B6 budget in the LHC quadrupoles

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- **B6 hysteresis** effects at injection in MQM and MQY magnets → a general overview
- **Comparison with MQ's**
  1. Detuning
  2. Driving terms
- **Conclusions and future plans.**

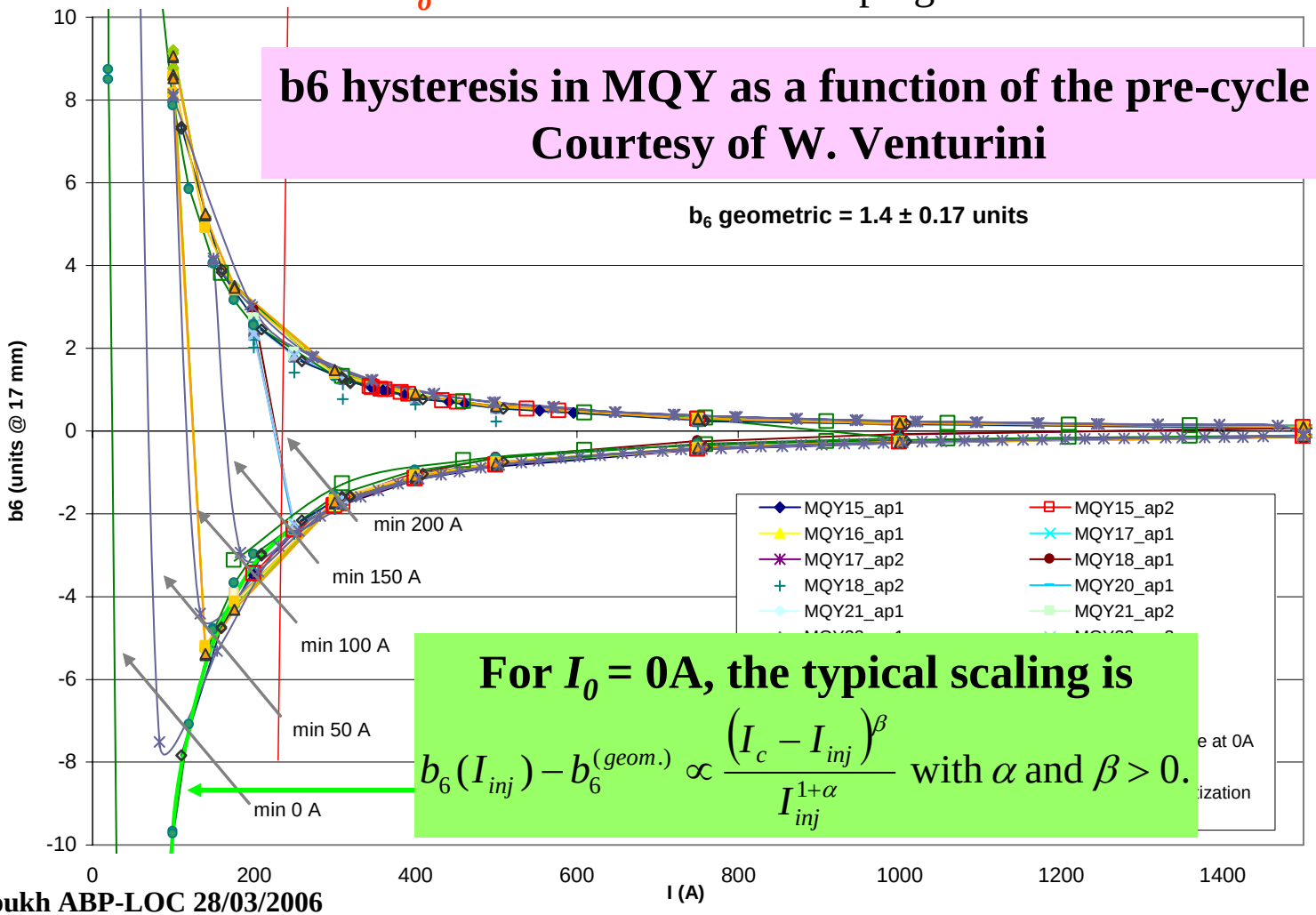
B6 hysteresis effects at injection (1/2)

