Magnetic measurements compared to specifications and updated consequences on beam dynamics

- 60 collared coils and 14 cryomagnets have been used to update the 9901 field error table for the main dipoles (E. Todesco et al., LHC Rep. 625).
- Except for b_1, only small sytematic differences (so-called "uncertainty") can be observed between the 3 different firms, i.e uncertainty $\approx$ or $\ll$ random components.
  $\longrightarrow$ A full mixing installation scenario can be envisaged.
- With cross-section 2, some multipoles are still out of specification, in particular b_5 and b_7 at injection (impact on the DA) and b_3 at high field (Q' correction at 7 TeV).

$\Rightarrow$ **Question 1:** Do we have to optimize further the dipole cross-section?

Question 2: If yes, what is the right moment to do it?

Contents

Integrated transfer function

- Compared to the other 2 producers, Firm 3 exhibits

  $\longrightarrow$ a systematic b_1 of 14.5 units (i.e. 17 units in the collared coil).

  $\longrightarrow$ but with small random fluctuations $\sigma_{b_1} < 3$ units.
- Depending on the *installation strategy*, possible reduction of the safety margin on the MCB strength at 7 TeV:

  Case 1. Full mixing of the 3 producers **at the level of each arc cell**:

  $\Rightarrow$ ”Effective random” b_1 exactly within specification, $\sigma_{b_1} < 8$ units.

  $\Rightarrow$ Safety margin of 50% (assuming $\delta x_{\rm MQ} = 0.37$ mm r.m.s.).

  Case 2. Few arc cells **fully equipped with Firm 3 magnets**:

  $\Rightarrow \langle b_1 \rangle_{\rm cell} \sim 2/3 * 16 \sim 10$ units but random b_1 of 3 units r.m.s .

  $\Rightarrow$Safety margin of 30% after local correction.

  $\Rightarrow$ Further reduced to 15% for $\delta x_{\rm MQ} = 0.5$ mm r.m.s. (other small effects not included as long. shifts of the MB mag. center, smoothness of the survey curve,...).
- A correction will remove ALL potential constraints on the installation:

  e.g. iron $\leftrightarrow$ nested laminations, -6.8 cm for Firm 3 and +3.4 cm for Firms 1&2, **symmetrically** on both magnet ends.

Budget for the strength of the arc closed orbit correctors MCB ($\theta_{\rm max} = 80.8\,\mu$**rad)**

Specification from LHC report 501	
Contribution	Required corrector strength [μrad]
MQ misaligned by 0.37 mm r.m.s. (T. Tortschanoff, Alignment workshop, CERN, Dec. 2000)	31 (at 3 σ)
BPM misaligned by 0.24 mm r.m.s. w.r.t. MQ (J.P. Papis, Alignment workshop, CERN, Dec. 2000)	10 (at 3 σ)
$b_1 = 8$ units r.m.s. in MB	21 (at 3 σ)
$\langle b_1 \rangle_{\rm cell} = 6.5$ units	16
Quadratic sum of random contributions Linear sum of all contributions (pessimistic)	$\sqrt{31^2 + 10^2 + 21^2} + 16 = 55$ $31 + 10 + 21 + 16 = 78$

Current status based on magnetic measurements	
Configuration	Required corrector strength [μrad]
Full mixing in each cell ($b_1 = 8$ units r.m.s. and $\langle b_1 \rangle_{\rm cell} = 0$)	Quadratic sum: 39 Linear sum (pessimistic): 62
Some arc cells equipped only with Noel magnets ($b_1 = 3$ units r.m.s. and $\langle b_1 \rangle_{\rm cell} = 10$ units)	Quadratic sum: 58 Linear sum (pessimistic): 73

Field direction ($\alpha = 1\,$mrad $\leftrightarrow a_1 = 10\,$units)

- *Specification:* ± 0.65 mrad systematic ± 0.8 mrad r.m.s., (including survey errors and ground motion after 1 year)
  $\Rightarrow$ Corresponds to 70% of the MCBV strength at 7 TeV.

