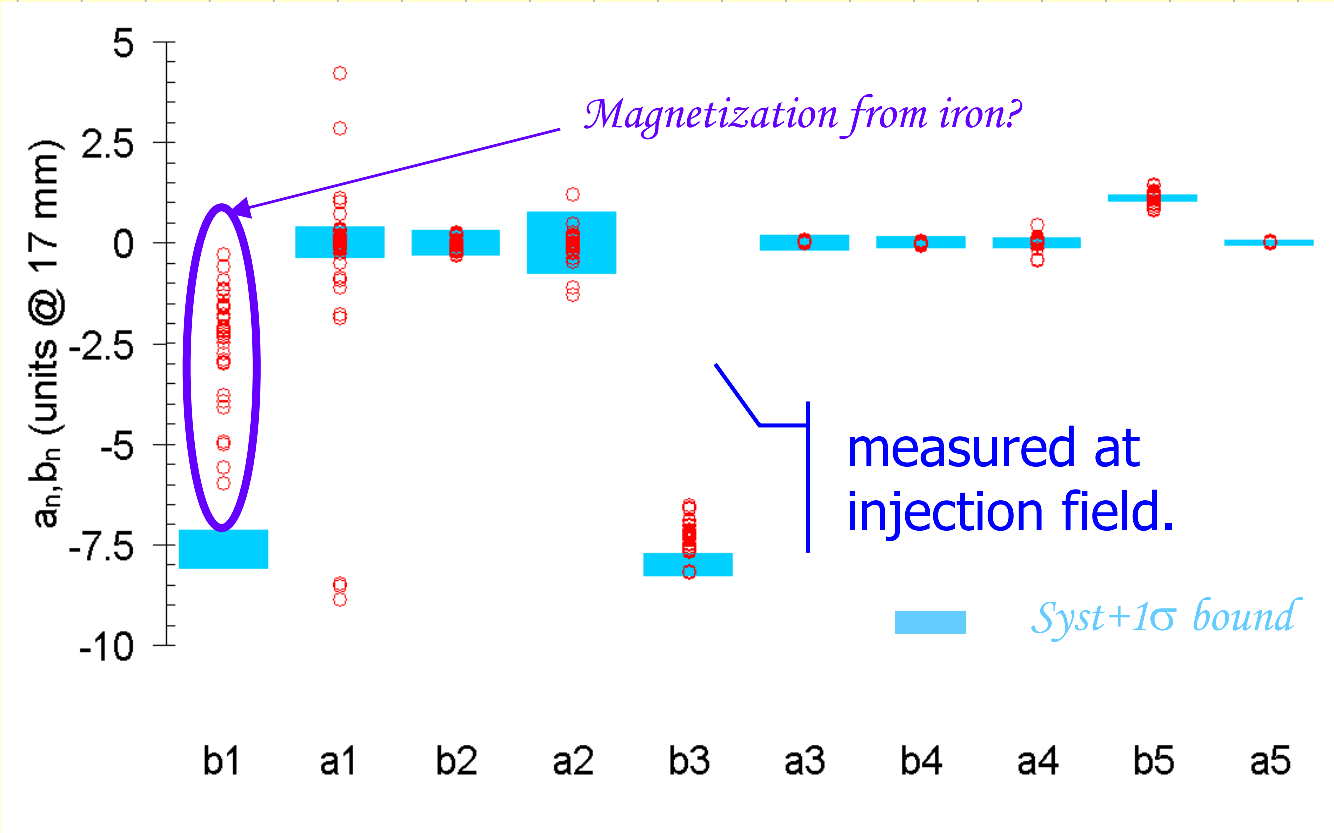


b_3^{geo} and b_5^{geo} vary roughly linearly with I_F^2 (last current achieved before the Mag.Meas).

The field quality has to measured when the magnet is trained up to 12.85 kA.

Persistent currents.

Field Component errors.



Magnetization from iron?

measured at injection field.

