Preliminary studies of beam-beam long range effects: orbit, tunes, chromaticity…

T. Pieloni, X. Barranco, D. Banfi, X. Buffat, C. Tambasco

Acknowledgements: H. Grote, W. Herr, R. Tomas

TRAIN CODE: some history...

F. C. Iselin TRAIN code for LEP: post-processor to MAD

Used by **E. Keil** for LEP studies:
"Truly Self-Consistent Treatment of the Side Effects with Bunch Trains", CERN/SL/95-075 (AP)

H. Grote and W. Herr made LHC studies with bunch trains:
"Self-Consistent Orbits with Beam-Beam Effects in the LHC", LHC Project Report 404 (2000)
"Nominal and Ultimate Luminosity Performance of the LHC", LHC Project Report 275 (2001)
"Features and Implications of different LHC crossing schemes", LHC Project Report 628 (2003) **all pictures for comparison to LHC are from this note**

...and much more....**and still a lot to be done!**

TRAIN

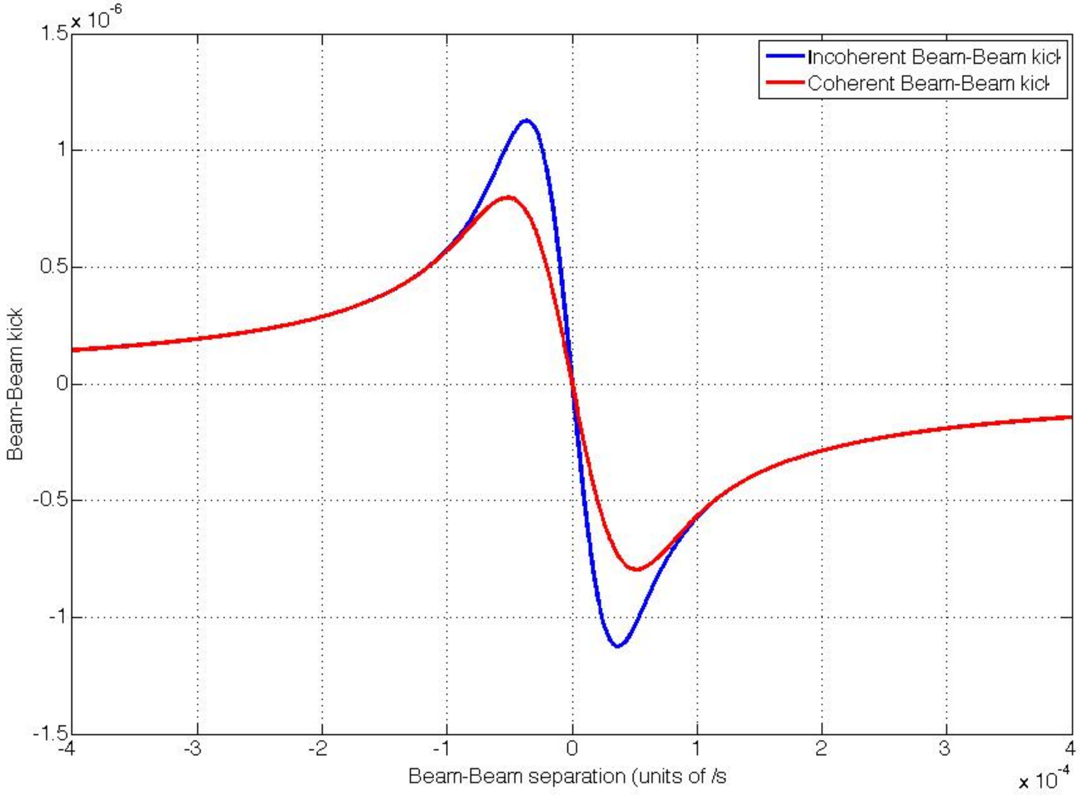
- **Written in 1994/95 By F. C. Iselin, FORTRAN 77 around 14000 lines…**
  Computes the orbit, tune, chromaticity and luminosity reductions (due to orbit offsets) for each bunch in a train self-consistently
- **MADX** part: 1st and 2nd order MAPS between collision points with BB elements and IP configurations: usual things…
  - Set-up the **optics**: crossing angles, separation bumps, using thin optics versions
  - Install the **BB elements** on LHCB2 backward "b" and LHCB1 forward beam "f"
  - Produce **2 files**: 1st "train.opt" and 2nd order maps "train.map" for both beams

- **TRAIN:**
  - Reads the MADX files
  - Reads filling scheme for B1 and B2 and bbb currents: allows for random variations of bunch by bunch currents or reads from bunch current files (direct read from measurements for LEP and LHC)
  - **TRAIN computes the coherent BB kicks** (describes the dipolar kick a bunch as a whole will receive) at each BB element

→

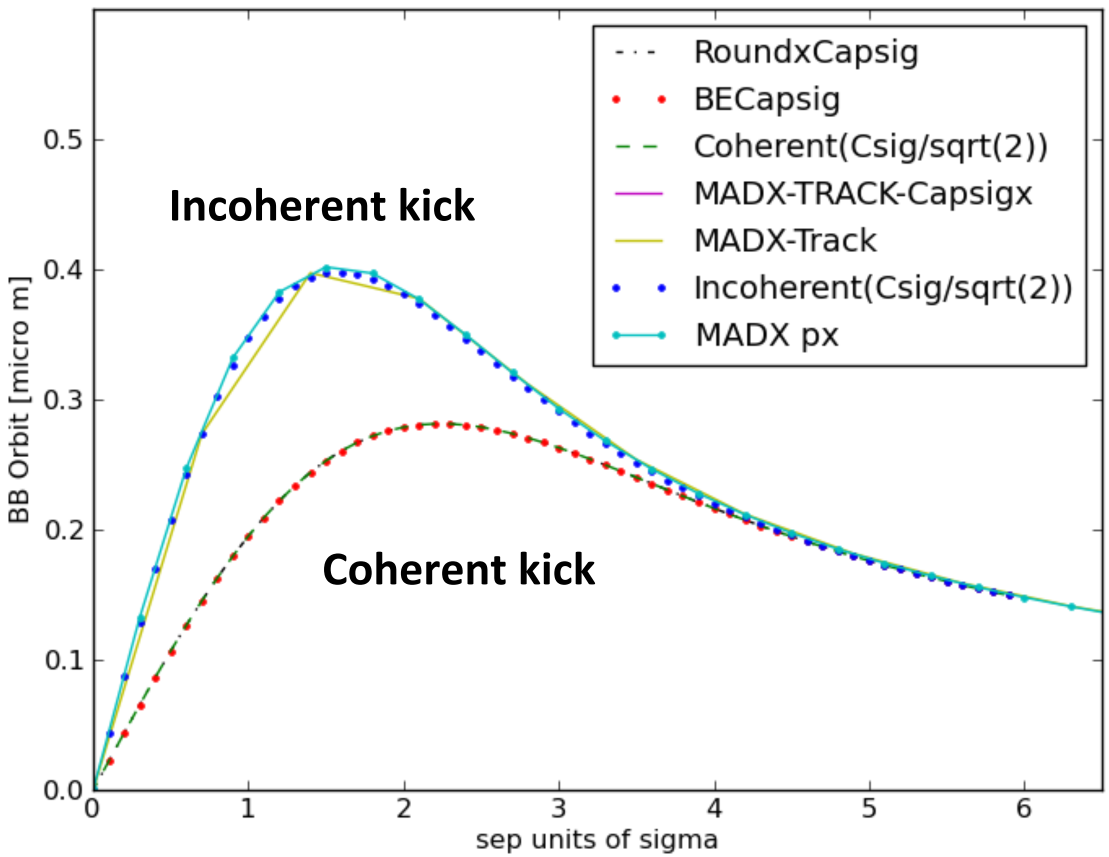
- Finds the **closed orbit** of all bunches which circulates and collide at parasitic and main IPs (HO and LR as defined in initial MADX file) with the coherent BB kicks ON
- Computes the **orbit parameters on these individual orbits** for each bunch and iterates
- Computes linear **ONE-TURN map** of the system of all bunches (coupled by BB effects) and calculates the eigenvalues (**frequencies** of coherent BB modes and **chromaticities**)

Beam-Beam kicks



Incoherent kick (single particle like in MADX) and Coherent kick (bunch)
TRAIN calculates the coherent BB kicks at each BB element:
Bassetti-Erskine formula for the incoherent kick
replacing the beam $\sigma_x^2 - \sigma_y^2$ with $2\sigma_x^2 - 2\sigma_y^2$ for $d_{sep} < 1\ \sigma$
Allows for round as well as flat beams configurations
This could be eventually be improved!

The approximation of the kicks:



$$\Sigma = 2\sigma^2$$

Same approximation we use to compute the orbit deflection on VdM scans: can use MADX or analytical formula

LHC IP5 only:

- Intensity 1.15e11 ppb
- Emittance 3.75 (16.6 μm at IP)
- Nominal LHC optic β* 0.55 collision
- 15 LR per side of IP
- IP5 only: H crossing (285 μrad)
- Nominal LHC filling scheme 25 ns

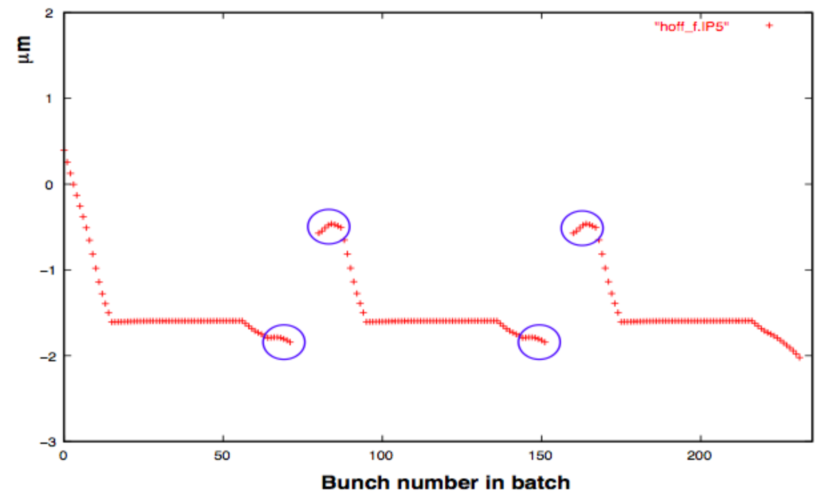
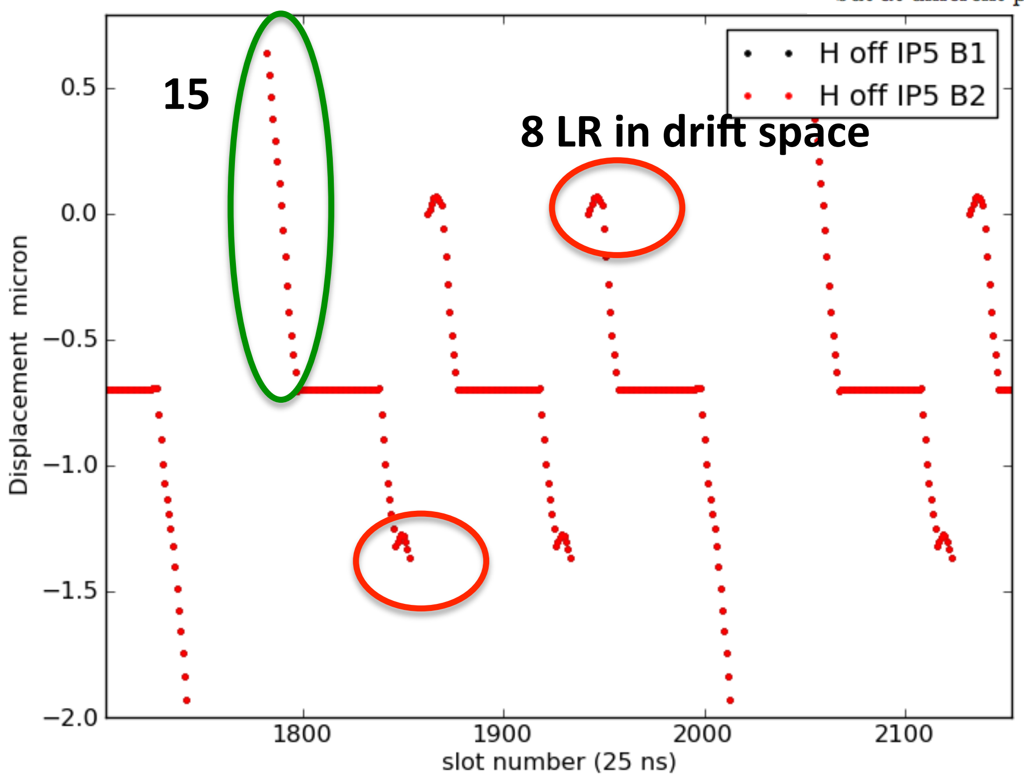


