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THE MAGNETIC MODEL OF THE LARGE HADRON COLLIDER IN THE EARLY PHASE OF BEAM COMMISSIONING

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The Magnetic Model of the LHC

- Relation between current and field for every type of LHC magnet
  - With its dependence on previous currents (history) to take into account
    - Hysteresis
    - Dynamic effects
- Based on the magnetic measurements carried out during the LHC construction
- Empirical set of equations whose parameters are fit to measurements
  - Components: geometric, magnetization, saturation, decay, ...
- Implemented in the LHC control system LSA

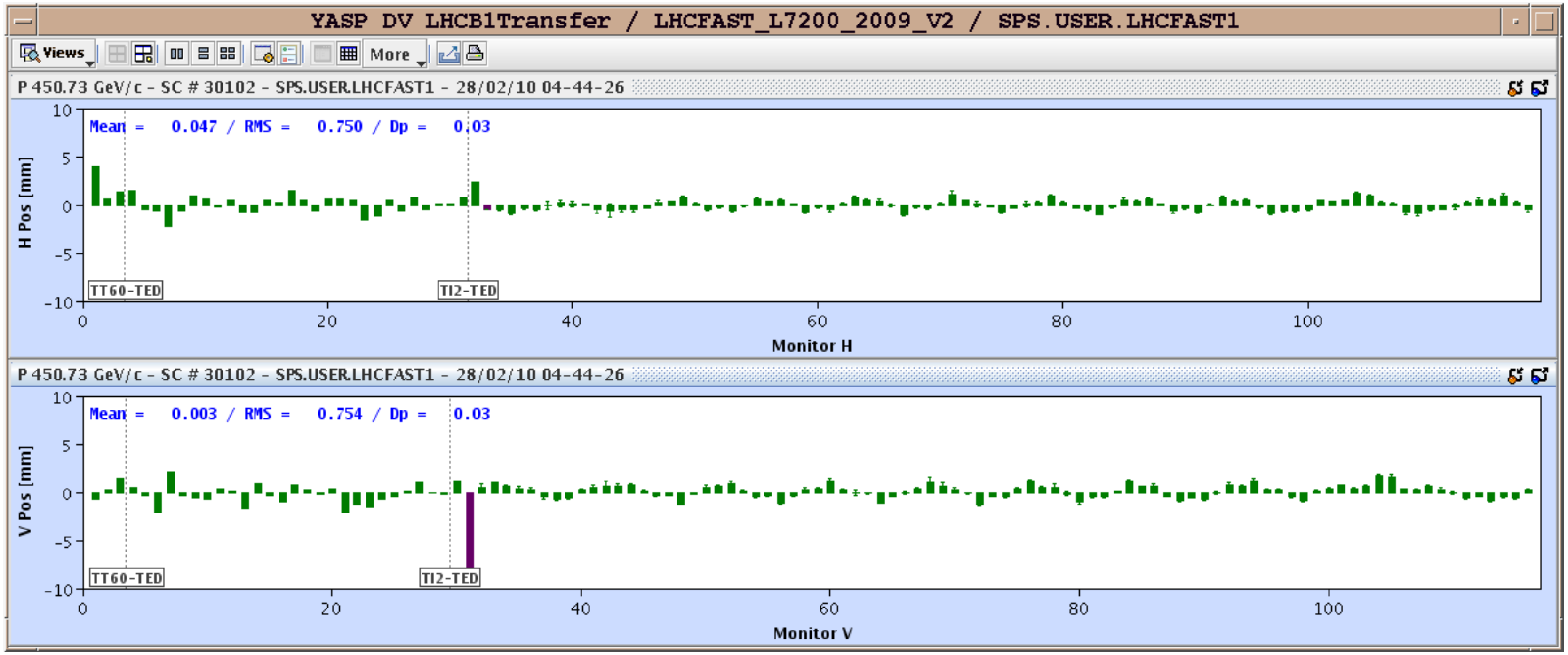
OUTLINE OF COMMISSIONING CONDITIONS

- 2009: ~1 month of operation
  - Dipoles limited at 2 kA (1.2 TeV), ramp rate 10 A/s
  - Stable beams at 450 GeV
  - Ramps at 1.2 TeV, with beta- beating measurements
  - At 1.2 TeV, squeeze of the optics up to 7 m

- 2010: ~ 3 months of operation
  - Dipoles limited at 6 kA (3.5 TeV), ramp rate limited to 2 A/s
  - Stable beams at 450 GeV
  - Ramp at 3.5 TeV, with beta- beating measurements
  - At 3.5 TeV, squeeze of the optics up to 2 m