Beam frame

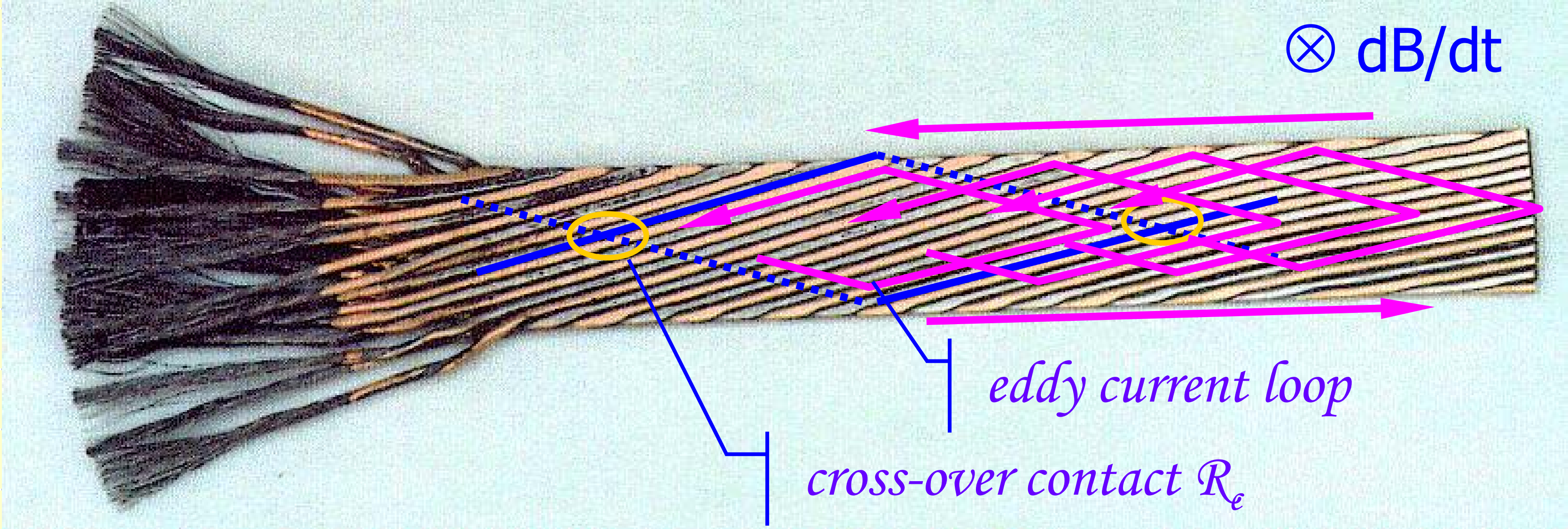
	average (units)	sigma (units)
b1	-2.50	1.36
a1	-0.65	2.74
b2	0.00	0.14
a2	-0.06	0.39
b3	-7.30	0.40
a3	0.01	0.02
b4	0.00	0.03
a4	-0.01	0.13
b5	1.14	0.14
a5	0.00	0.01
b6	0.00	0.01
a6	0.00	0.03
b7	-0.36	0.04

Calculated field errors: R.Wolf et al. LHC Project note 230 (2000).

Discrepancy for b_1.
For the multipoles : Agreement within 10 %.
Random match with expectations.

Ramp rate induced field errors.

Field Component errors.