Figure 8: Horizontal offset in IP5 with horizontal-horizontal crossing. Details in first three batches. Indicated bunches have all the same number of long range interactions (i.e. 22), but at different positions. Leftmost and rightmost bunches miss 15 long range interactions.



LHC filling scheme:

38-39 empty slots for LHC injection kicker
And 8 empty slots between trains of 72
due to SPS injection kicker

Orbit variation of 1 μm due to long-range deflection

IP5 H&V offset

- Intensity 1.15e11 ppb
- Emittance 3.75 (16.6 μm at IP)
- Nominal LHC optic β* 0.55 collision
- 15 LR per side of IP
- IP5 only H crossing (285 μrad)
- Nominal LHC filling scheme 25 ns

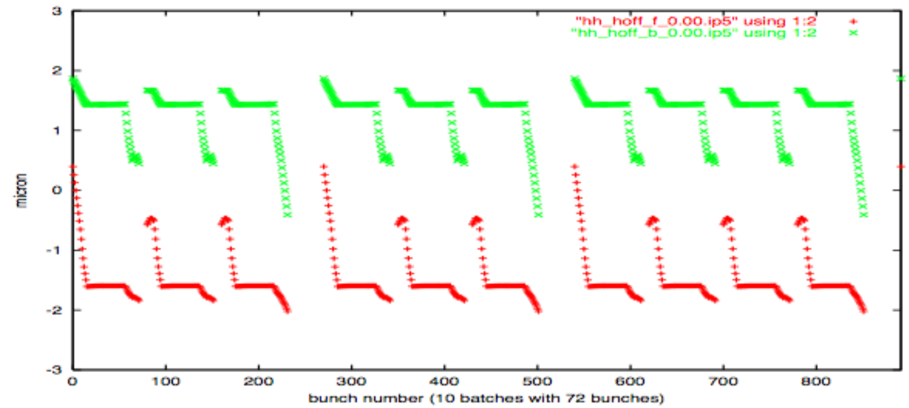
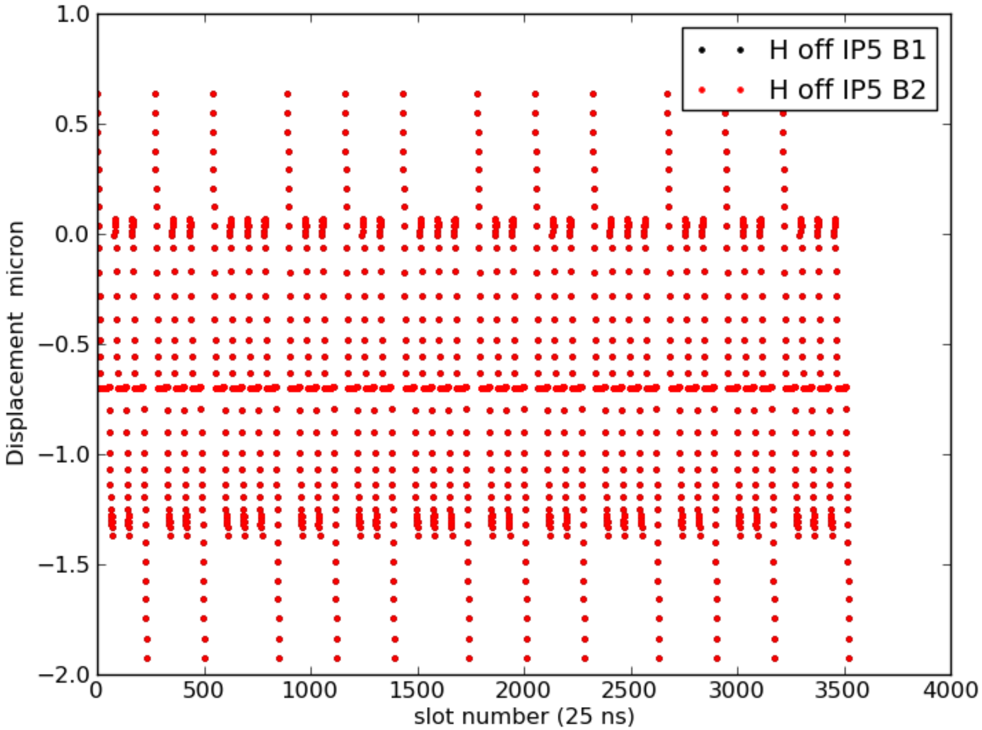
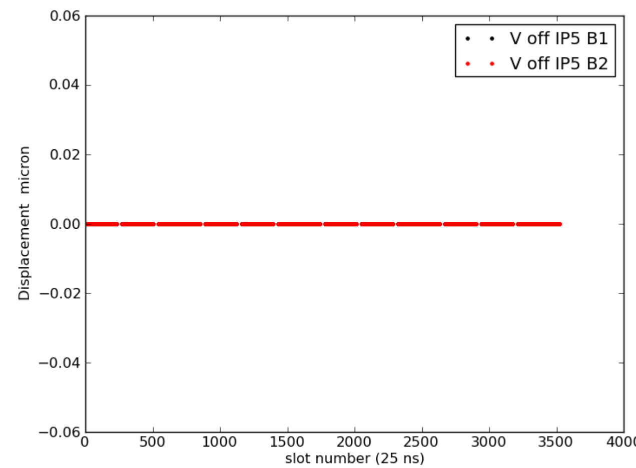


Figure 11: Horizontal offset in IP5 with horizontal-horizontal crossing.





IP5&IP1 Collisions HV crossing: we observe in IP1

For IP1

Separation Plane: H
These effects come LR in IP5

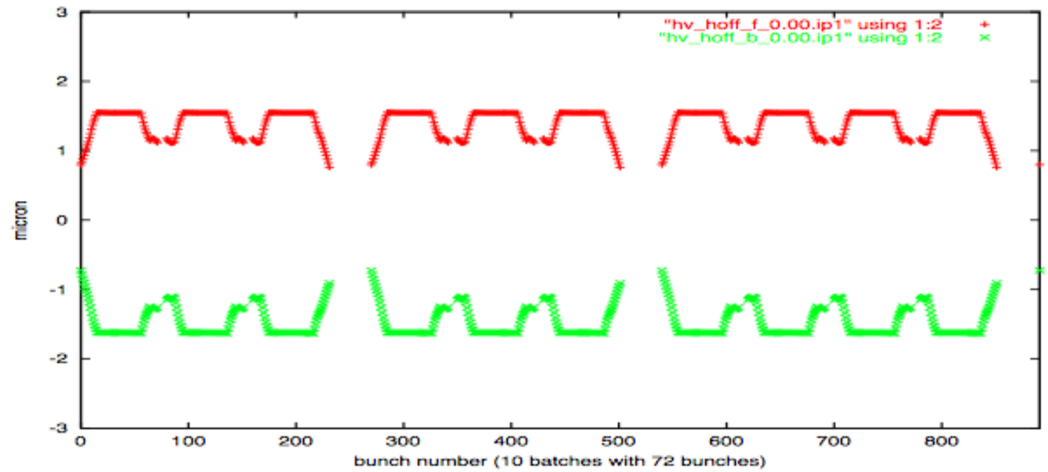


Figure 14: Horizontal offset in IP1 with vertical-horizontal crossing.

Crossing plane: V
These effects come LR in IP1

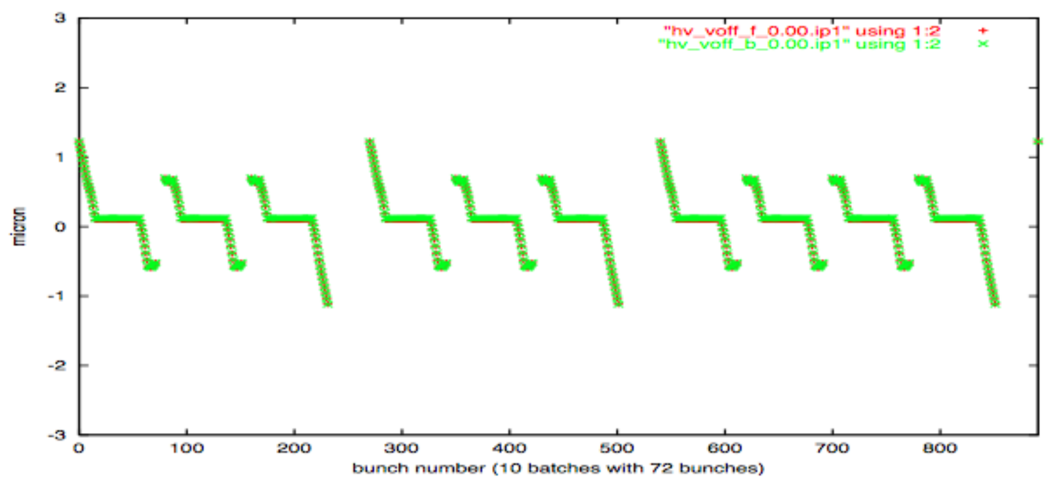


Figure 20: Vertical offset in IP1 with vertical-horizontal crossing.