ORBIT

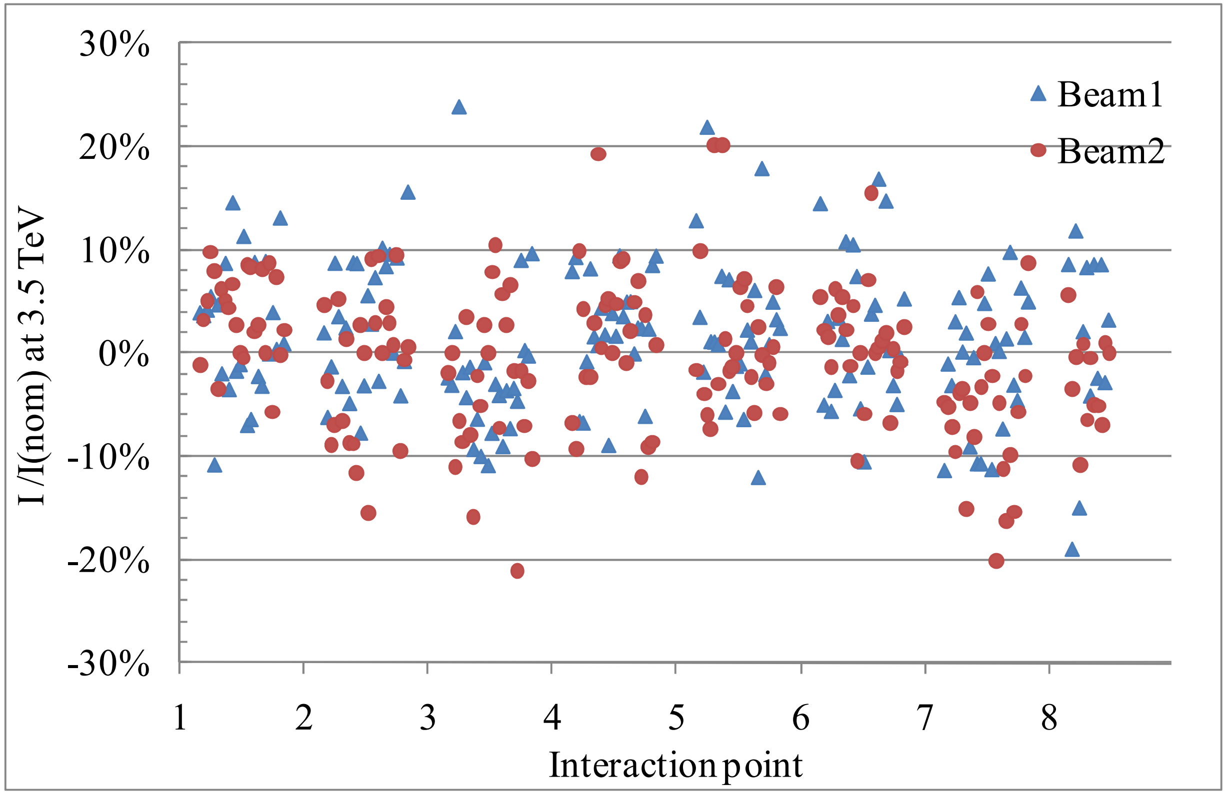
- Steering of the orbit successful
  - No problem with hysteresis of the correctors