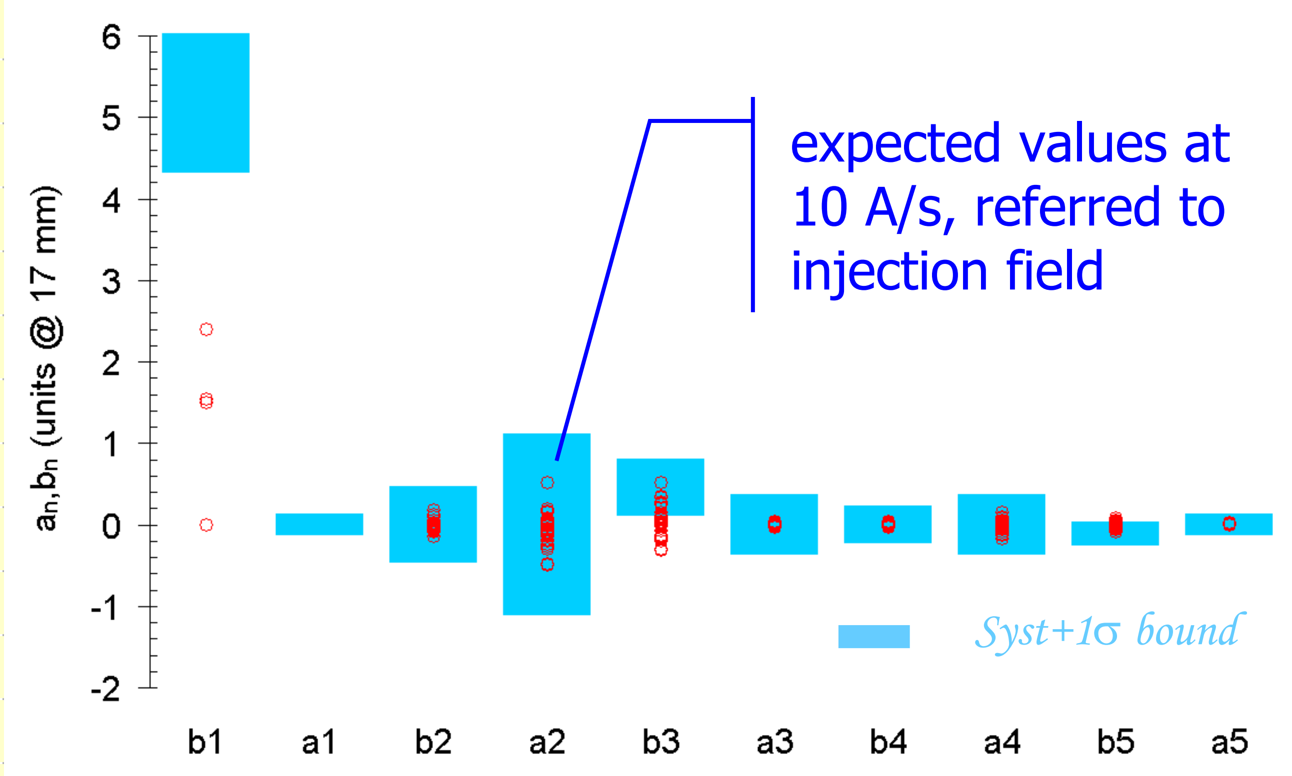
- Heat loss $P_{eddy} \propto$ dB/dt and 1/R_c
- Advance in field $\Delta b_1 \propto$ dB/dt and 1/R_c
- Allowed and non allowed multipole errors Δb^{rr}_n, Δa^{rr}_n.

But if R_c too high (>> 100 μΩ) : Premature quench.

R&D to Control R_c : Specified for LHC > 15 μΩ.

Eddy currents summary.

Field Component errors.



expected values at 10 A/s, referred to injection field

Beam frame

	average (units)	sigma (units)
b1	1.36	0.92
a1	0.00	0.00
b2	-0.01	0.07
a2	-0.06	0.19
b3	0.01	0.19
a3	-0.01	0.02
b4	0.00	0.02
a4	-0.02	0.07
b5	0.01	0.04

Calculated field errors based on Rc~15 μΩ and σ~30% for 1/Rc: R.Wolf (2002).