Very low injection setting (< Nom. / 16) for MS and DS quadrupoles MQM& MQY

→ Inducing a **very negative b6** (and large b10) depending on

1. The **injection current** I_{inj} and the **critical current** I_c the magnet,

2. The **minimum current** I_o reached after the de-ramping

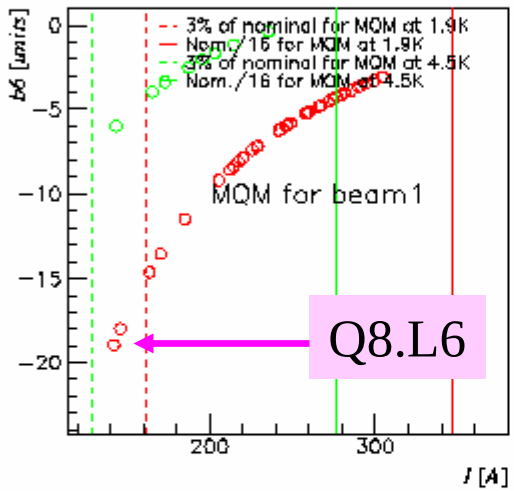


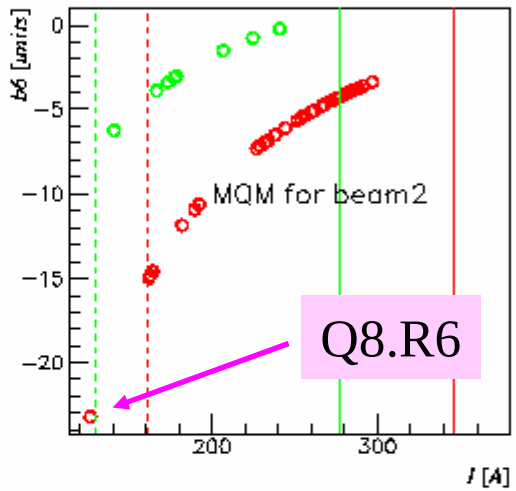
B6 hysteresis effects at injection (2/2)

→ I_o = 0 A warrants the monotony of the TF at the start of ramp and in particular during snap-back but is a worst case for b6.

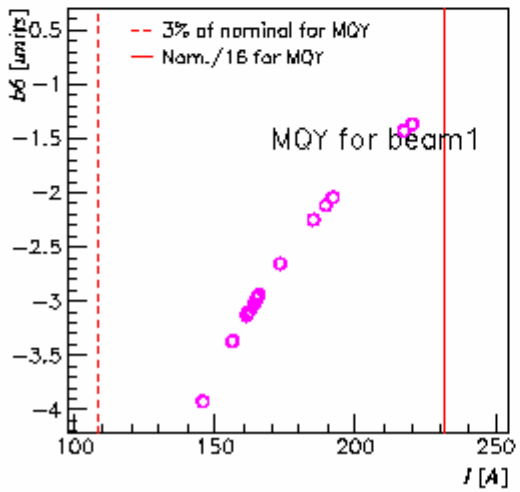
b6 estimate in **MQMs and MQYs** for LHC injection optics V6.5 based on measurement and FiDEL magnetisation model for I_0 =0A

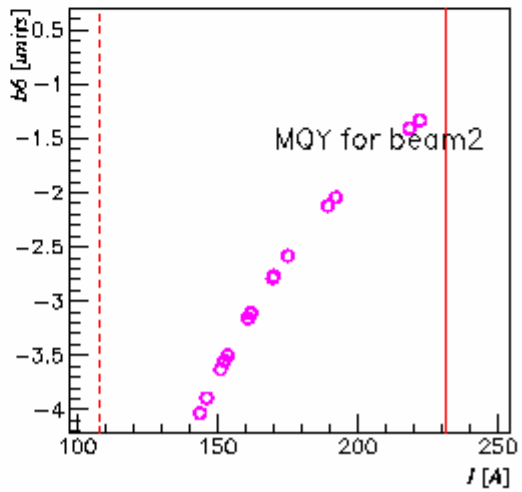
→ b6 as low as **-20→-25 units in some MQM's** :