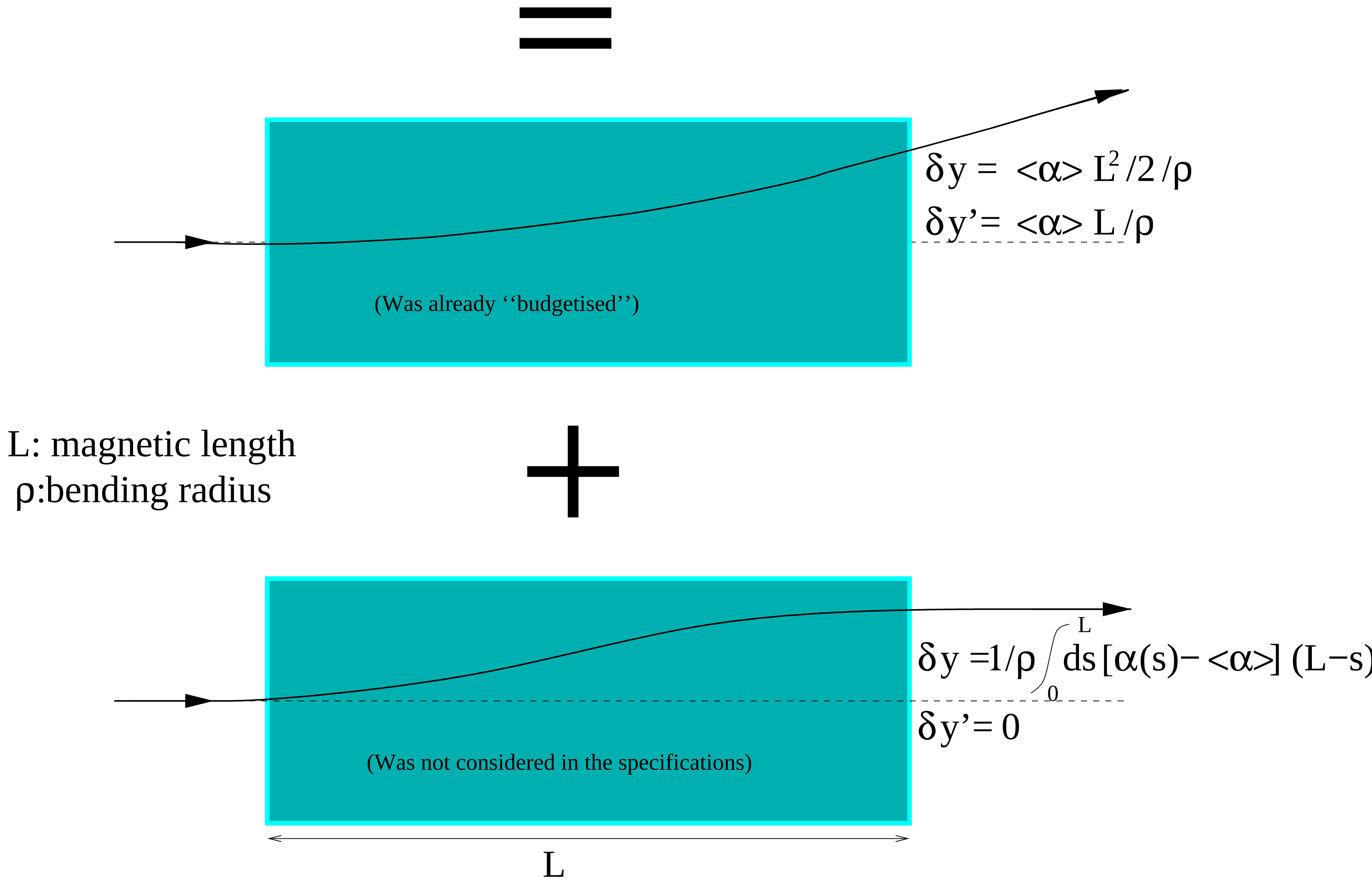
- *Average field direction* (FD):
  $\longrightarrow$ Discrepancy between the two measurement procedures:
  - FD around $\pm 0.5 - 1$ mrad with the stretched wire method.
  - FD up to 2.5 mrad for some dipoles when measured with the shaft.

- *Local field direction* $\alpha(s)$ (mainly induced by mechanical twist between the 2 apertures).
  $\longrightarrow$ can reach 6 mrad (hard limit of 10 mrad from MA constraint).
  $\longrightarrow$ the impact on the vertical CO depends on the convolution integral

$$I_0 \equiv \int_0^L ds\,(\alpha(s) - \langle\alpha\rangle) \times (L - s)\,.$$

  $\longrightarrow$ Using less than 10% of the MCBV strength $\Rightarrow I_0 < 0.18\,\mathrm{m}^2$.
  $\Rightarrow$ Not very critical. At present, all MB's meet the spec.