$P_{eddy} \approx$ 0.2 W/magnet at 10 A/s

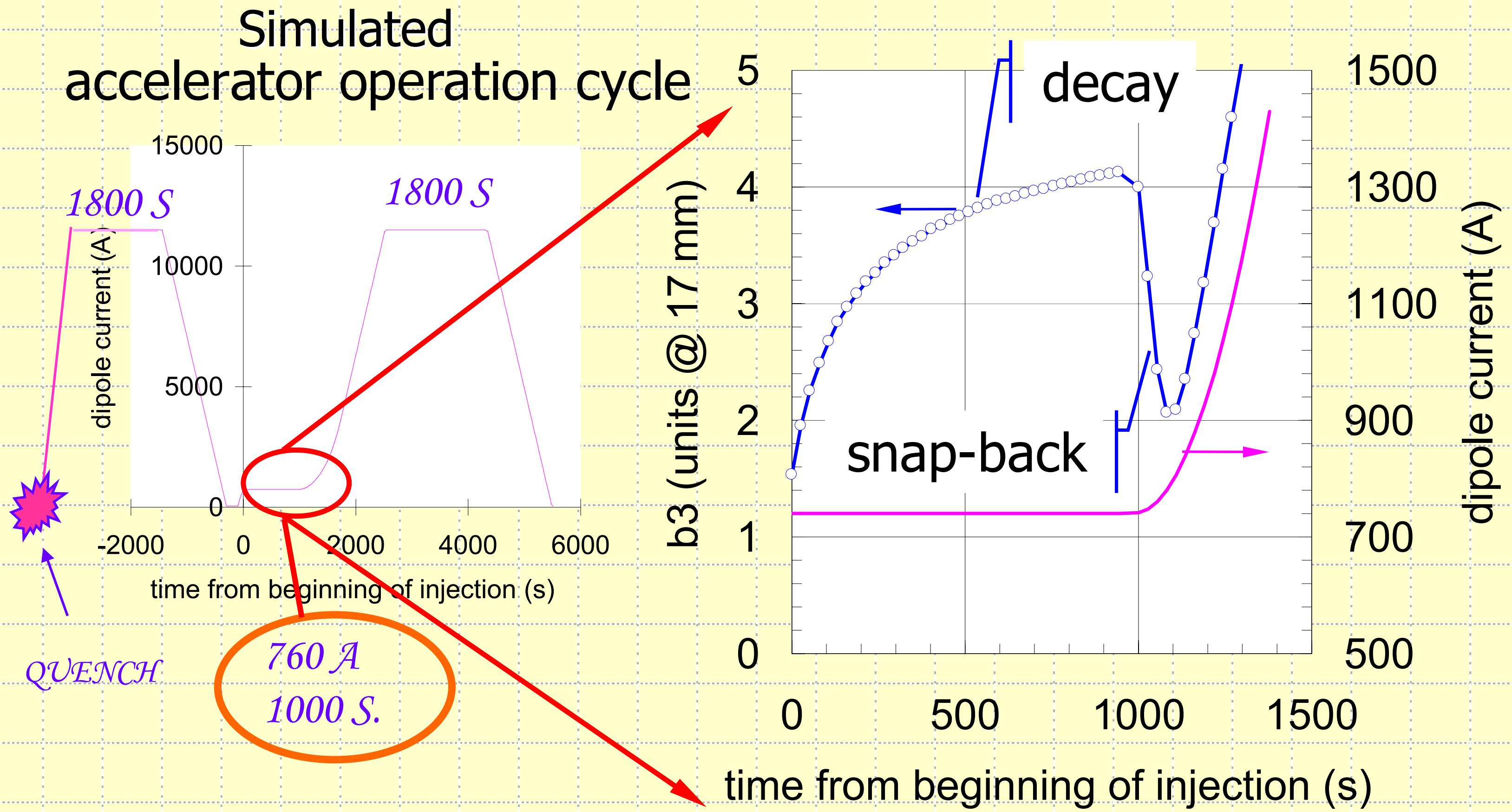
Small AC Loss and ramp rate effect on the multipoles.

R_c control works (>>30μΩ) !

Decay at injection.

Field Component errors.

Simulated accelerator operation cycle



It affects the allowed and non allowed multipoles.

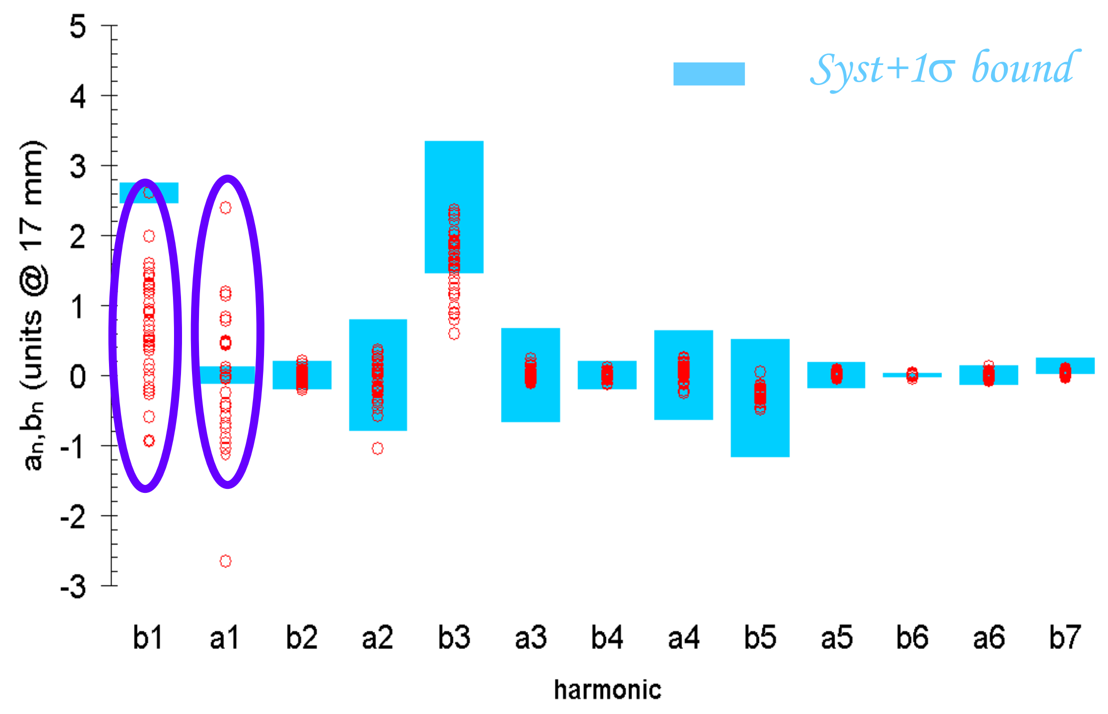
Depends on the history of the magnet.