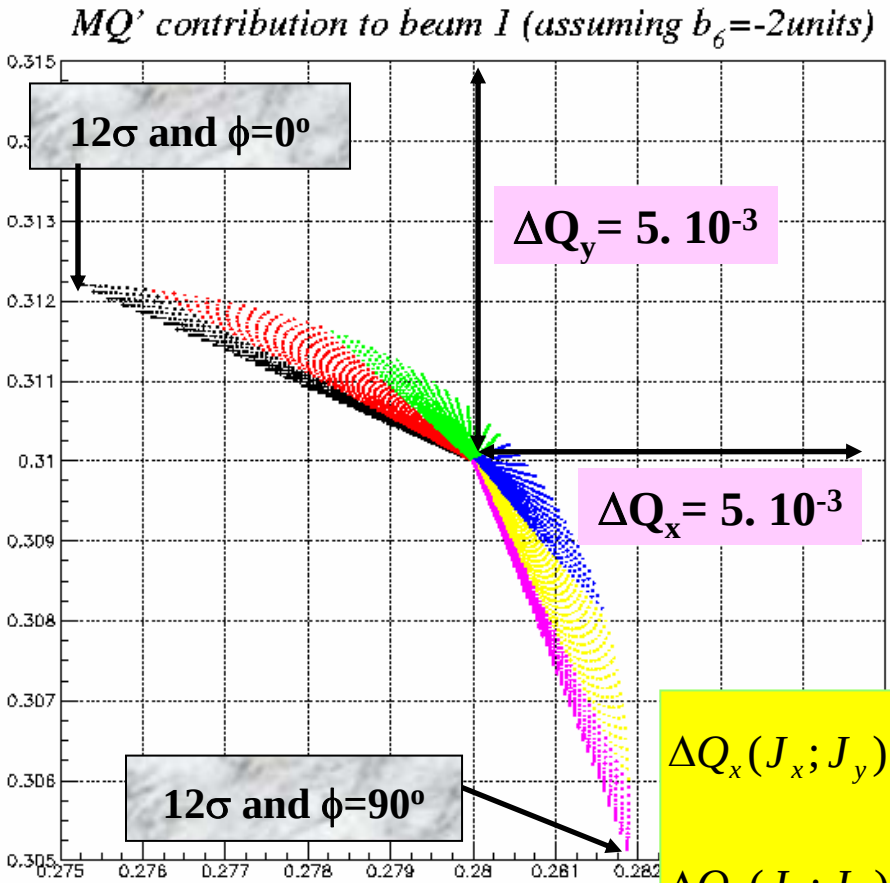
→ b6 up to **–4 units in MQY's:**





Comparison with MQ's: detuning (1/3)

• MQ **target for was set to –2<b6<0** imposed by the control of **b6-like detuning terms** (i.e. $\Delta Q \propto J^2$)



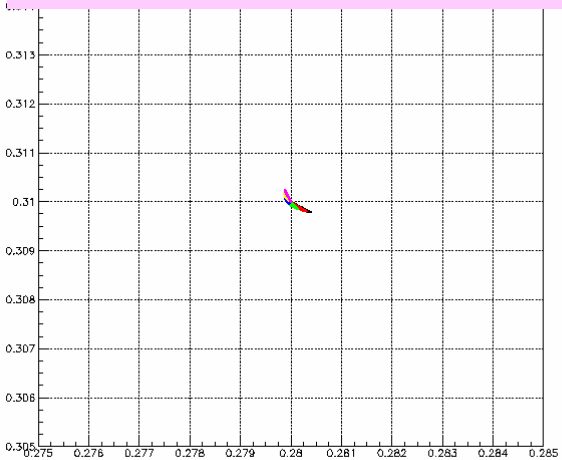
→For the overall production,
<b6> ~ 0 at injection (E.T.)!
→ **Margin of *ΔQ ~ 5. 10-3***
to be redistributed amongst MQM, MQY, MQTL and MQX

$$\Delta Q_x(J_x;J_y) \equiv \frac{(KL)\, b_6}{24\pi R_r^4}\left(15\beta_x^3 J_x^2 - 90\beta_x^2\beta_y J_x J_y + 45\beta_x\beta_y^2 J_y^2\right)$$

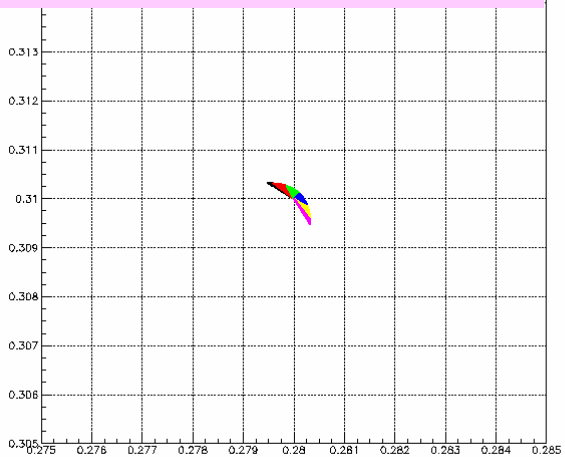
$$\Delta Q_y(J_x;J_y) \equiv -\frac{(KL)\, b_6}{24\pi R_r^4}\left(15\beta_y^3 J_y^2 - 90\beta_y^2\beta_x J_x J_y + 45\beta_y\beta_x^2 J_x^2\right)$$

Comparison with MQ's: detuning (2/3)