Orbit on 27th February 2010, after restart

ORBIT

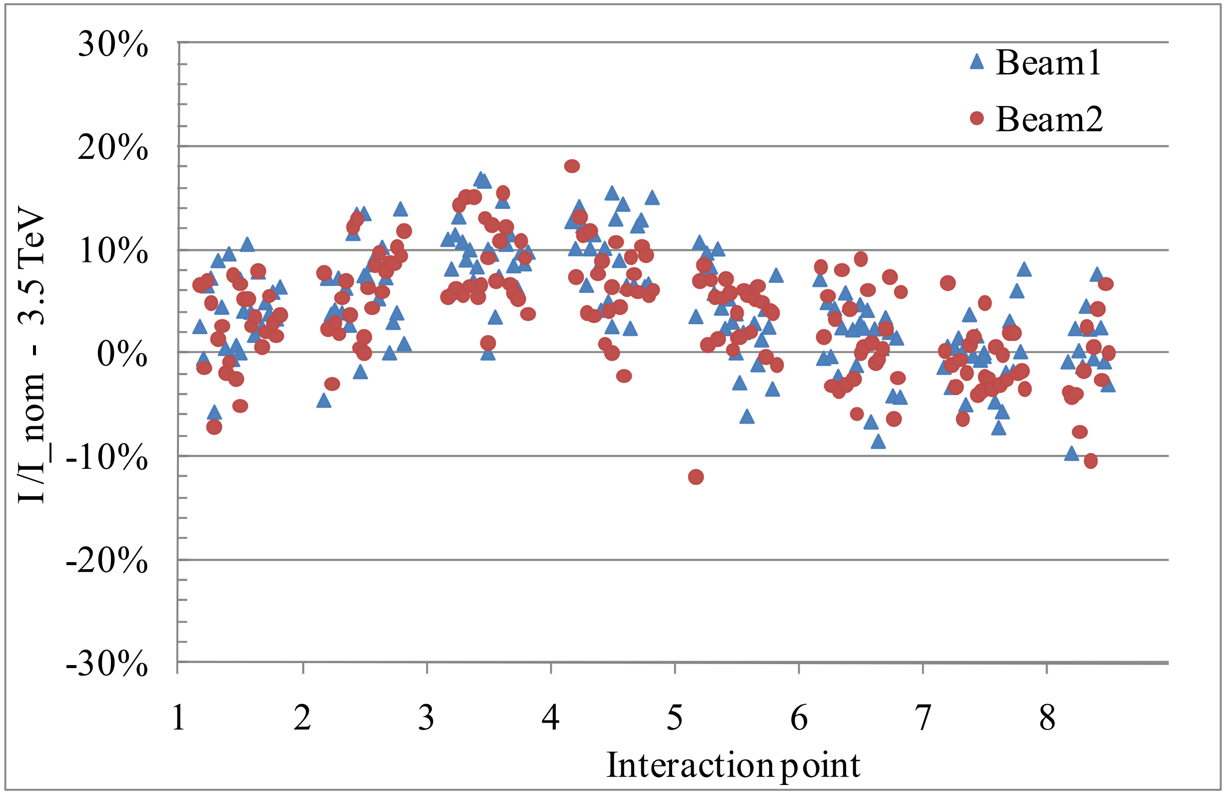
- At 3.5 TeV, we use up to 20% of the corrector strength
  - We should have no problems at 7 TeV



Used strength in horizontal orbit correctors on April 1st at 18h16m

ORBIT

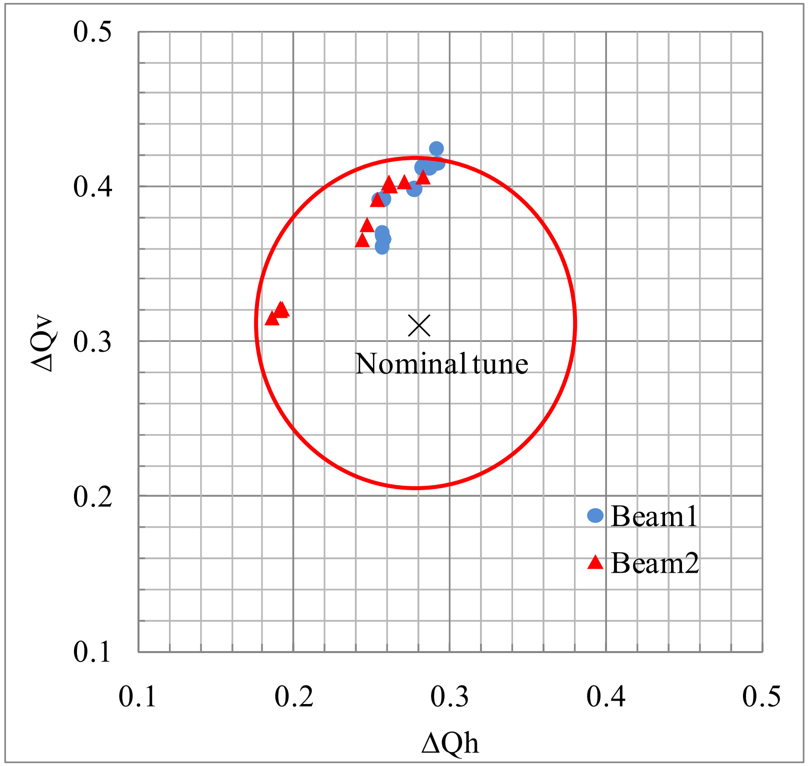
- Strange pattern in the vertical orbit correctors
  - Systematic offset in 3 sectors of about 1-2 mm – not understood