Decay at injection.

Field Component errors.

Short run before injection (30 minutes).

Injection plateau of 1000 s.



Max systematic :Δb_{decay} max=1/3 $\Delta b_{persistent}$

Beam frame

	average (units)	sigma (units)
b1	0.69	0.76
a1	-0.[illegible]6	2.47
b2	-0.02	0.09
a2	-0.05	0.28
b3	1.63	0.42
a3	0.03	0.07
b4	-0.01	0.05
a4	0.03	0.11
b5	-0.26	0.10
a5	0.01	0.03
b6	0.00	0.02
a6	0.00	0.04
b7	0.04	0.03

Critical for CO distorsions.

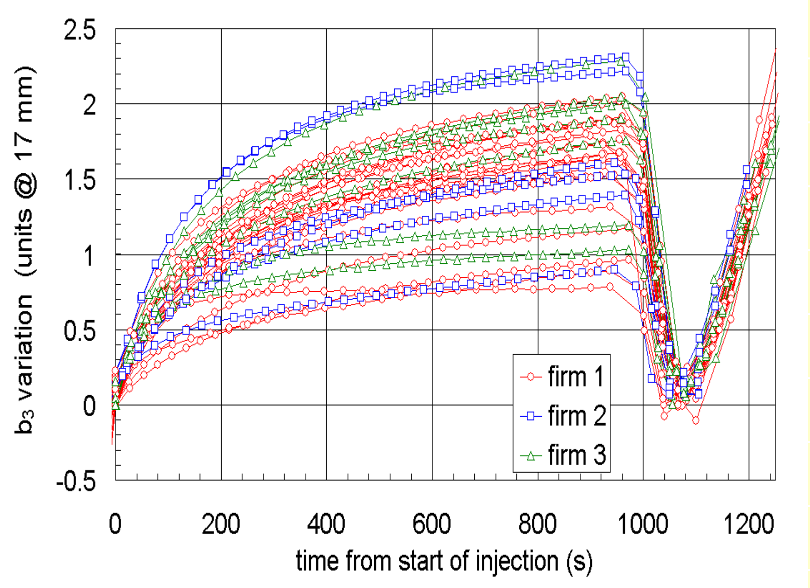
Multipoles within the expectations. But values increase by 40 % for long run and 10000s injection! Decay of b_1 not explained.

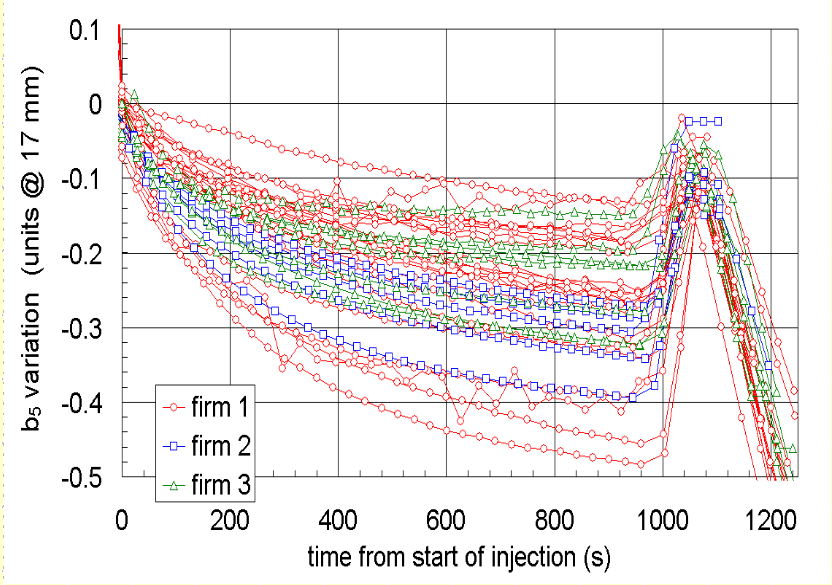
Harmonics decay at injection

Change of b_3 and b_5 averaged over the whole magnet length.