IP5&IP1 Collisions HV crossing: Observe IP5

For IP5 the opposite

Crossing plane: H
These effects come LR in IP5

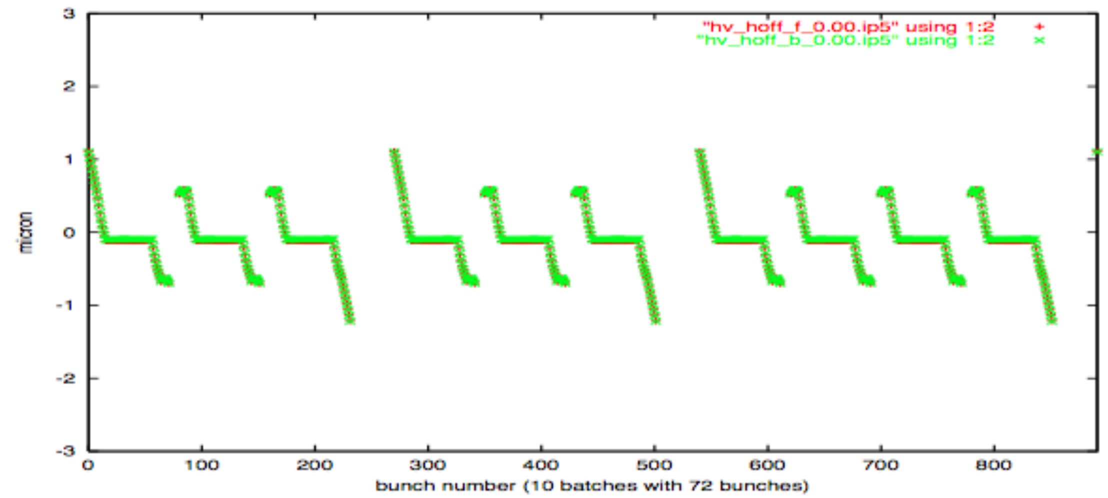


Figure 17: Horizontal offset in IP5 with vertical-horizontal crossing.

Separation Plane: V
These effects come LR in IP1

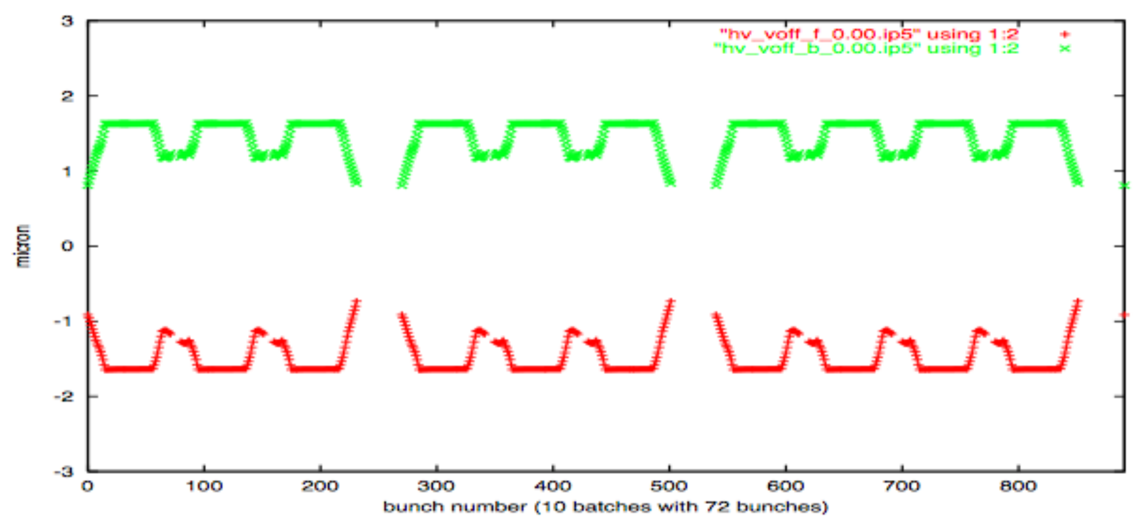


Figure 23: Vertical offset in IP5 with vertical-horizontal crossing.

IP5&IP1 Collisions HV crossing: we observe in IP1

The long-range interaction in IP5 in Vertical plane result in **displacements in IP1 of maximum 1 μm**

→ **Offset at head-on collision of less than 0.1 σ**

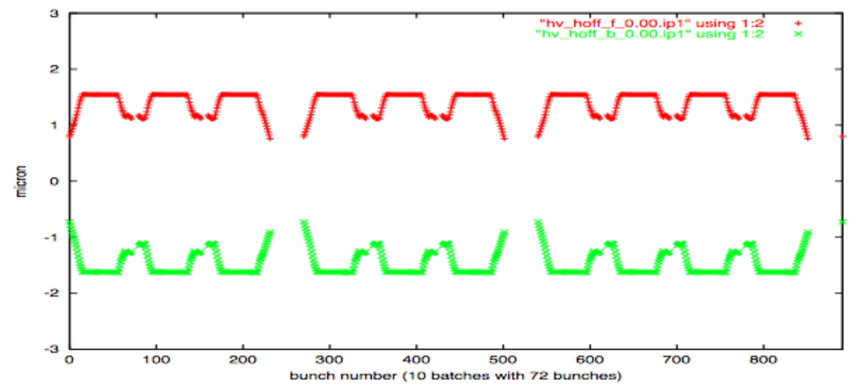
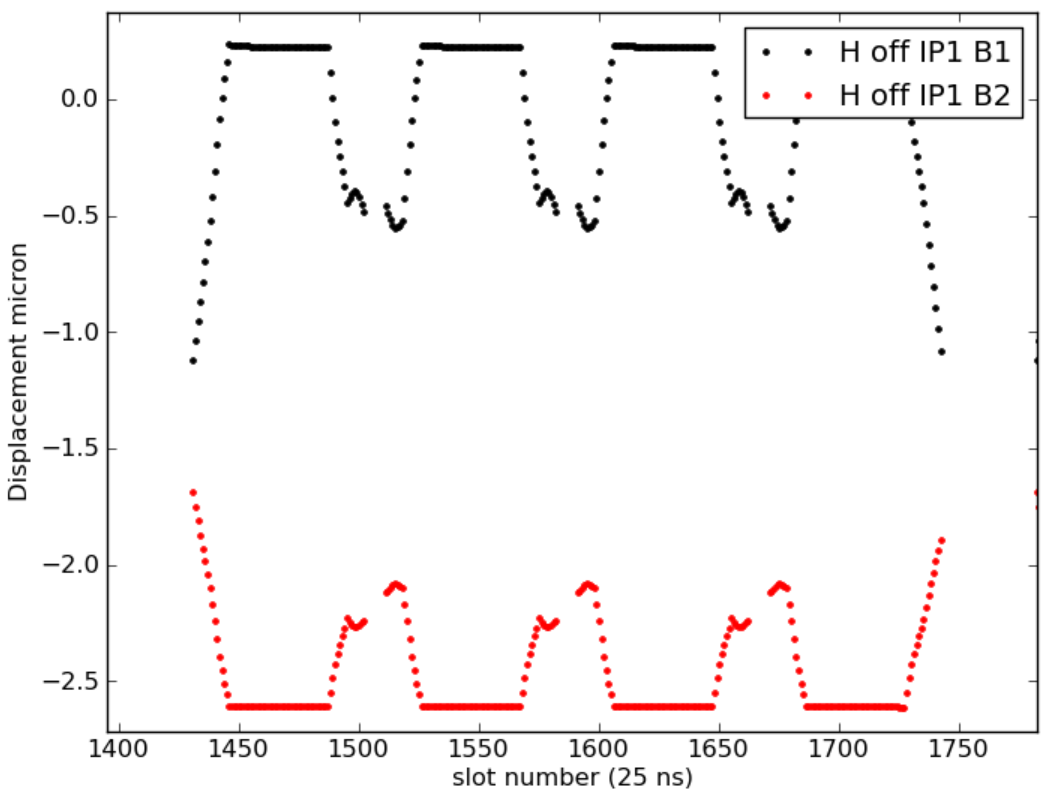
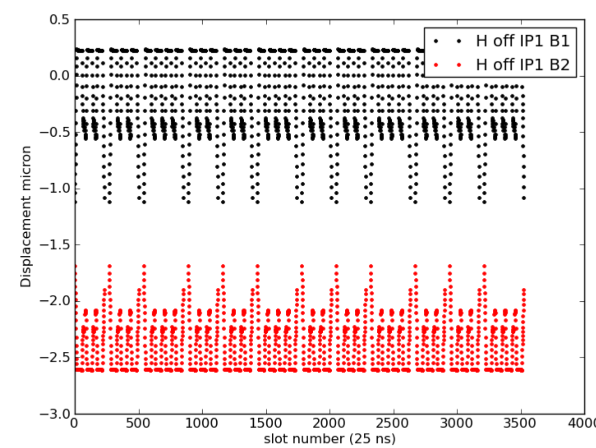


Figure 14: Horizontal offset in IP1 with vertical-horizontal crossing.





IP5&IP1 Collisions HV crossing: Observe IP1

The long-range interactions in IP1 in Vertical plane come back to IP1 result in **symmetric displacements for the two beams in IP1 of maximum 1 μm**