Used strength in vertical orbit correctors on April 1st at 18h16m

TUNE

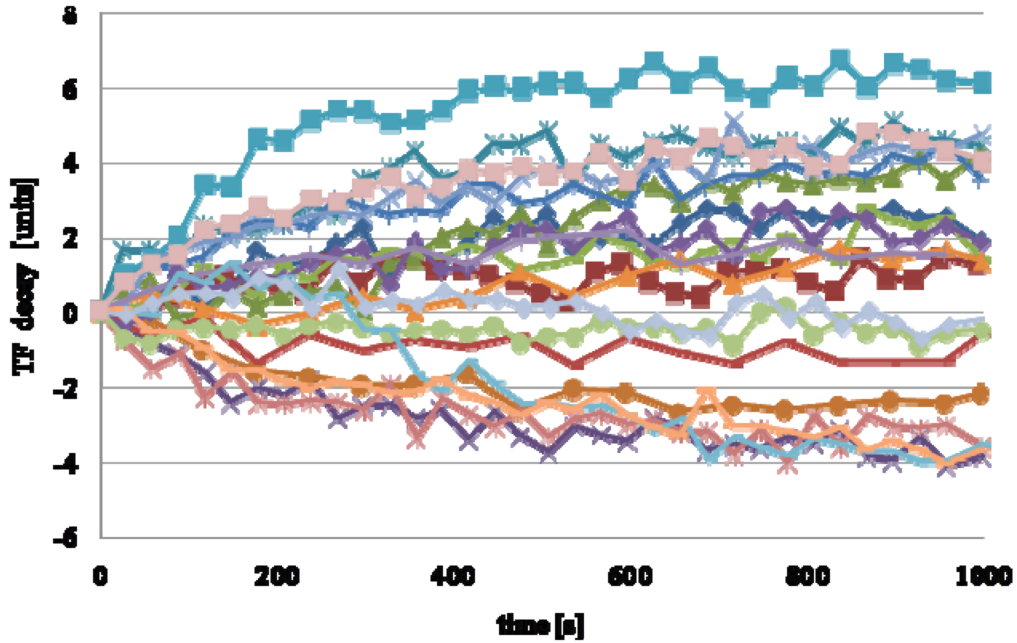
- At 450 GeV tune of the bare machine agrees within ~0.1 from nominal (59.28, 64.31) 0.1/60 ~0.16%
  - This implies a 0.1% error on absolute knowledge of B_2, B_1 !!!



Reconstructed tune of the bare machine in 13 ramps, 2009 and 2010

TUNE SNAPBACK

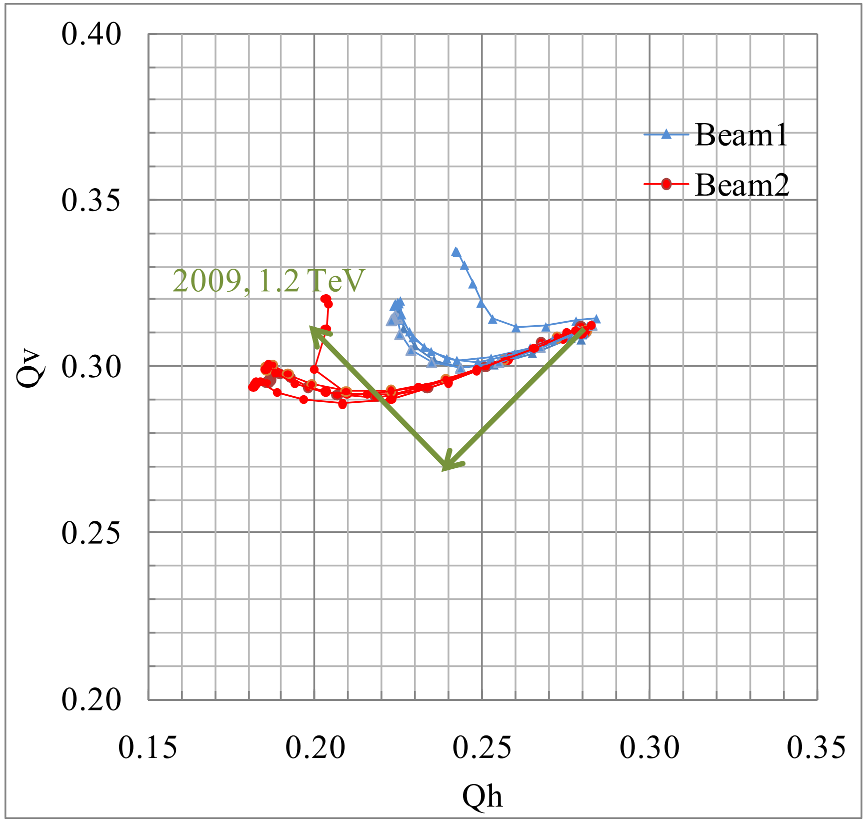
- At the beginning of the ramp the tune drifts by less than 0.005 0.005/60 ~0.01%
  - This implies that the snapback of main component in dipole and quadrupoles is smaller than 0.01% (1 unit), as measured