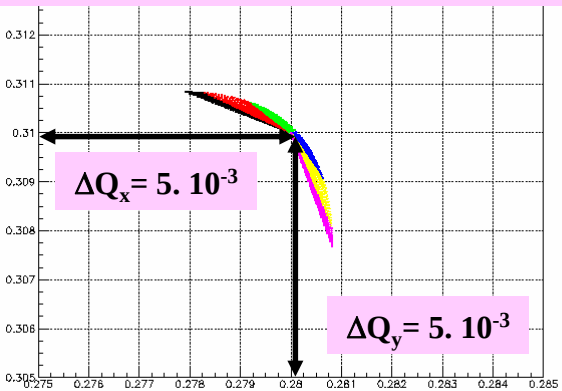
MQTL contribution (beam1)
<b6> = + 7.3 units
(as measured at warm)



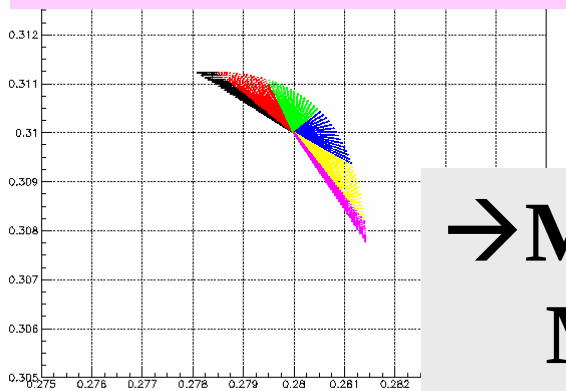
MQX contribution (beam1)
$<b6>_{MQXA/B}$ = -0.8/-1.6 units
(as measured at cold)



MQM contribution (beam1)
b6(I_{inj}) based on measurements and FiDEL model



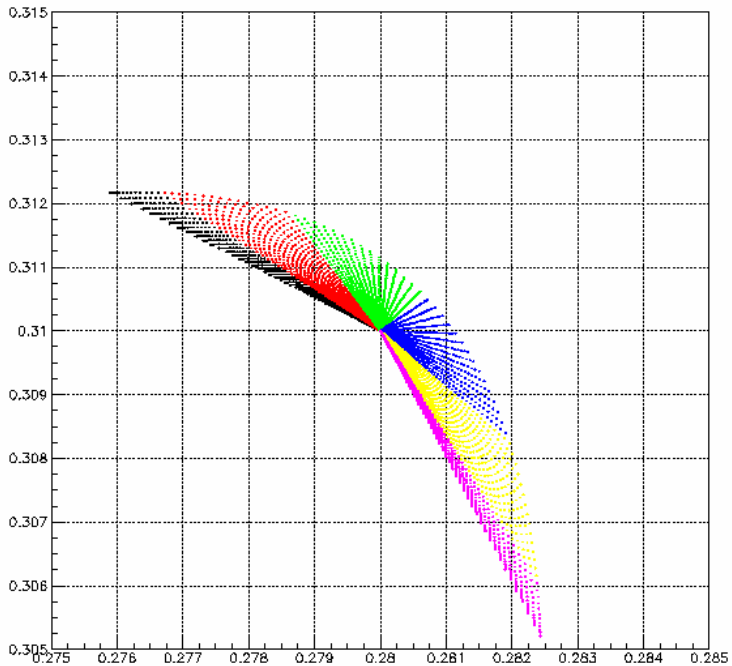
MQY contribution (beam1)
b6(I_{inj}) based on measurements and FiDEL model



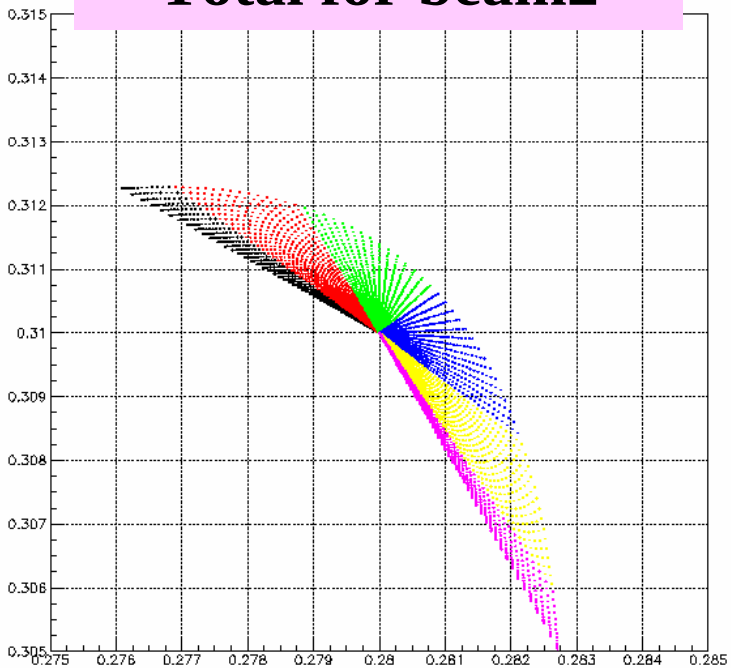
→Main contribution: MQM and MQY

Comparison with MQ's: detuning (3/3)