→ **Displacement of collision centroid of 0.1 σ**

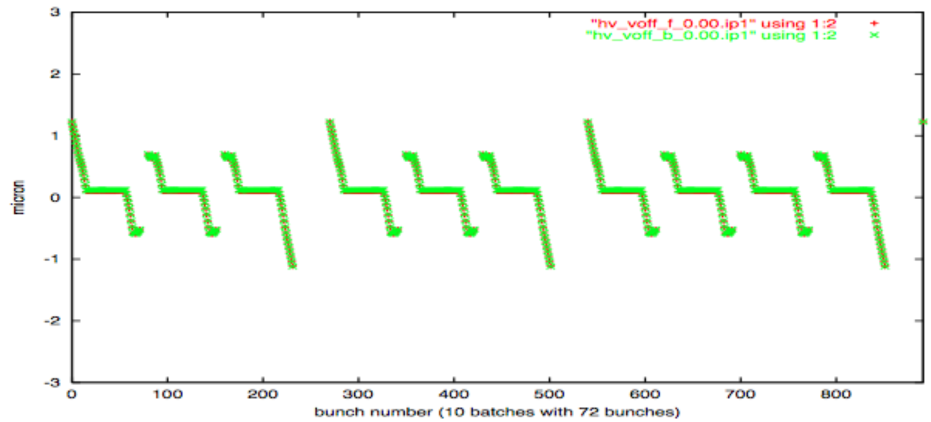
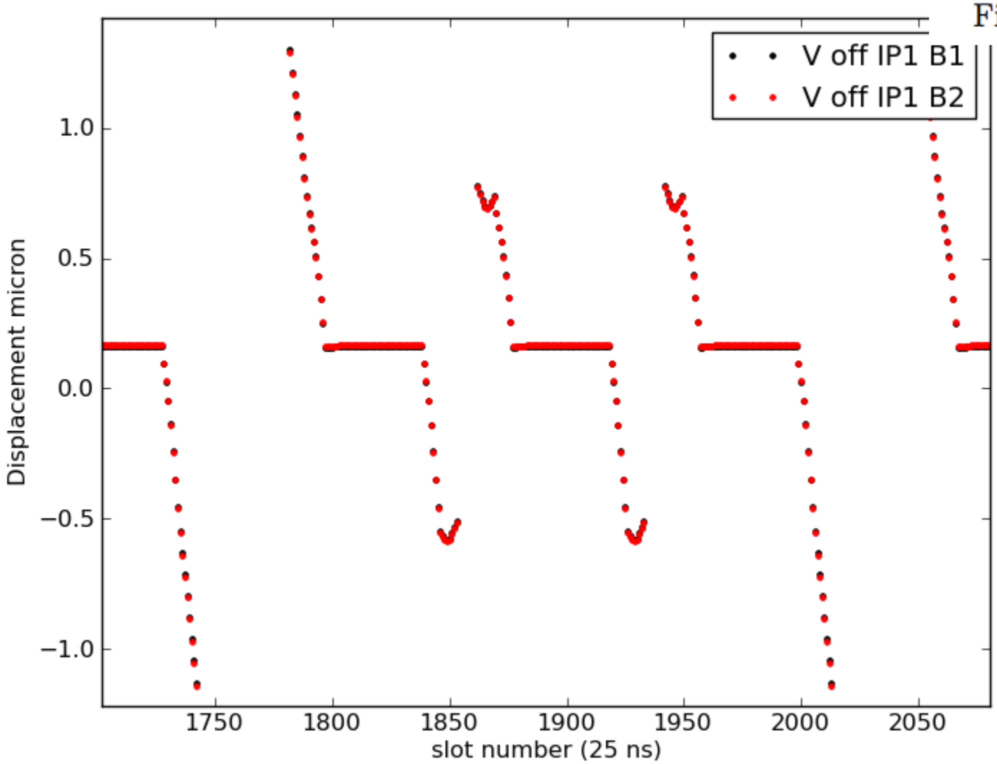
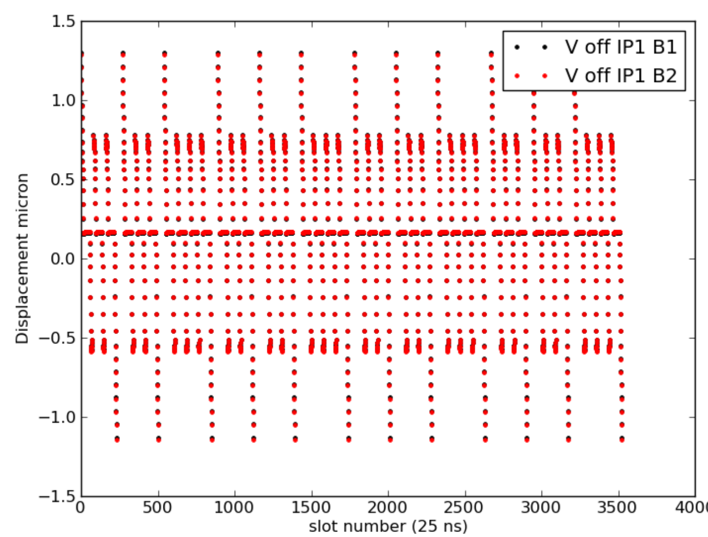


Figure 20: Vertical offset in IP1 with vertical-horizontal crossing.





LHC IP5: Qx

The long-range interactions in IP5 only in V plane: **tune shifts 0.0015 in tune units**

IP1 and IP5 HH crossing 2 time the effect

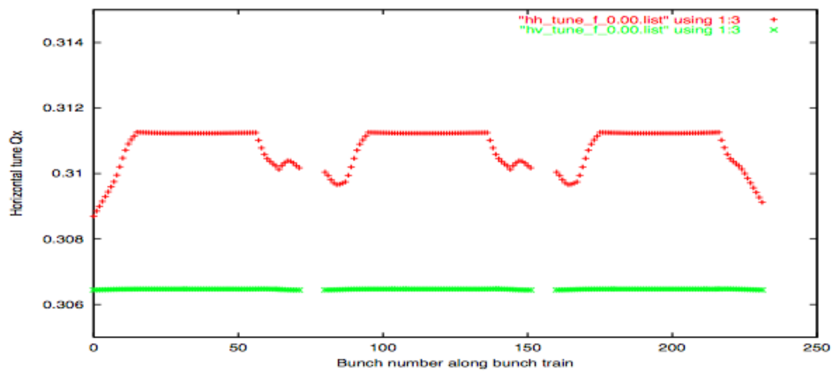
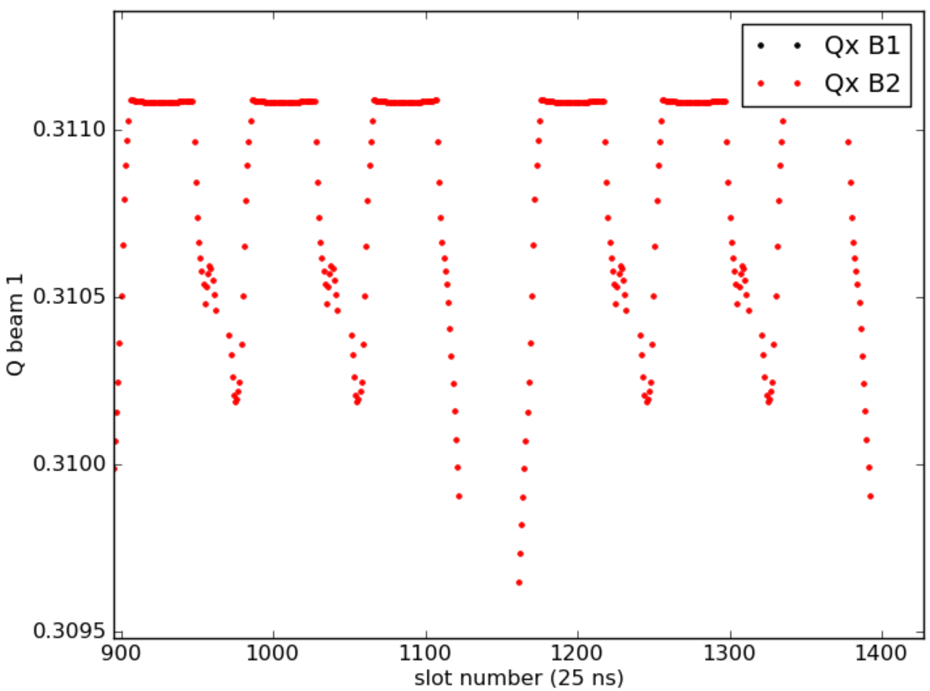
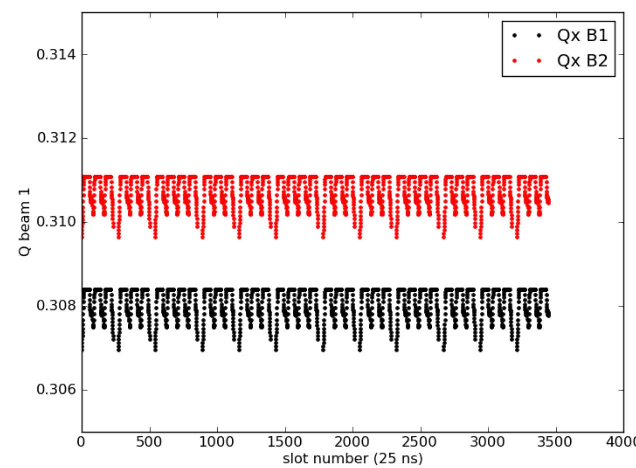


Figure 30: Horizontal tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.





LHC IP5: Qy

The long-range interactions in IP5 only in V plane: **tune shifts 0.0015 in tune units**

IP1 and IP5 HH crossing 2 time the effect

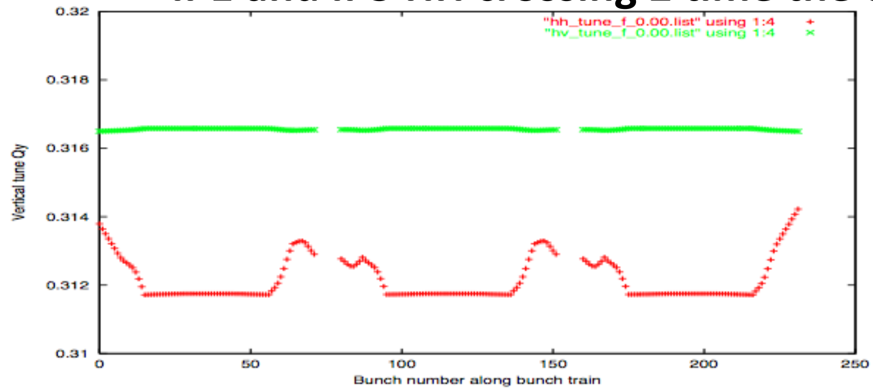
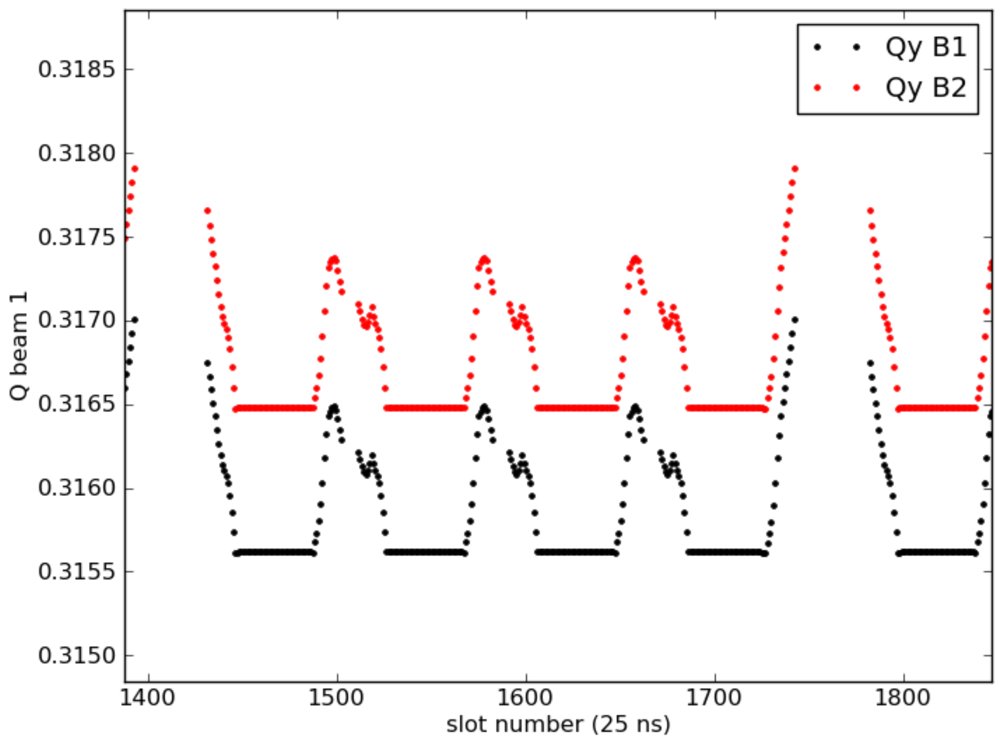
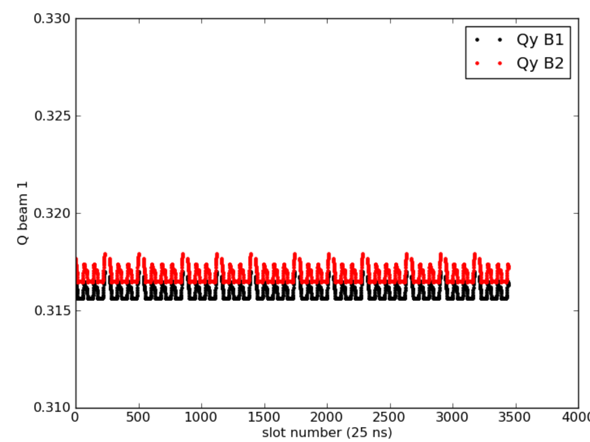


Figure 31: Vertical tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.