Decay of the main component of the main quadrupoles measured during individual test

Tune drift during ramp

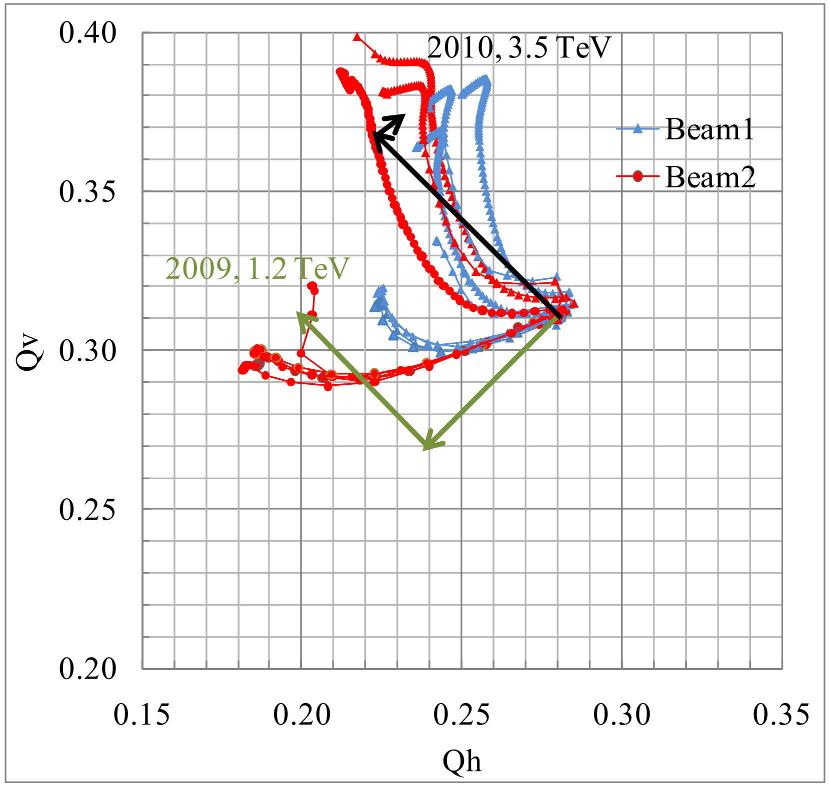
- 2009: tune drift during ramp at 1.2 TeV of about 0.1
  - Corrected through feedback system without problem