Total for beam1



Total for beam2



→ **Similar to <b6> = - 2units in MQs:**

$\Delta Q_x\ (12\sigma) \sim \Delta Q_y\ (12\sigma) \sim -5.\ 10^{-3}$

→ **Just at the limit**

Comparison with MQ's: driving terms (1/4)

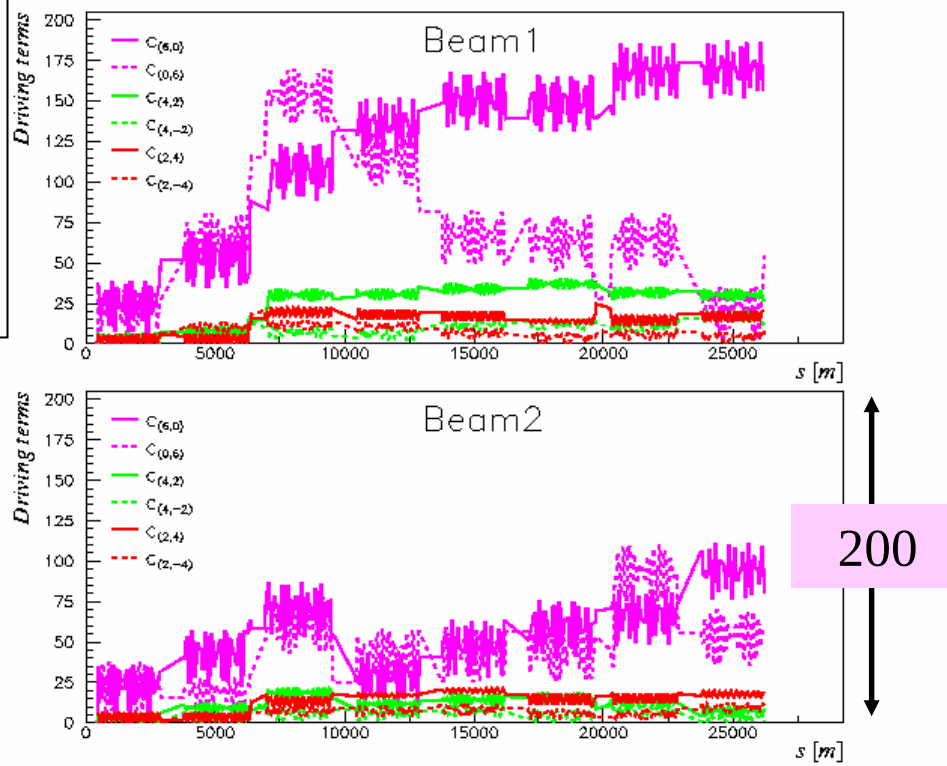
- Even if not zero, the **systematic b6** in MQ's do not really contribute to the sixth order driving terms due to **self-compensation from cell to cell** ($\pi/2$ phase advance in the LHC arc cell):

- Then, the contribution from the **random b6** is typically 400 r.m.s.:

$$c_{(0,6)}^{(r.m.s)} \alpha \sqrt{N_{QD}}\,(KL)\,\beta_{\max}^{3}\,\sigma_{b6} \sim 400$$