LHC IP5:Qpx

The long-range interactions in IP5 only in V plane: **Q' spread of less than 1 unit**

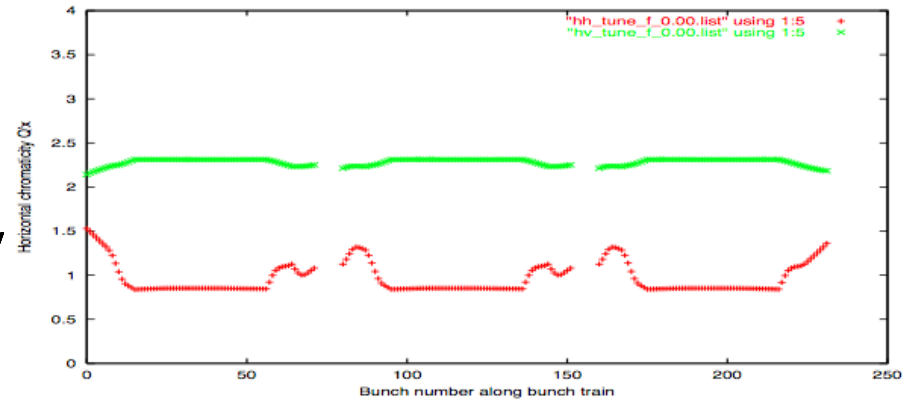
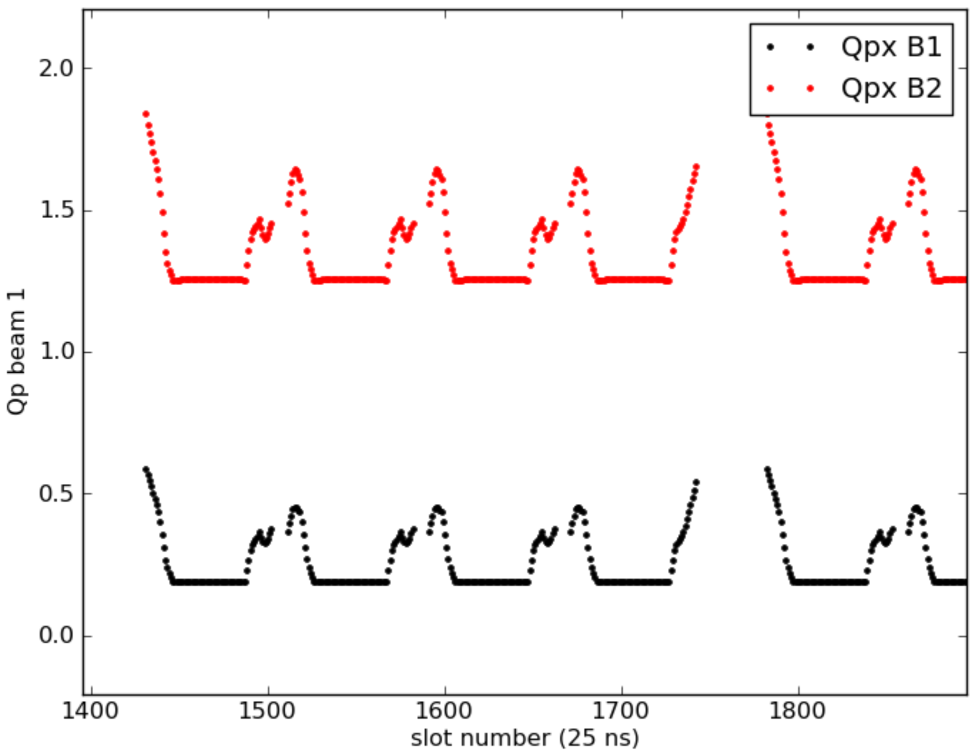


Figure 36: Horizontal chromaticity variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.



LHC IP5: Qpy

The long-range interactions in IP5 only in V plane: **Q' spread of less than 1 unit**

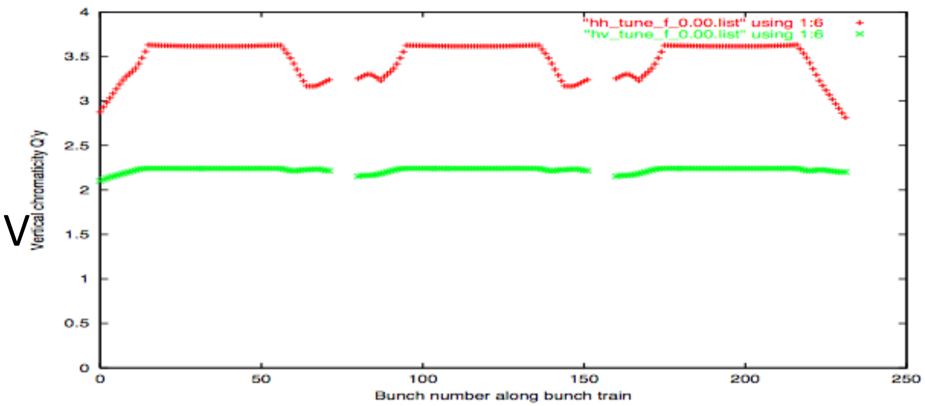
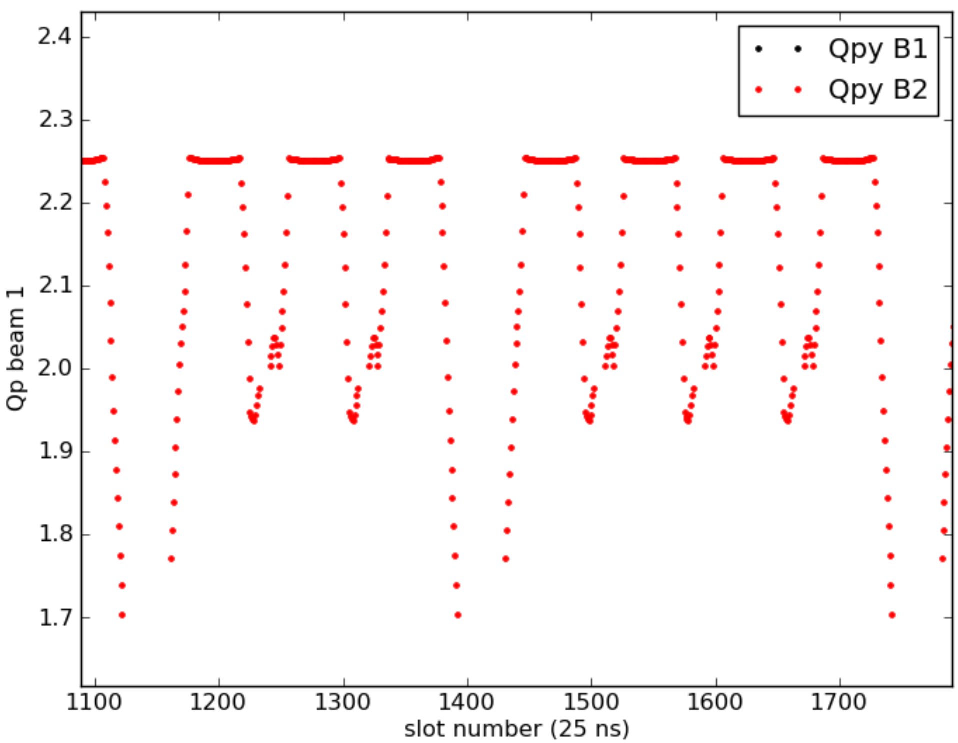


Figure 37: Vertical chromaticity variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.



Alternating crossing

The long-range interactions in IP5 only in V and IP1 in H compensates the tune and chroma effects of long ranges plane

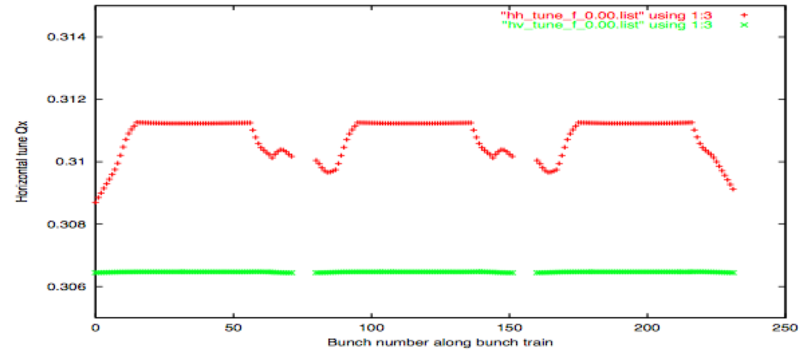
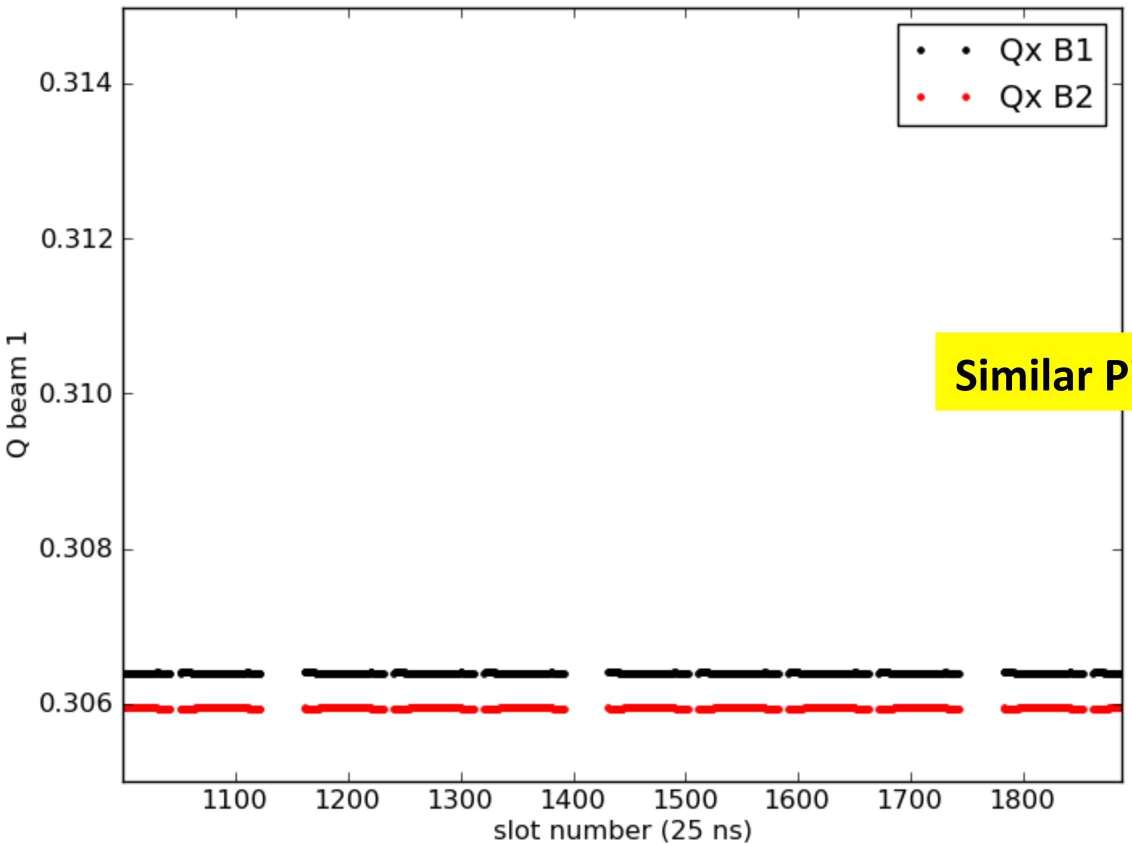
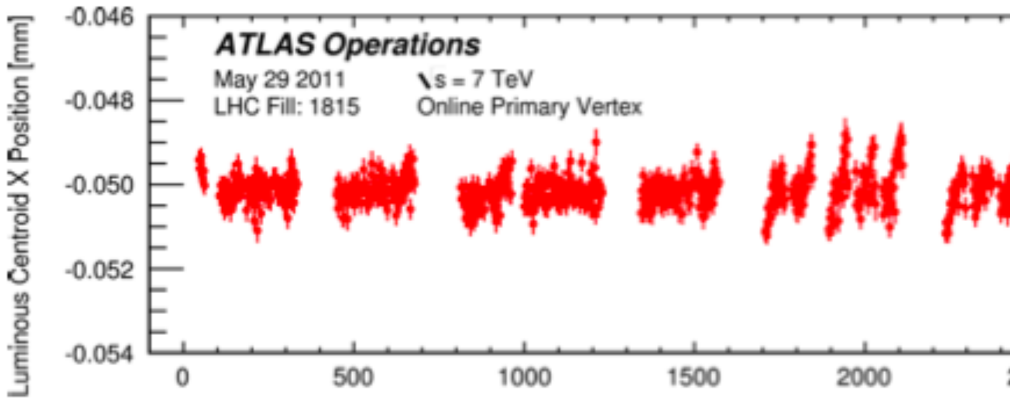