Local field direction α(s) inducing vertical orbit



a_2 & b_2 field errors

- *β-beating*
  The β-beating should be within specifications at injection ($\Delta\beta/\beta < 20\%$ from MA constraint):
  $\longrightarrow$ Expected random b_2 within specifications (0.7 units r.m.s.).
  $\longrightarrow$ Expected systematic b_3 well within specifications **at injection** (-3.8 units against -10.7 specified).
  $\Rightarrow$ reduction of feed-down effects coming from MCS misalignment.

- *Coupling*
  $\longrightarrow$ Both the random a_2 and the a_2 running average are well within the specifications.
  $\Rightarrow$ Safety margin of 40-50% in the MQS strength at high field.

Non-linear multipoles at injection. Tracking studies (1/3)

- *Comparison with the specifications at injection*

Randoms (combined data of dipoles with X-section 1 & 2)

$\longrightarrow$ All randoms meets the specifications except the random b_3

$\longrightarrow$ but **very pessimistic** estimate (non nominal shims and change of the X-section in the meantime),

$\longrightarrow$ e.g. $b_3 \sim 2.4$ units r.m.s. for the present estimate, compared to 1.2 for the dipoles with cross-section 2, and 1.4 in the specifications.

Systematic, i.e. running average (only MB with X-section 2)

1. The running averages of all skew and even normal multipoles (i.e. $b_2, b_4, b_6, \ldots$) meet the specifications.

2. At injection, $\langle b_5 \rangle = 1.38$, $\langle b_7 \rangle = 0.33$, $\langle b_9 \rangle = 0.77$ instead of 1.1 and 0.1 specified, and 0.38 expected in the 9901 error table.

a_n & b_n	Systematic: Aperture V1/V2 (Systematic $\pm$ Uncertainty if applicable)			Random (r.m.s. value)		
	9901 error table	Specification	Expected	9901 error table	Specification	Expected
b_2	$-1.40 \pm 0.85/+1.40 \pm 0.85$	$-1.40 \pm 0.80/+1.40 \pm 0.80$	$+1.31/-1.10$	0.75	0.70	0.63
b_3	$-9.70 \pm 1.38/-9.70 \pm 1.38$	$\langle b_3 \rangle < 10.7$	$-3.86/-3.69$	1.50	1.40	2.39
b_4	$+0.22 \pm 0.34/-0.22 \pm 0.34$	$+0.2 \pm 0.4/-0.2 \pm 0.4$	$-0.01/-0.01$	0.51	0.50	0.11
b_5	$+0.89 \pm 0.44/+0.89 \pm 0.44$	$\langle b_5 \rangle < 1.1$	$+1.33/+1.43$	0.43	0.50	0.50
b_6	$-0.01 \pm 0.06/+0.01 \pm 0.06$	none	$-0.02/+0.00$	0.09	none	0.04
b_7	$-0.16 \pm 0.05/-0.16 \pm 0.05$	$-0.3 < \langle b_7 \rangle < 0.1$	$+0.32/+0.34$	0.22	none	0.24
b_8	$+0.00 \pm 0.00/-0.00 \pm 0.00$	none	$-0.01/+0.01$	0.04	none	0.02
b_9	$+0.36 \pm 0.03/+0.36 \pm 0.03$	none	$+0.77/+0.77$	0.07	none	0.12
b_{10}	$+0.00 \pm 0.00/-0.00 \pm 0.00$	none	$+0.00/+0.01$	0.00	none	0.02
b_{11}	$+0.57 \pm 0.00/-0.57 \pm 0.00$	none	$+0.59/+0.59$	0.00	none	0.03
a_2	$-0.00 \pm 0.51/-0.00 \pm 0.51$	$+0.00 \pm 0.90/+0.00 \pm 0.90$	$-0.37/-0.37$	1.86	1.90	1.21
a_3	$-0.08 \pm 0.87/+0.08 \pm 0.87$	$+0.00 \pm 1.50/-0.00 \pm 1.50$	$-0.26/-0.23$	0.48	0.70	0.33
a_4	$+0.00 \pm 0.13/+0.00 \pm 0.13$	$+0.00 \pm 0.13/+0.00 \pm 0.13$	$-0.03/-0.04$	0.51	0.50	0.28
a_5	$+0.01 \pm 0.42/-0.01 \pm 0.42$	$+0.00 \pm 0.40/-0.00 \pm 0.40$	$+0.03/+0.02$	0.34	0.40	0.10
a_6	$+0.00 \pm 0.06/+0.00 \pm 0.06$	none	$-0.01/+0.00$	0.17	none	0.08
a_7	$+0.02 \pm 0.00/-0.02 \pm 0.00$	none	$+0.04/+0.04$	0.08	none	0.04
a_8	$+0.00 \pm 0.00/+0.00 \pm 0.00$	none	$+0.01/+0.00$	0.08	none	0.03
a_9	$-0.01 \pm 0.00/+0.01 \pm 0.00$	none	$-0.01/-0.01$	0.12	none	0.03
a_{10}	$+0.00 \pm 0.00/+0.00 \pm 0.00$	none	$+0.00/-0.01$	0.01	none	0.01
a_{11}	$+0.00 \pm 0.00/+0.00 \pm 0.00$	none	$-0.04/-0.04$	0.00	none	0.04