$$\text{for } \sigma_{b6} = 1.75 \text{ units r.m.s. (E.T.)}$$

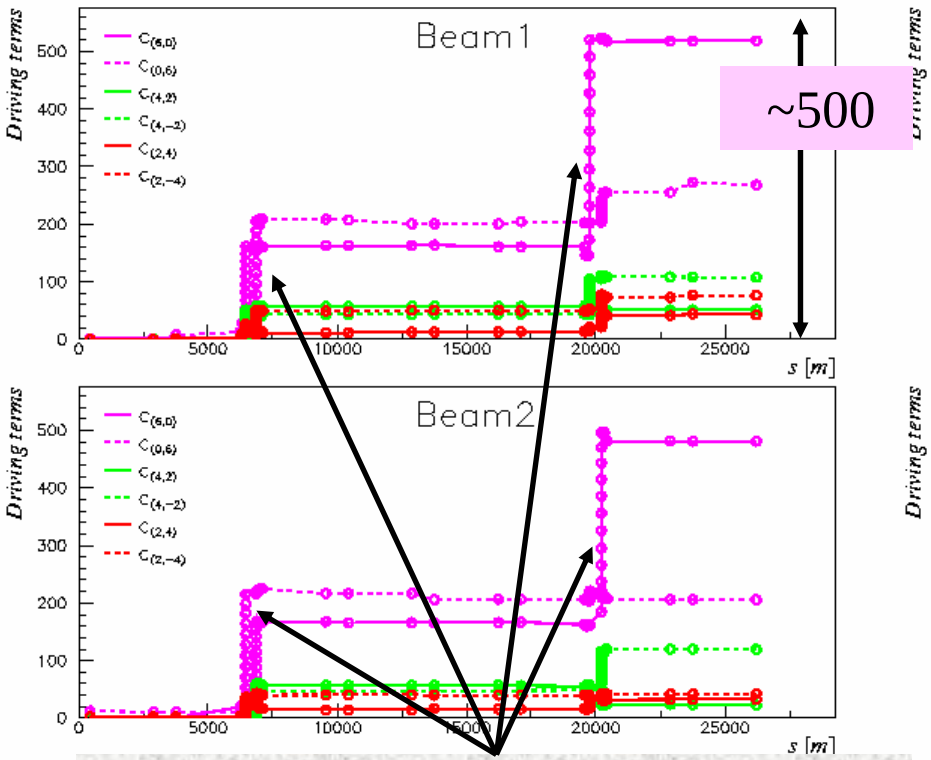
Example with <b6>= - 2 units in MQs



→ **While much less stronger than the MQs, DS and MS magnets will dominate in particular MQYs in IR4 and IR6 (high beta's).**

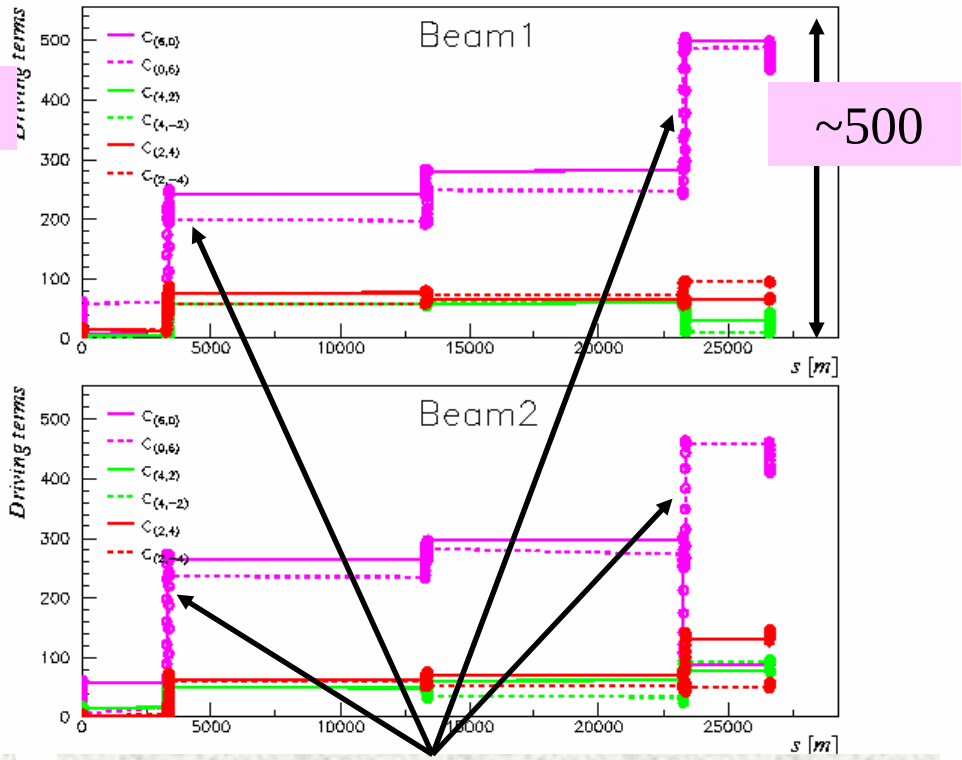
Comparison with MQ's: driving terms (2/4)