Short run before injection (30 minutes).

Injection plateau of 1000 s.





Large spread measured among magnets of the same population.

Watch out for changes of local b_3 and b_5 w/r to average !

NB : $\Delta\, b_3 = 0.02$ unit $\Rightarrow \Delta\, \xi = 1$ units, $\Delta\, b_5 = 0.2$ unit $\Rightarrow 1\, \sigma$ on D.A.

Conclusions (main field).

- *Standard deviation in the Field Integral at the limit of the specs. Attention is needed to the 300X dipoles!*
- *Field direction : dipoles within the limits at the present state.*
- *High field behavior of transfer function well understood.*
- *Features related to* b_1 *and* a_1 *have to be investigated :*
  - *persistent (systematic, spread)*
  - *decay*

Conclusions (multipoles).

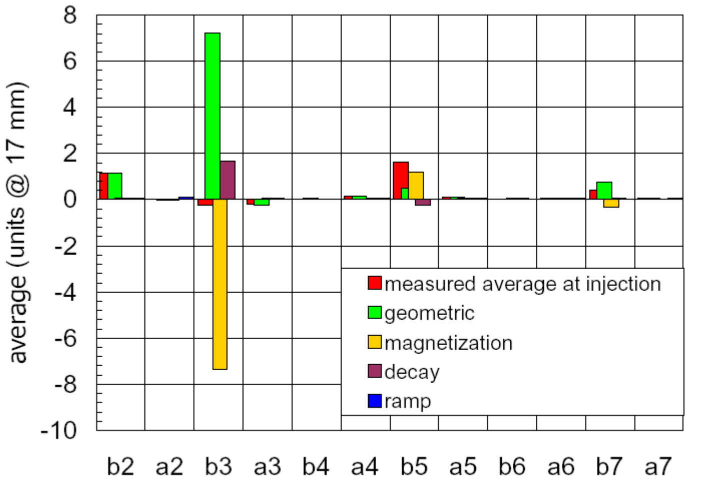
- *Coil geometry is (at present) the source of largest field errors, (both Systematic and spread). It dominates the F.Q at flat top and injection field.*
  Improved situation with magnets with nominal shims and X-section 2 but b_3, b_5 still far from optimal values (by 3.5 and 0.4 units).

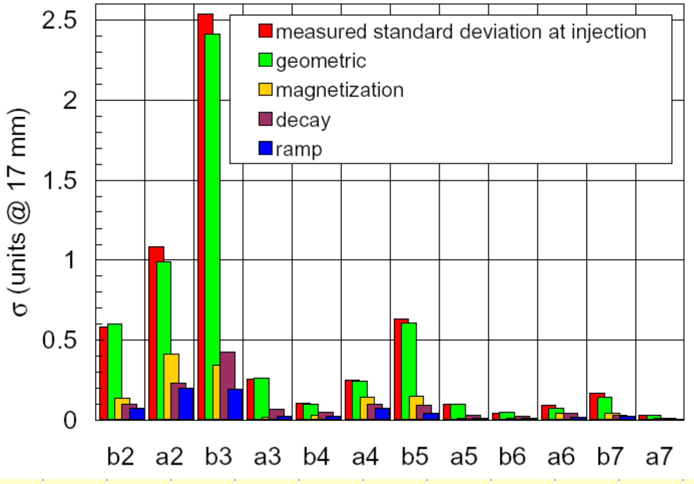
- *Good warm/cold correlation but still early to assess the statistical relevance (distribution?)*

- *Saturation effect: OK*
  But effect of the Lorentz force to be taken into account (geometric, high field behavior for b_3,b_5).