Drift of the tune during ramp at 1.2 TeV, 7 ramps in 2009

Tune drift during ramp

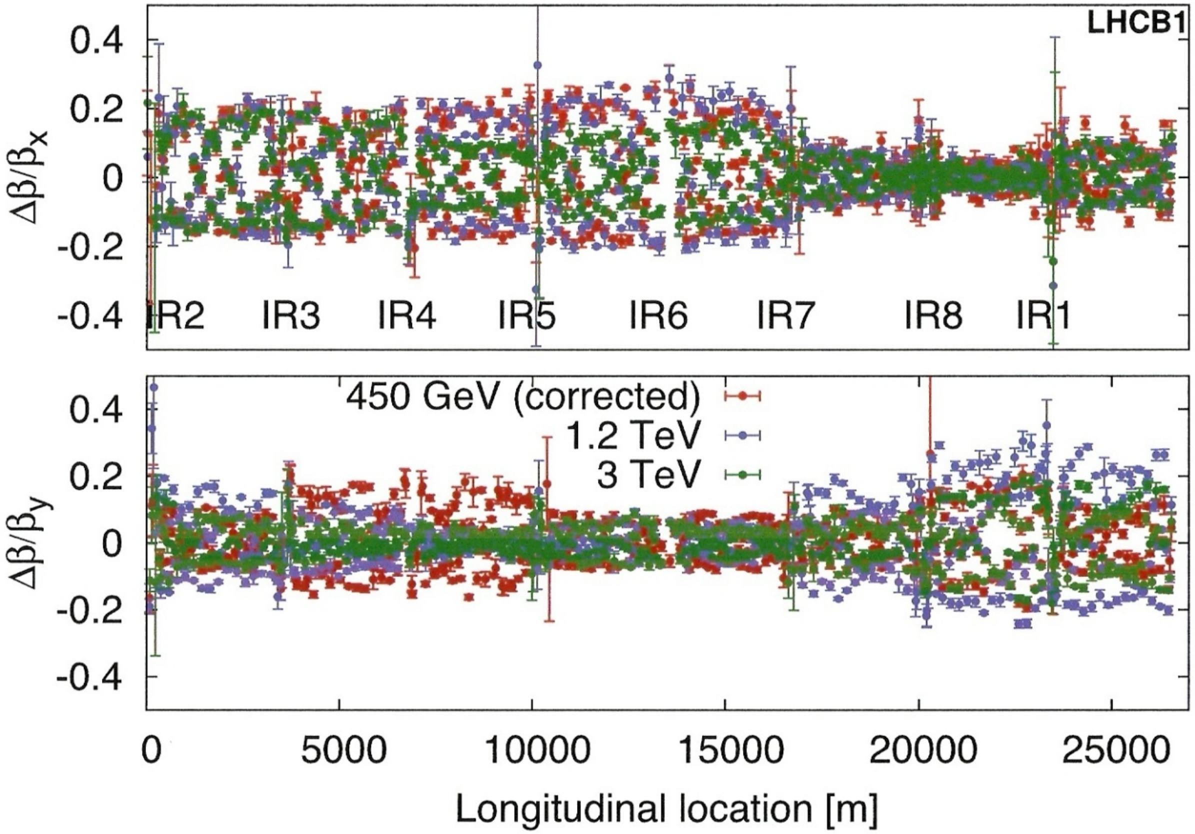
- 2010: correction of wrong precycle of resistive quadrupoles MQWA accounting for -0.04 drift along the diagonal
  - Drift along the diagonal disappears – residual drift unknown origin



Drift of the tune during ramp at 1.2 TeV, 7 ramps in 2009-10, and at 3.5 TeV, 6 ramps in 2010

BETA BEATING

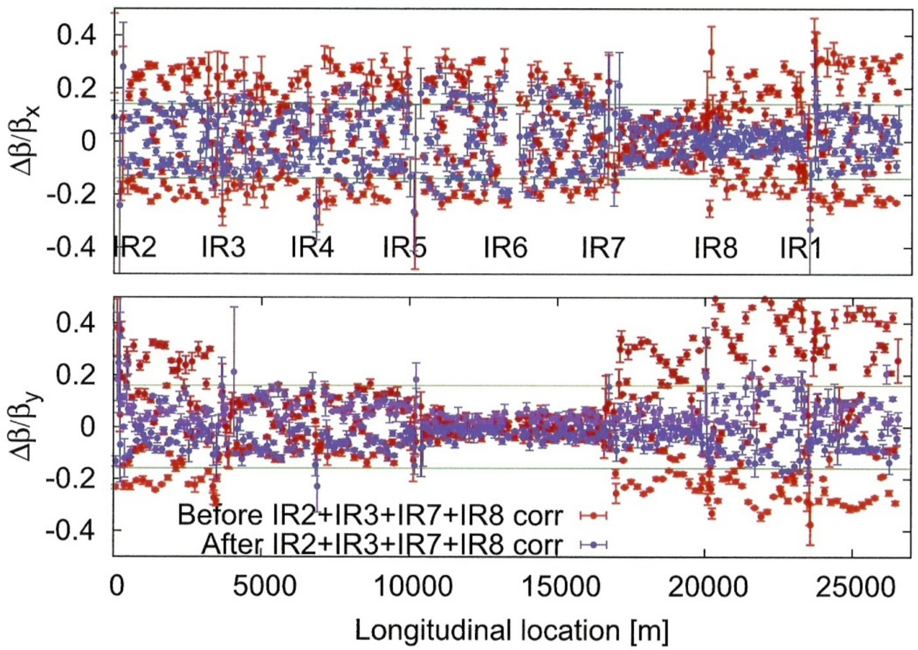
- Within 20% at 1.2 and at 3.5 TeV !!!
- 50% at injection (not so bad)