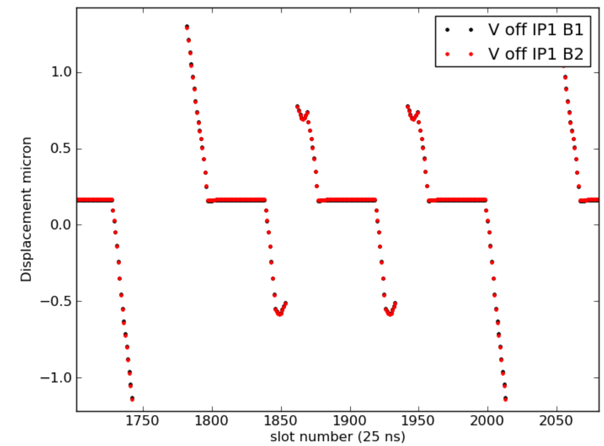
Figure 30: Horizontal tune variation along the batch. Horizontal-horizontal crossing in red, vertical-horizontal crossing in green.

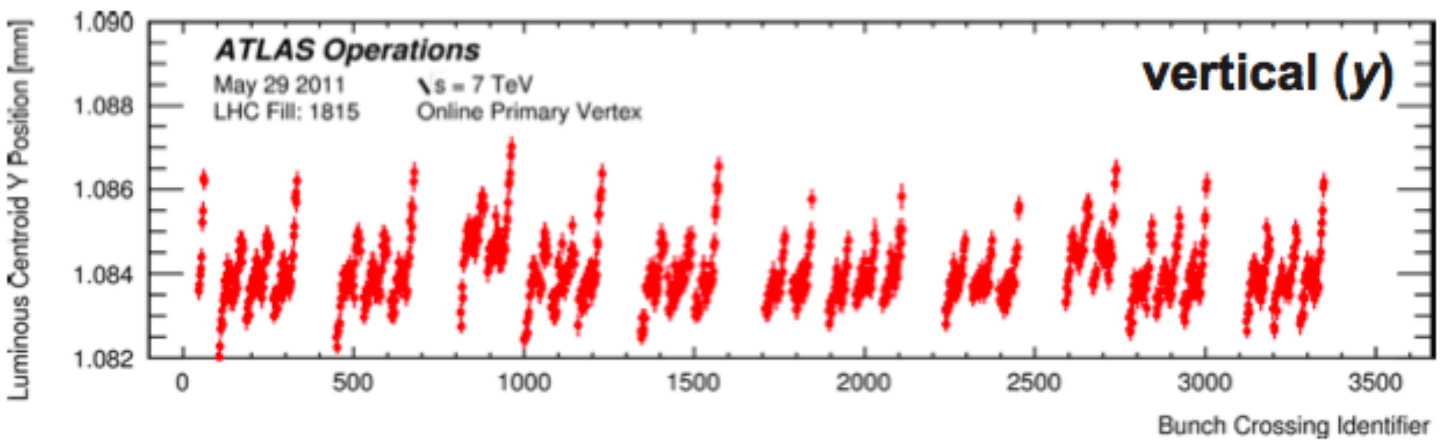


Similar Pictures for other plane and chroma.

Can we cross check with data? ATLAS vertex detector 2011 data



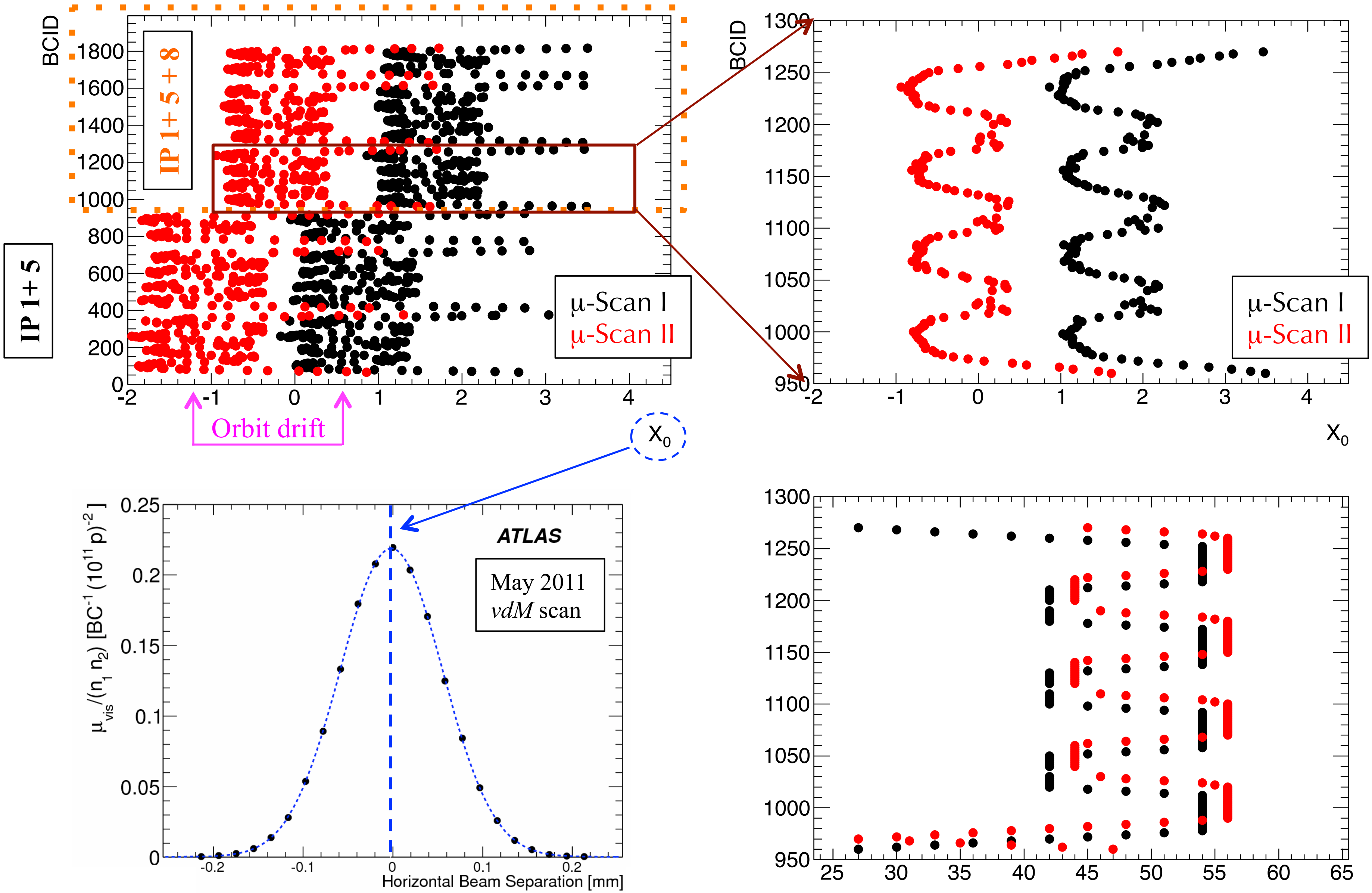




Courtesy of R. Bartoldus and W. Kozanecki ATLAS collaboration

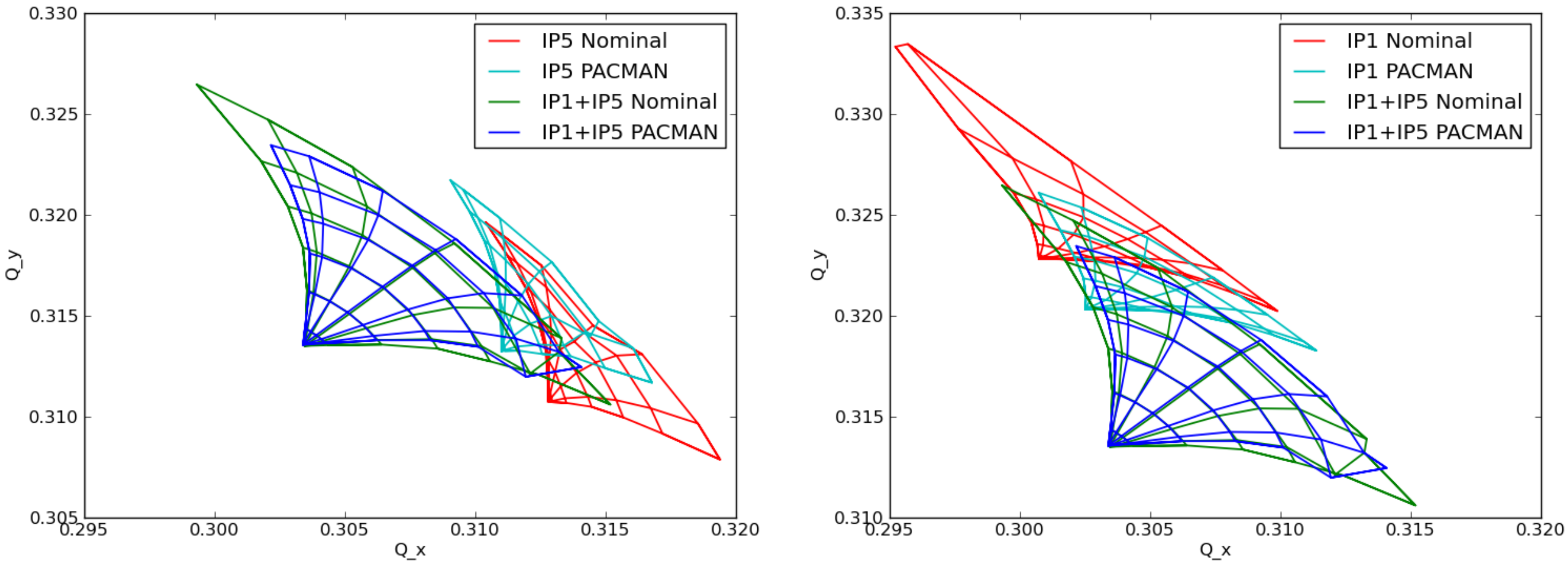
Vertical centroid displacement can be measured and we can check few cases