- *Eddy current errors are well below the allocated budget.*

- *Attention is needed to the other error sources:*
  - *persistent (systematic)*
  - *decay (spread).*





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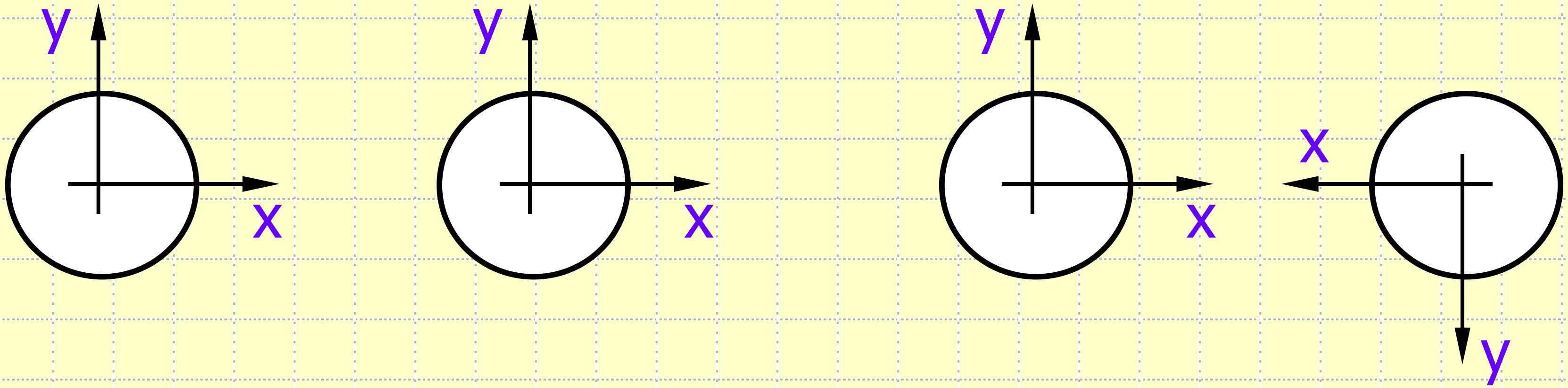
-V.Remondino, E. Wildner, E. Todesco (AT-MAS) for warm measurement data.

- the AT-MTM measurement team in SM-18.

Annex 1:Frames



beam reference

field reference

Aperture 1 Aperture 2 Aperture 1 Aperture 2

Annex 2: FORMULAS

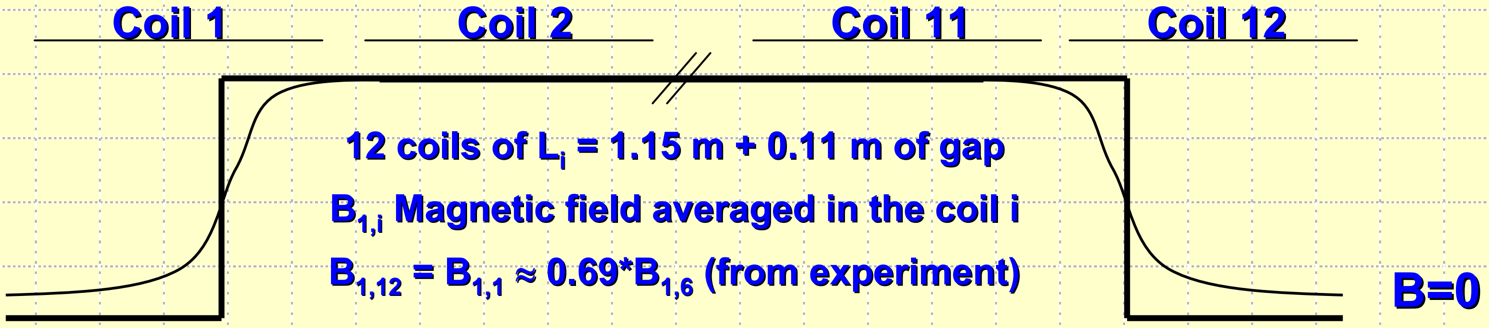
- **Transfer function**

$$TF = \frac{\int_{L_{magnet}} B_m(x)dx}{I}$$

- **Field direction**

$$FD = \frac{\int_{L_{magnet}} \alpha_m(x) B_m(x)dx}{\int_{L_{magnet}} B_m(x)dx}$$

Annex 2: FORMULAS



Coil 1 **Coil 2** **Coil 11** **Coil 12**

12 coils of L_i = 1.15 m + 0.11 m of gap

$B_{1,i}$ Magnetic field averaged in the coil i

$B_{1,12} = B_{1,1} \approx 0.69 * B_{1,6}$ (from experiment)

B=0

Lyre side

For each coil (I): $b_{3,i} = \frac{B_{3,1}}{B_{1,i}}$

i=1,12 : coil ends, the magnetic field in the body is measured by the coils i=2 to i=11

$$b_3^{int} = \frac{\sum_{i=1}^{i=12} b_{3,i} * B_{1,i} * L_i}{\sum_{i=1}^{i=12} B_{1,i} * L_i} \text{ [unit]}$$

$$b_3^{body} = \frac{\sum_{i=2}^{i=11} b_{3,i} * B_{1,i} * L_i}{\sum_{i=2}^{i=11} B_{1,i} * L_i} \text{ [unit]}$$