MQTL contribution



→ Main contribution: Q6 in IR3 and IR7

MQX contribution

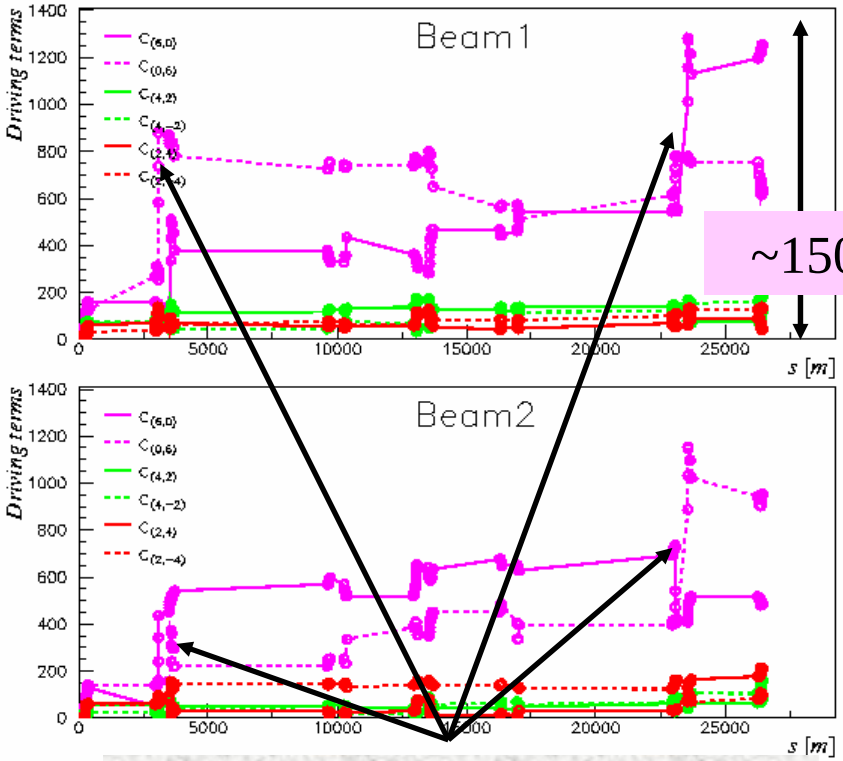


→ **Main contribution: IR2 and IR8 (β*=10 m)**

→ **Still comparable to the contribution of the MQ random b6**

Comparison with MQ's: driving terms (3/4)