ATLAS data 2012 April VdM Horizontal plane



Courtesy of W. Kozanecki

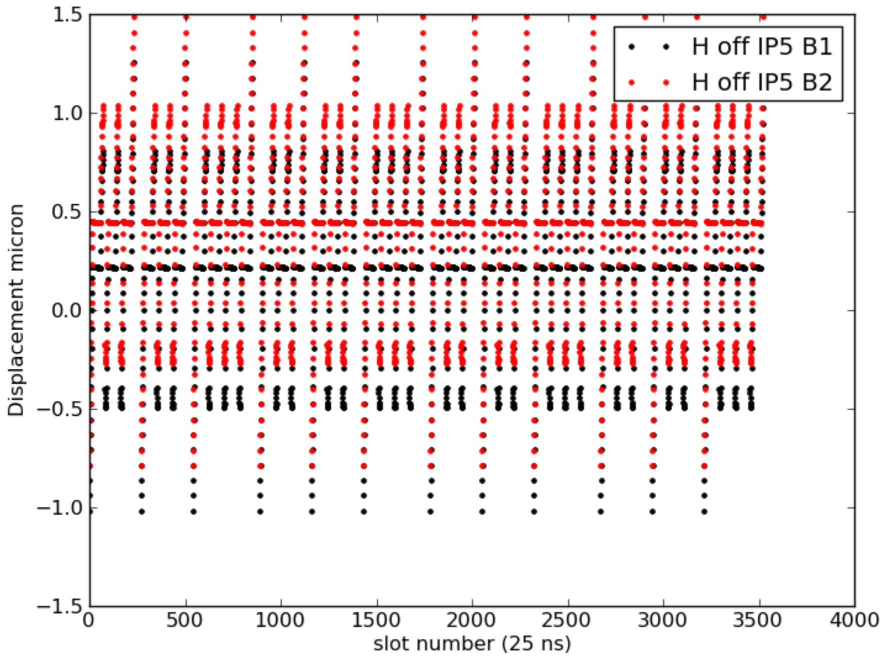
HL-LHC case



IP5 Nominal
IP5 PACMAN
IP1+IP5 Nominal
IP1+IP5 PACMAN
Q_y
Q_x
0.330
0.325
0.320
0.315
0.310
0.305
0.295
0.300
0.305
0.310
0.315
0.320
IP1 Nominal
IP1 PACMAN
IP1+IP5 Nominal
IP1+IP5 PACMAN
Q_y
Q_x
0.335
0.330
0.325
0.320
0.315
0.310
0.295
0.300
0.305
0.310
0.315
0.320

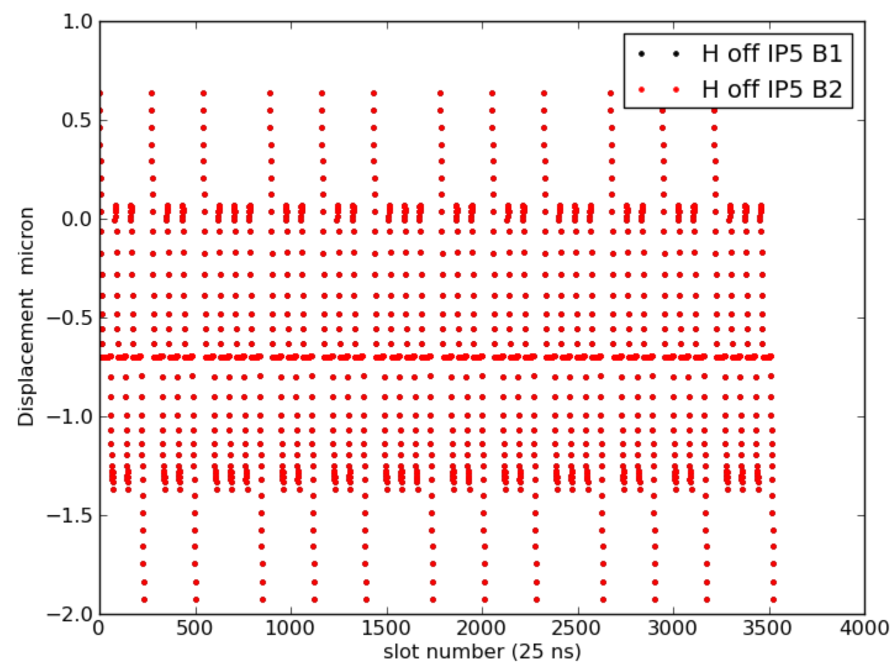
HL-LHC: IP5 only

Int 2.2e11



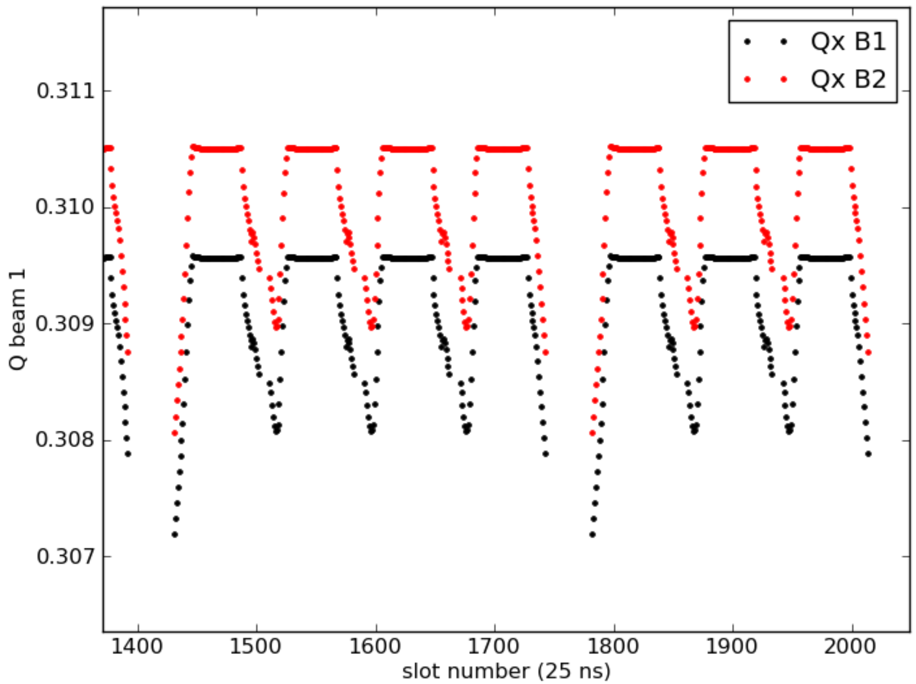
- **Intensity 2.2 and 1.1e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Int 1.1e11



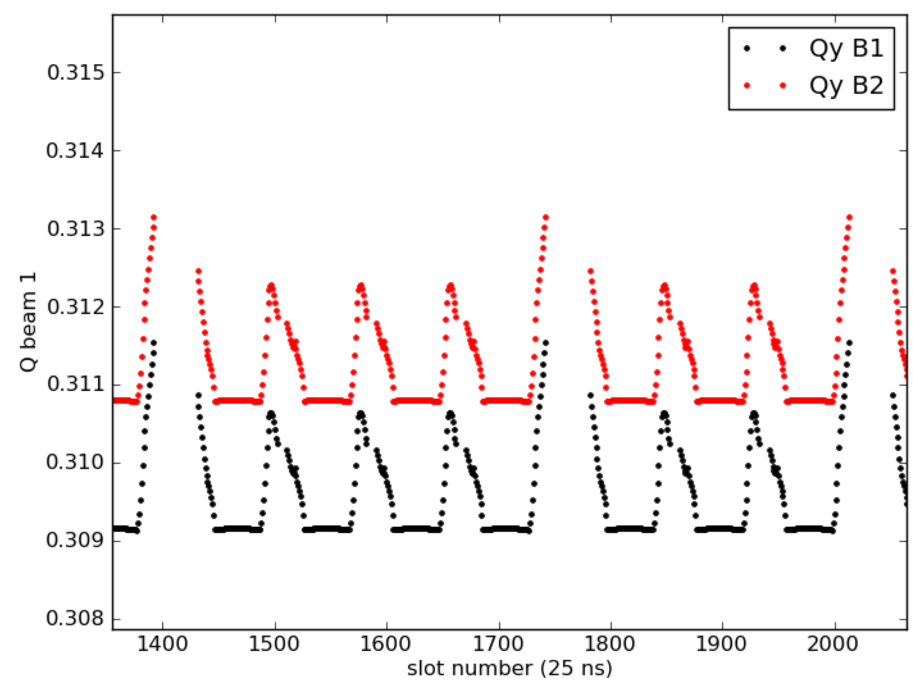
HL-LHC: IP1 only tune shifts

Int 2.2e11



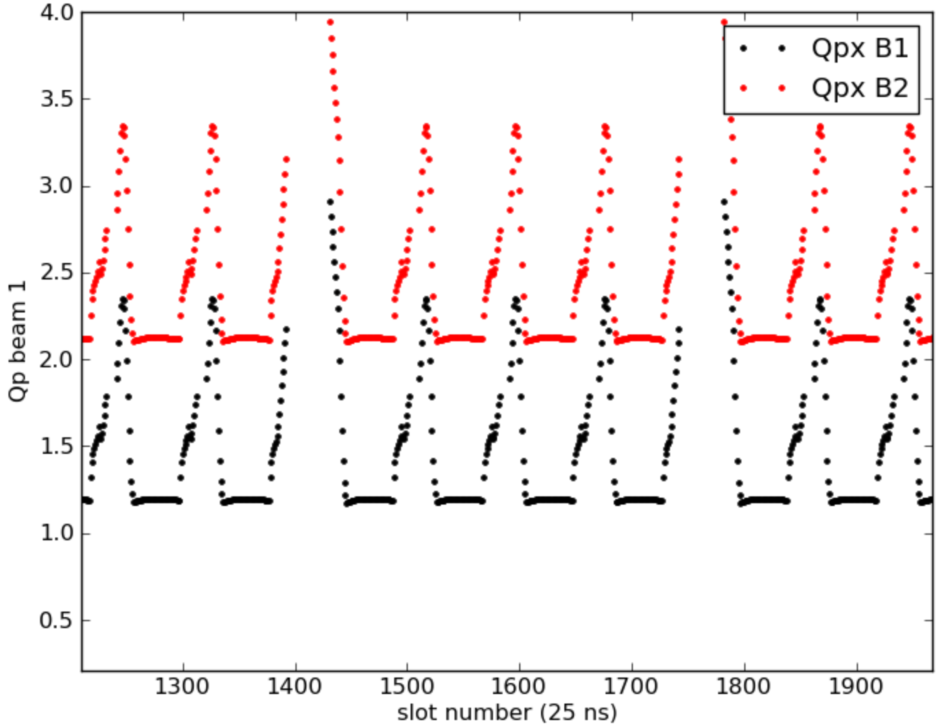
- **Intensity 2.2 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Due to one IP LR DQ in the range 0.0025