Beta beating at injection, 1.2 TeV and 3.5 TeV ,and at 450 GeV, corrected

Beta beating

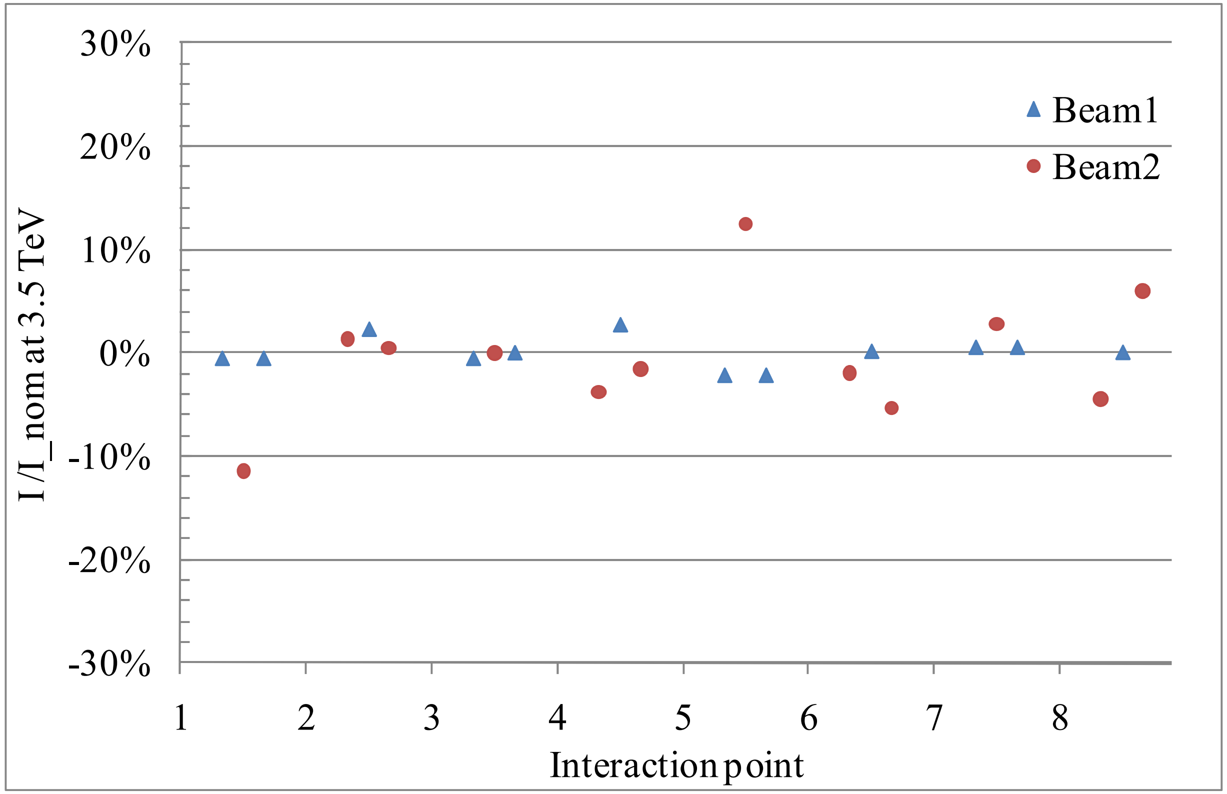
- Correction resistive quadrupoles (3%) and inner triplet (0.5%) brings it back to nominal also at injection
  - After correction of precycle in resistive quadrupoles reduced to 1.8%
  - New settings based on additional magnetic measurements



Beta beating before and after correction at injection energy (450 GeV)

COUPLING

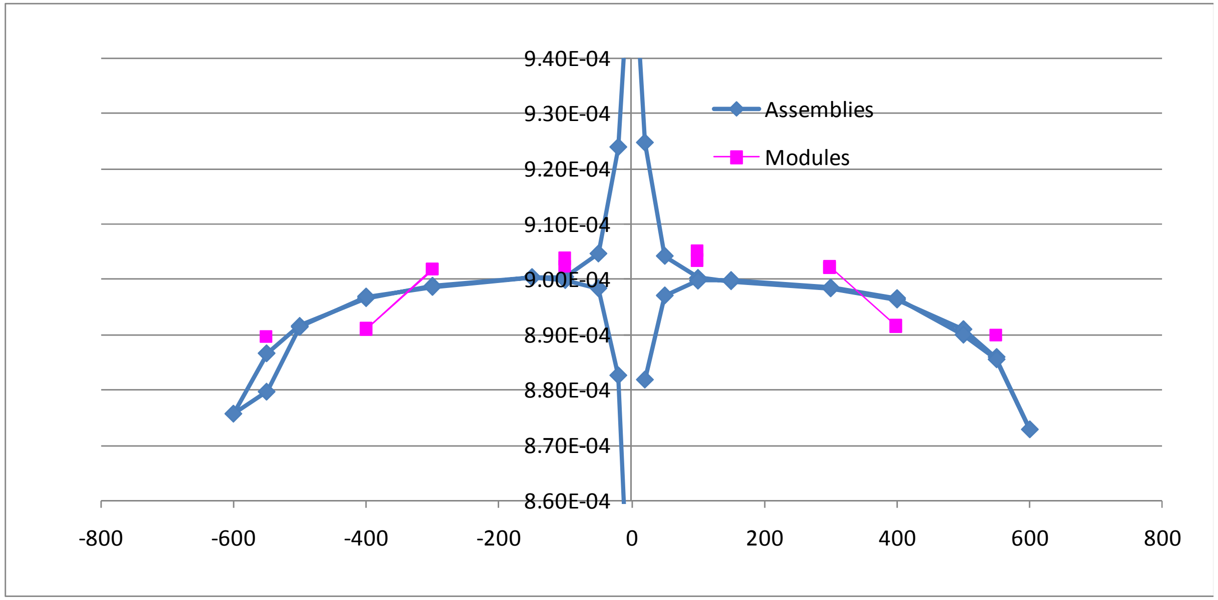
- Coupling corrected through 24 families of skew sextupoles
  - Three per octant
  - At 3.5 TeV powered at ~5%, up to a maximum of 15%