Comparison between 9901 error table (FQWG), specification table (LHC Report 501) and field harmonics expected **at injection** *in the LHC main dipoles (LHC Report 626). a_n and b_n are given in units of 10^{-4} relative field error at a radius $R_{ref} = 17$ mm.*

$\longrightarrow$ Red multipoles do not fulfill the specifications for the systematic and/or random.

$\longrightarrow$ Magenta multipoles disagree significantly with the systematic of the 9901 error table.

Non-linear multipoles at injection. Tracking studies (2/3)

- *Dynamic aperture at injection* (nominal tunes 64.28/59.31)
  $\longrightarrow$ Specification: DA=12 $\pm$ 0.5 σ (error bars on DA calculation estimated to 0.5σ)
  $\longrightarrow$ Using ”blindly” the new error table (i.e. with pessimistic estimate for the random multipoles, in particular b_3):

Configuration	DA $[\sigma]$ $(10^5$ turns)
Specification error Table (LHC Rep. 501)	11.5
New error Table (LHC Rep. 625)	10.1
New error Table, $\langle b_7 \rangle$ reduced to 0.1 unit	9.9
New error Table, $\langle b_9 \rangle$ reduced to 0.38 unit	9.7
New error Table, σ_{b_3} reduced to 1.4	11.2
New error Table, σ_{b_3} and $\langle b_7 \rangle$ reduced to 1.4 **and** 0.1 unit, resp.	11.6

$\longrightarrow$ DA non- or only slightly sensitive to b_7 and b_9.

$\longrightarrow$ With a reduced random b_3, the DA is almost recovered at 450 GeV.

$\longrightarrow$ No visible effect induced by b_5 (0.25 out of spec.), but feed-down effects still to be evaluated. (e.g. $b_5 \rightarrow a_4$ for vert. misalignment of the MCD’s).

Non-linear multipoles at injection. Tracking studies (2'/3)

- $\langle b_5 \rangle$ *is out of spec. by 0.25 units at injection*

  $\longrightarrow$ No visible effect on the DA, but assuming the the b_5-integral to be perfectly corrected.

  $\longrightarrow$ Lost of 0.6 σ on the DA, i.e. just outside the tracking resolution, when the b_5-integral is mis-corrected by $\pm 20\%$.

  $\longrightarrow$ potential danger with feed-down effects.

  $\Rightarrow$Urgent need of realistic inputs to launch the study.

Non-linear multipoles at injection. Tracking studies (3/3)

- Considering 2 different statistics for the MB's with X-section 1 & 2:

Relevant parameters	X-section 1 (from 16 cryo-magnets)		X-section 2 (from 25 collared coils using warm-cold corr.)	
	Av.	r.m.s.	Av.	r.m.s.
b_3 [units]	-0.72	1.84	-3.78	1.15
b_5 [units]	1.98	0.54	1.38	0.40
b_7 [units]	0.12	0.17	0.33	0.09
Number	35		1197	
Type	Type B		Type A & B	

1. to study the impact of the pre-series on the DA and observables such as off-momentum beta-beating, Q'' and/or $\partial Q/\partial J$.