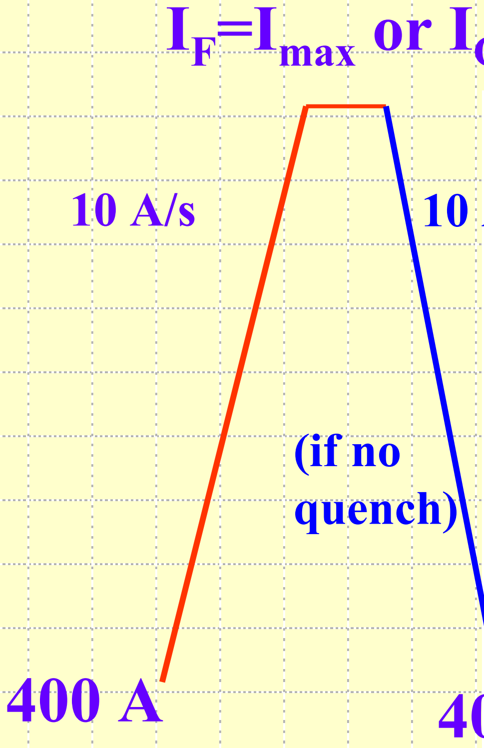
$$\boxed{b_3^{end} = b_3^{int} - b_3^{body} \text{ [unit]}}$$

In reality gap correction is applied (invisible to users)

See specification in
:http://mtauser.home.cern.ch/mtauser/archives/DAP/guides/specsguide

Annex 3: Training study.

Current cycle or ramp to quench



$I_F=I_{max}$ or I_Q

10 A/s

10 A/s

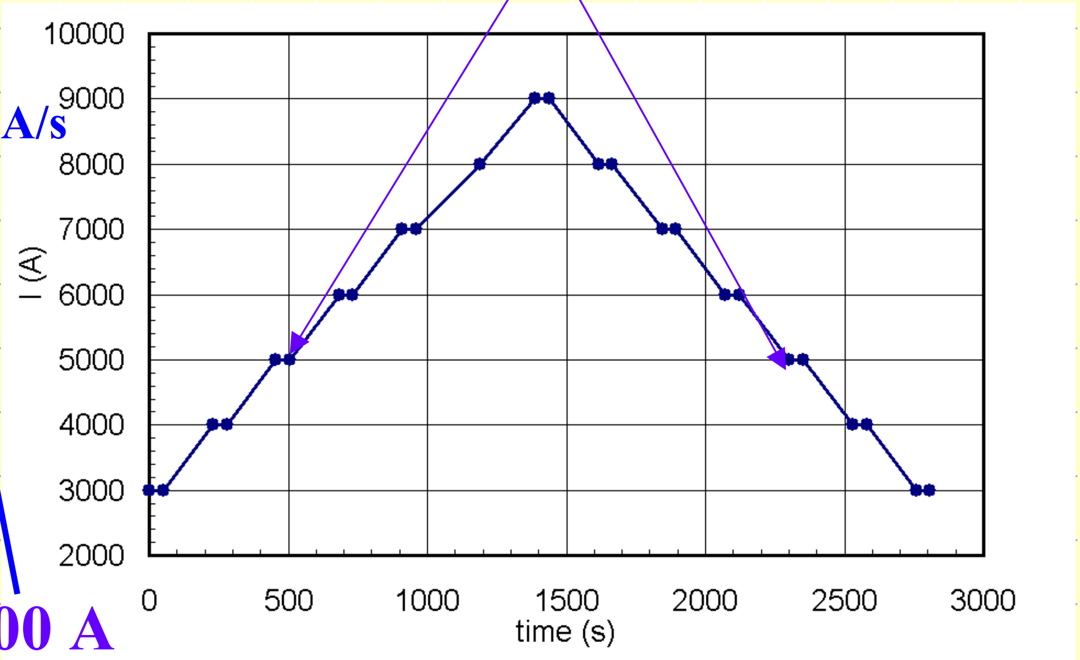
(if no quench)

400 A

400 A

Magnetic measurement

b_n geometric



Study of b_n geometric = $f(I_F)$