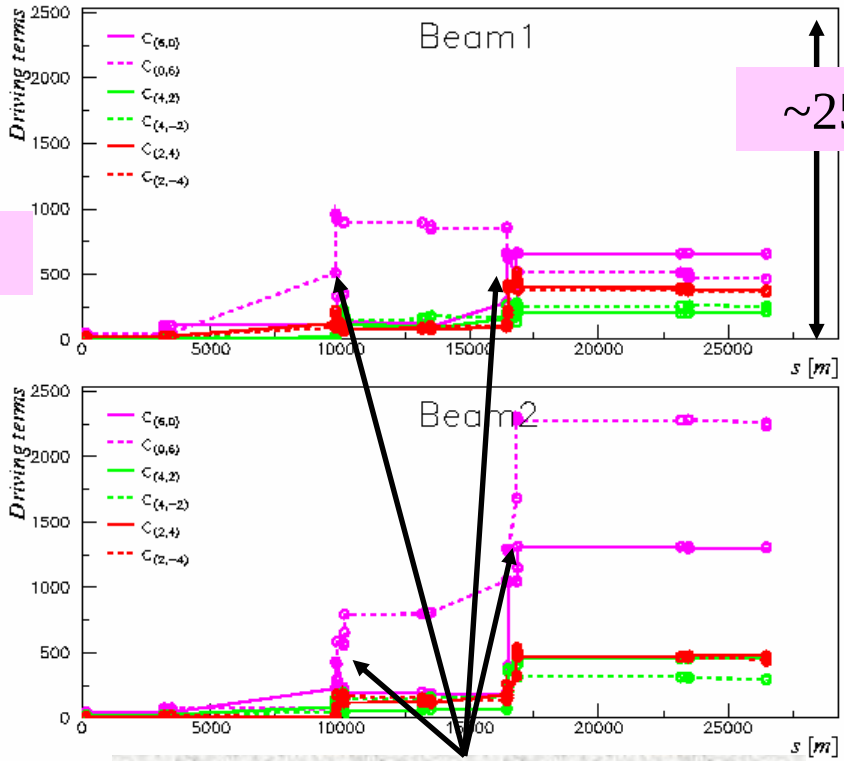
MQM contribution



~1500

→ Main contribution: IR2 and IR8

MQY contribution



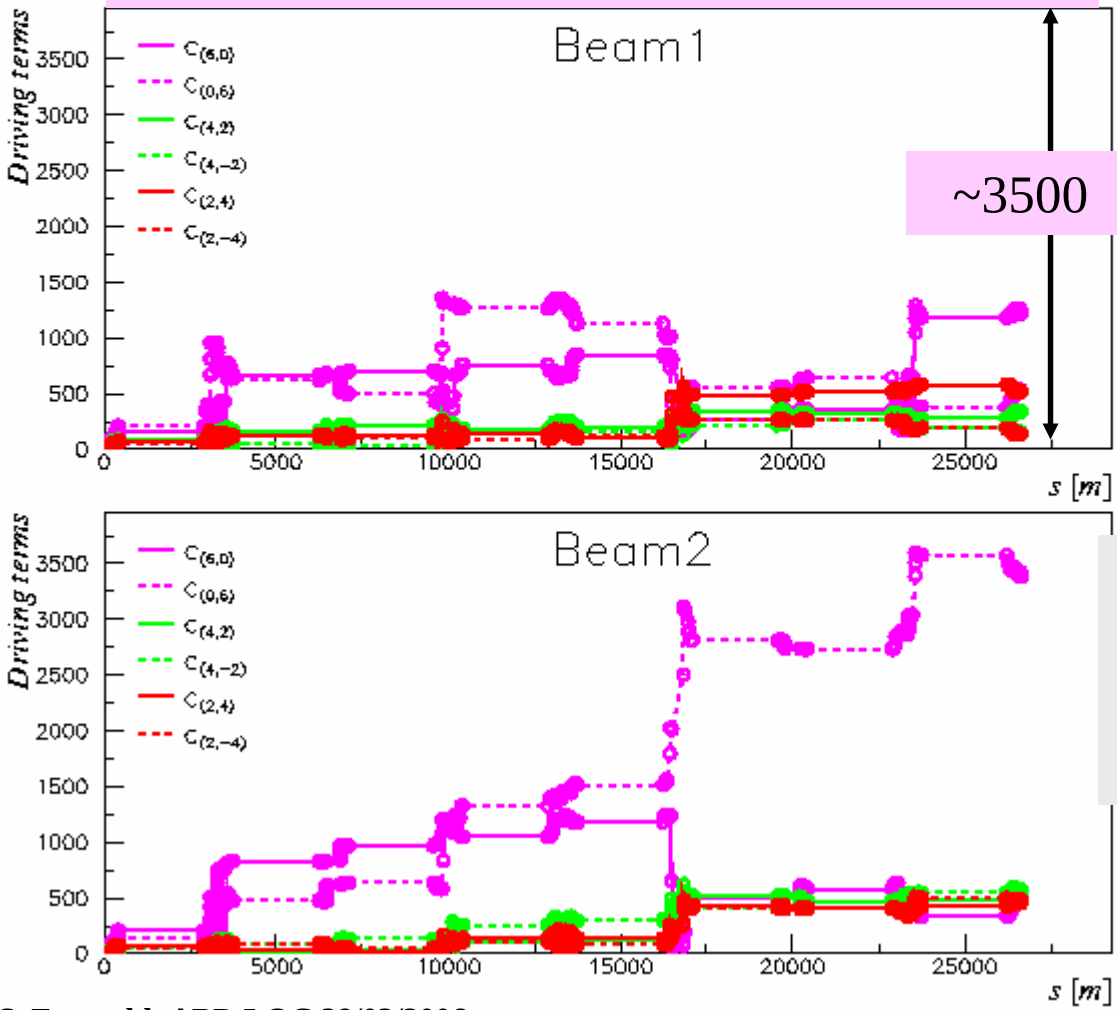
~2500

→ **Main contribution: IR4 and IR6**

→ MQY (IR4/IR6) dominant with dissymmetry beam1/2 (≠ phase advance in ring1 and ring 2 between the few critical MQYs)

Comparison with MQ's: driving terms (4/4)

All contributions (MQM, MQY, MQTL, MQX)



→ **One order of magnitude higher than the contribution of the MQ random b6!**

→ **Worst case is beam 2 for LHC V6.5, conversely for LHC V6.4**

Conclusions and future plans

- At injection, the main contribution to b6 comes from the **MQM/MQY** magnets (huge hysteresis effect for magnets with low injection settings).
  1. Inducing an **amplitude detuning of the order of 0.005 at 12σ** just at the limit.
  2. Exciting the **sixth order driving terms,** in particular the most dangerous one $c_{(6,0)}$ (one order of magnitude larger compared to MQ contribution)
  3. Possibly **dissymmetrising** the non-linear dynamics in beam1 and beam2.

- **DA tracking studies** still needed to fully assess the impact of the b6 (and b10) hysteresis effects in MQMs and MQYs.

→ Should the impact be large, possible cures are

1. A correction of the driving terms by **the use of MCTX triplet corrector magnets.**

2. Dedicated cycles for each MQM/MQY magnets in view of magnet to magnet self-compensation but with some draw-backs at the beginning of the ramp and an increase of complexity.