2. to justify or not a sophisticated installation strategies for these magnets, e.g.

$$\text{MB} \longleftarrow \pi \;\text{(2 cells)} \longrightarrow \text{MB} \longleftarrow \pi/2 \;\text{(1 cell)} \longrightarrow \text{MB} \longleftarrow \pi \;\text{(2 cells)} \longrightarrow \text{MB} \quad \text{, or}$$

$$\text{MB} \longleftarrow \pi/2 \;\text{(1 cell)} \longrightarrow \text{MB} \longleftarrow \pi \;\text{(2 cells)} \longrightarrow \text{MB} \longleftarrow \pi/2 \;\text{(1 cell)} \longrightarrow \text{MB}$$

(batches possibly interleaved to minimize the installation constraints).

$\longrightarrow$ *Preliminary results* indicate that the DA is slightly sensitive to the installation of the 35 pre-series, DA=$11.1 - 11.6\sigma$ (should be confirmed next week).

Dynamic effects

- *Decay and snap-back effects* (based on data of 14 cryo-magnets).
  Average effect still critical but a factor from 2 to 3 lower than expected.
  $\longrightarrow$ e.g. $\langle \Delta b_3 \rangle_{\rm snap-back} = 1.7 \Rightarrow \Delta Q' \sim 80$ (compared to 150 with previous estimates).
  Random effects (from magnet to magnet) larger than expected.
  $\longrightarrow$ e.g. $b_1^{\rm decay} \sim 0.7$ units r.m.s. (much larger than the 0.16 units given in the 9901 error table) and $a_1^{\rm decay} \sim 2.6$ units r.m.s. (measurement noise?).
  $\longrightarrow$ If real, strong impact on the design of the orbit feed-back system, since the corresponding vertical closed orbit amounts to 7σ peak, if not dynamically corrected!

- *Ramp induced effects* $\propto dI/dt$ small enough to be neglected for the LHC operation (inter-strand resistance higher than targeted).
  $\longrightarrow$ In average, less than 0.05 units for all multipoles at 450 GeV assuming a ramp speed of 10 A/s.

Non-linear multipoles at high field (1/1)

- *Comparison with the specifications*
  $\longrightarrow$ All the harmonics specified at 7 TeV meets the specifications, namely a_2, b_2, a_3, b_4 and b_5, **except the systematic b_3.**

- Just at the limit to correct Q' at 7 TeV (with the nominal current of 550 A in the MCS spools).

- Current specification @ 7 TeV:	3.0 units with a safety margin (see below)
- Expected $\langle b_3 \rangle$ @ 7 TeV:	3.7 units
- Hard limit @ 7 TeV:	4.3 units (MCS strength)
$\Rightarrow$ Margin @ 7 TeV:	0.6 units (note the beam-screen contribution, $\Delta b_3^{\mathrm{b.s.}} = -0.42$).

- Strictly speaking, no margin in the lattice sextupoles:
  1. To preserve the optics flexibility (e.g. IP1-IP5 phase advance).
  2. To anticipate any LHC upgrade (e.g. new triplets and reduced β^*).

Non-linear multipoles at high field (1’/1)

$\longrightarrow$ Strictly speaking, no reserve in the chromaticity sextupoles MS’s, in order to preserve the optics flexibility and anticipate the LHC upgrade:

Optics configuration	Only Q' correction Results from LHC V6.4	Q', Q'' and $\partial\beta/\partial\delta$ correction Results from LHC V6.0 with $\mu_y \sim \pi/2$ from IP1 to IP5	Q', Q'' and $\partial\beta/\partial\delta$ correction: Results from LHC V6.0 with $\mu_y \equiv \pi$ from IP1 to IP5
$\beta^* = 0.5$ m in IR1& IR5	3.5	3.1	1.3
$\beta^* = 0.5$ m in IR1, IR2 & IR5	2.9	1.3	depends on $\mu_y^{1\rightarrow 2}$
$\beta^* = 0.25$ m in IR1& IR5	2.3	1.1	-2.0 (missing strength)

Reserve given by the lattice sextupoles to correct Q' at 7 TeV and expressed in units of un-corrected b_3 in the the main dipoles.

Conclusions (1/2)

- *Summary*

  $\longrightarrow$ Transfer function under control (some further optimization needed) but random b_1 during snap-back larger than expected by a factor of 5.

  $\longrightarrow$ Unclear situation concerning measurement results of the field direction (a_1) (injection, decay and snap-back).

  $\longrightarrow$ Coupling and β-beating under control.

  $\longrightarrow$ DA of $11.1 \pm 0.5\sigma$ at injection (loss of $0.5\,\sigma$ due to b_7).

  $\longrightarrow$ No visible effect of b_5 on the DA at injection (0.3 units out of spec.).