Strength of the skew sextupoles used at 3.5 TeV, April 1st at 18h20m

CHROMATICITY

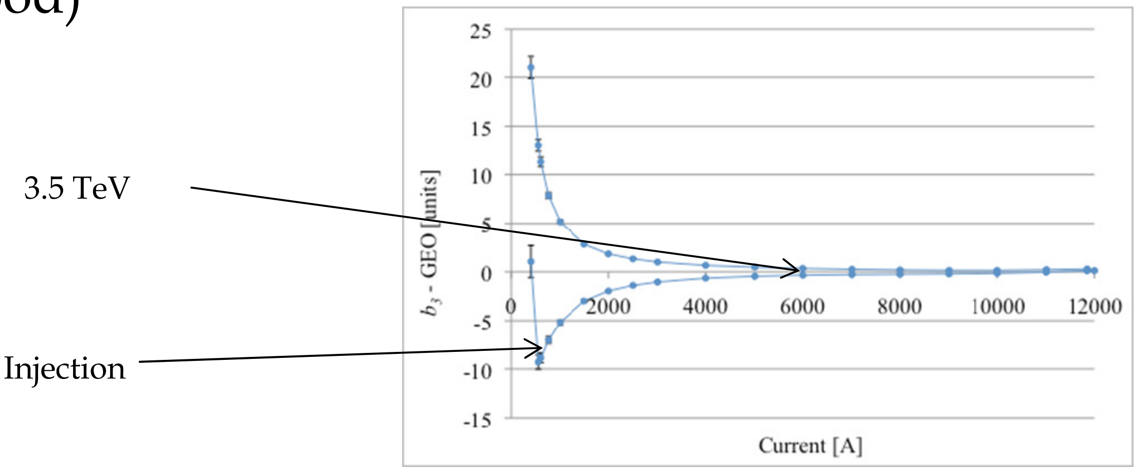
- Natural chromaticity of 85 corrected through lattice sextupoles – constant during the ramp
  - Their settings are 5 -10 A at injection where the magnet transfer function is non-linear (of the order of 10%)
  - But with a couple of iterations fine tuning of chromaticity works



Measured hysteresis of the transfer function of corrector sextupoles

CHROMATICITY

- Additional -180 units of chromaticity at injection from the b_3 in the dipoles (-4 units) is corrected through spool pieces
  - During ramp this contribution changes from -180 to +130
- Stability of chromaticity at injection is within 15 units
  - 0.3 units of b_3
- During the ramp, chromaticity is reduced by about 15 units
  - This corresponds to correcting up to 0.3 units of b_3 (out of 7, i.e. 5% error – very good)



Chromaticity - Snapback

- We are ramping at 2 A/s and having a precycle of a physics run at 6 kA
  - These conditions are very far from what we measured (10 A/s)
  - At 6 kA 2 A/s we should have 0.1 units snapback
  - We rather see 0.5 units – to be further analysed

CONCLUSIONS

- LHC field model well established
  - B2/B1 tracking 0.16%
  - No tune, no coupling decay or snapback
  - Correction of b_3 in the dipoles during ramp within 5%
  - Beta beating within 20% at 1.2 and 3.5 TeV
  - Orbit and tune feedback effective – negligible hysteresis
  - Chromaticity steering works

- Critical points
  - Some corrections needed at injection on MQW, MQX – under analysis – related to residual magnetization
  - Orbit vertical drift ?
  - Tune drift origin
  - Chromaticity reproducibility and drift during ramp