  $\longrightarrow$ b_3 at high field very close to the hard limit of 4.3 units (MCS strength).

- The complete picture requires further studies including feed-down effects

  $\longrightarrow$ due to *closed orbit and MB misalignments*: real danger $b_7 \rightarrow (a_6, b_6)$.

  $\longrightarrow$ due to *spool-piece misalignment w.r.t. MB* (e.g. if dipole ends not under control in the vertical plane): potential danger $b_5 \rightarrow a_4$.

  $\longrightarrow$ due to *chromatic effects* during off-momentum beam measurement (e.g. for Q' and/or dispersion measurement): mainly $b_7 \rightarrow b_6$.

Conclusions (2/2)

- If one **can warrant that nothing will get worst during the production**, there is no strong argument to justify any additional change (but, feed-down effects still to be evaluated).

- If not, an action should be taken rapidly, **ideally at the end of the first octant** (i.e., preferably not at the middle of a given octant), by order of priority,

  $\longrightarrow$ reduction of the geometric b_3: target value of $\langle b_3 \rangle = 3$ at high field

  (which minimises the feed-down effects at injection while keeping a safety margin corresponding to 2 octants for the correction of Q' at 7 TeV.)

  $\longrightarrow$ make profit of the change to reduce b_5 and recover the systematic b_7, i.e $\langle b_7 \rangle \sim 0.1$ at injection.

  $\Rightarrow$ which is clearly beneficial for any type of feed-down effects (alignment in the tunnel, dipole geometry, chromatic effects).

- *Acknowledgments:* L. Bottura and E. Todesco for measurement data.

Non-linear multipoles at injection. Tracking studies (2"/3)

- *Dynamic aperture with new field error table for the main dipoles* (60 seeds, 10^5 turns, error table 9901 for the MQ's).

Dynamic Aperture [σ] vs phase-space angle $\phi = \mathrm{atan}(A_y/A_x)$	15°	30°	45°	60°	75°
LHC V6.2, Error table 9901					
Minimum over 60 seeds	11.8	11.8	13.4	13.9	15.0
Average over 60 seeds	13.3	13.6	15.3	15.5	16.1
LHC V6.4, Error table 9901					
Minimum over 60 seeds	11.7	11.4	12.8	≥ 14	≥ 14
Average over 60 seeds	13.3	13.2	≥ 13.9	≥ 14	≥ 14
LHC V6.2, Specification table					
Minimum over 60 seeds	11.5	11.6	12.4	12.9	14.5
Average over 60 seeds	12.7	13.1	≥ 13.9	≥ 14.0	≥ 14.6
LHC V6.4, New Error table for MB's					
Minimum over 60 seeds	10.1	10.2	12.4	14.5	14.2
Average over 60 seeds	11.8	12.9	14.3	16.2	15.7

$\longrightarrow$ Loss of 1.5-2 σ (but with pessimistic value for the random b_3).

Non-linear multipoles at injection. Tracking studies (2”’/3)

- *What is (are) the multipole(s) responsible for the loss of DA?*

LHC V6.4, New Error table for MB’s					
Minimum	10.1	10.2	12.4	14.5	14.2
Average	11.8	12.9	14.3	16.2	15.7
LHC V6.4, New Error table for MB’s with $\langle b_7 \rangle = 0.1$					
Minimum	9.9	10.1	12.6	14.0	14.6
Average	12.3	13.0	14.5	16.1	16.2
LHC V6.4, New Error table for MB’s with $\langle b_9 \rangle = 0.38$					
Minimum	9.7	10.2	> 12	> 12	> 12
LHC V6.4, New Error table for MB’s with $b_3^{\mathrm{ran}} = 1.4$					
Minimum	11.2	12.0	13.3	15.2	14.8
Average	12.2	13.4	14.7	16.8	15.9
LHC V6.4, New Error table for MB’s with $b_3^{\mathrm{ran}} = 1.4$ and $\langle b_7 \rangle = 0.1$					
Minimum	11.6	12.1	13.8	15.2	15.6
Average	12.6	13.6	14.9	16.8	16.8

$\longrightarrow$ DA non- or only slightly sensitive to b_7 and b_9.

$\longrightarrow$ With a reduced random b_3, the DA is almost recovered at 450 GeV (due to $\partial Q/\partial J \propto b_3^2$ **and/or** the excitation of the 3$^{\mathrm{rd}}$ order resonances).