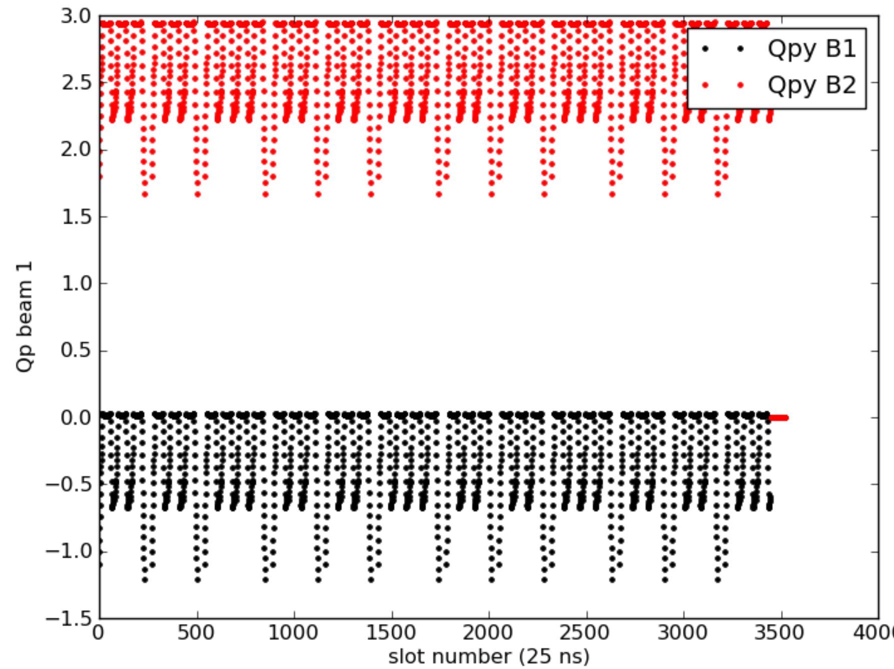


HL-LHC: IP1 only chroma

Int 2.2e11



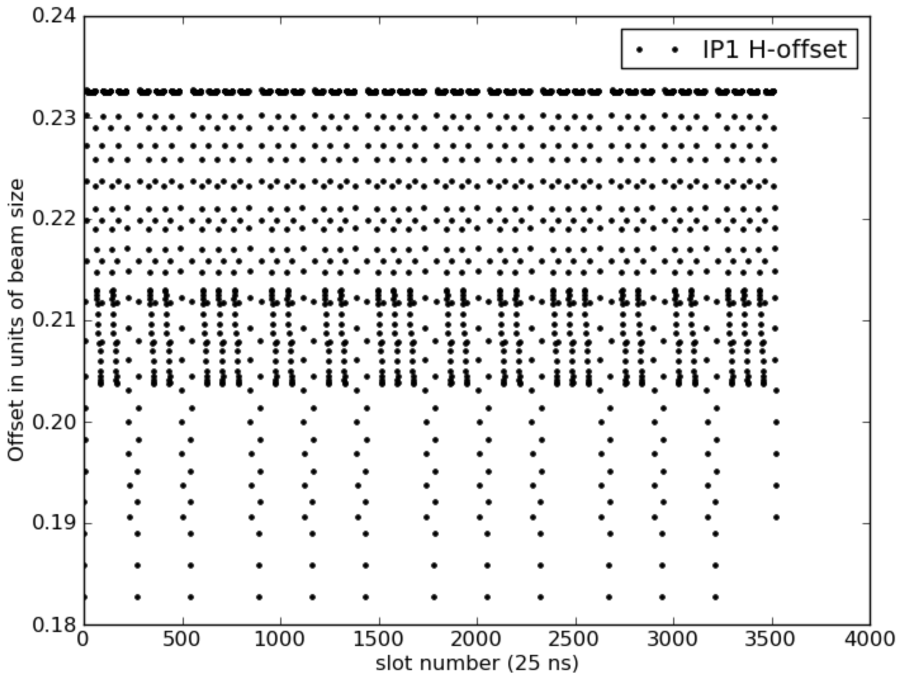
- **Intensity 2.2 and 1.1e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**



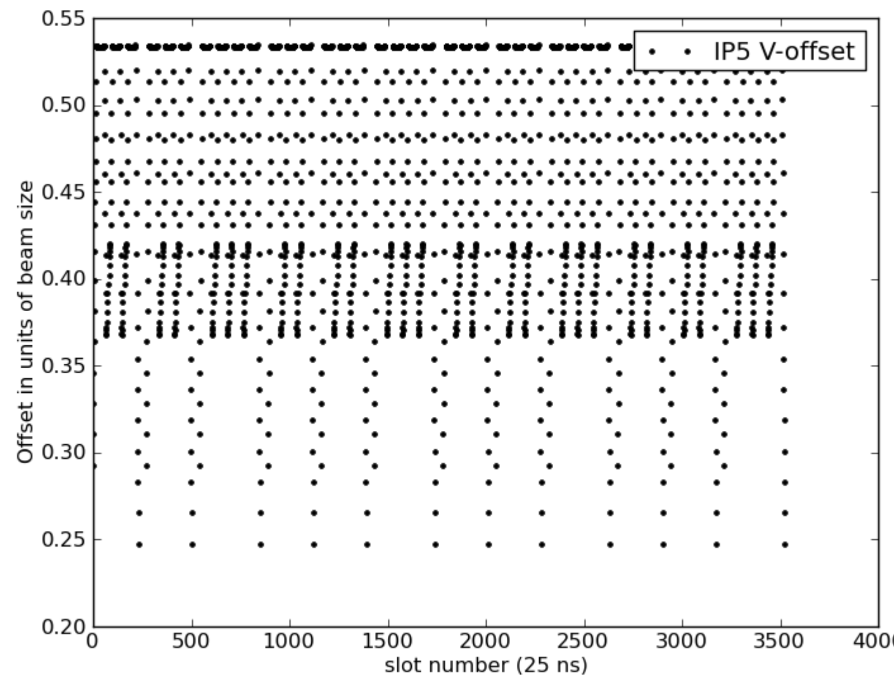
Due to one IP LR Q' spread of 2 units

HL-LHC: IP1&IP5 offsets

Int 2.0 e11



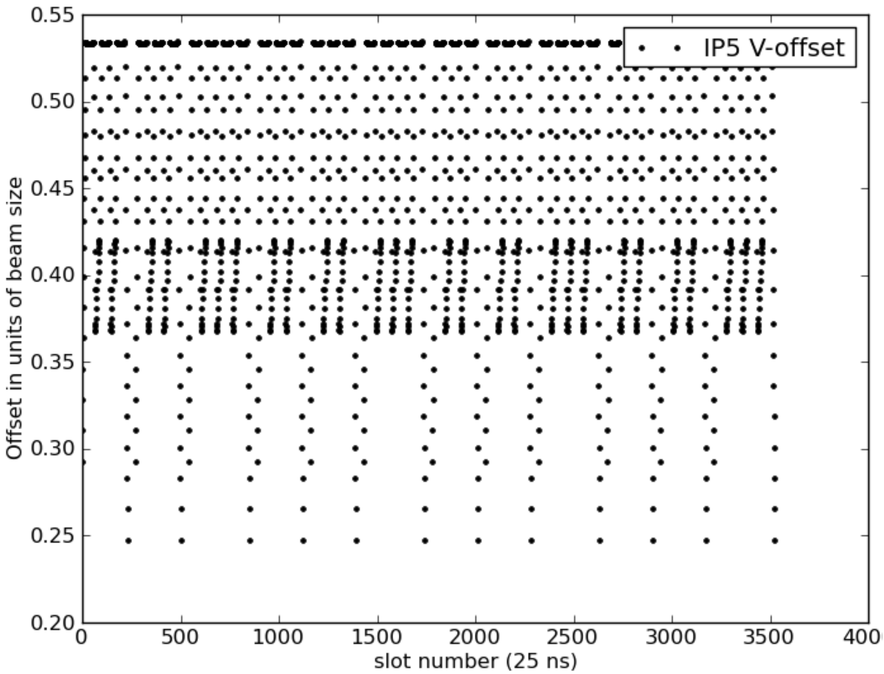
- **Intensity 2.0e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**



Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.3 σ at intensities of 2.0e11 ppb

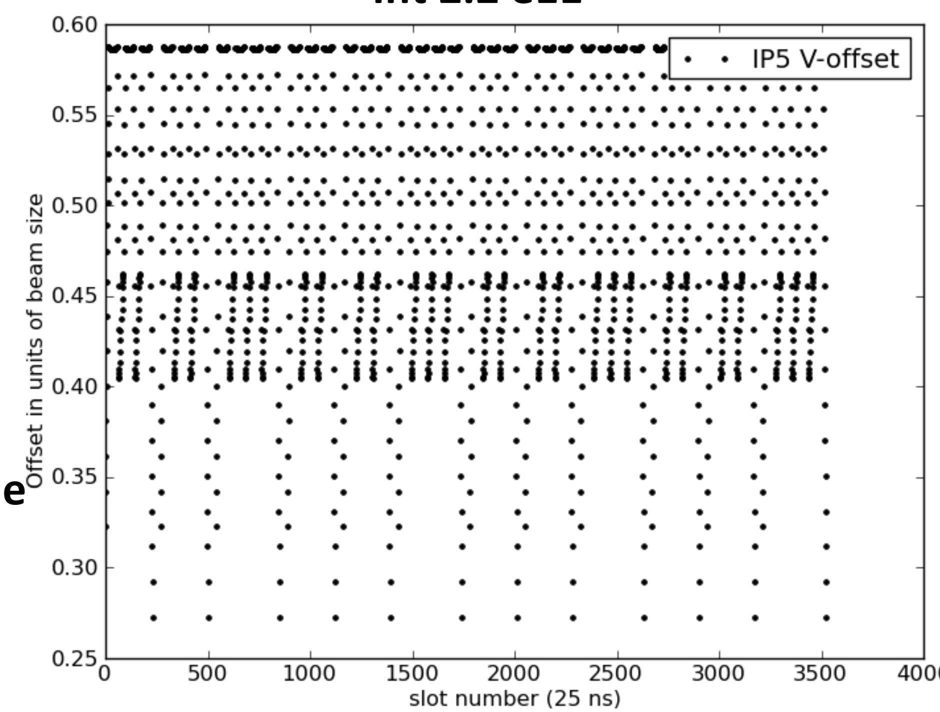
HL-LHC: IP1&IP5 offsets

Int 2.0 e11



- **Intensity 2.0 and 2.2e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

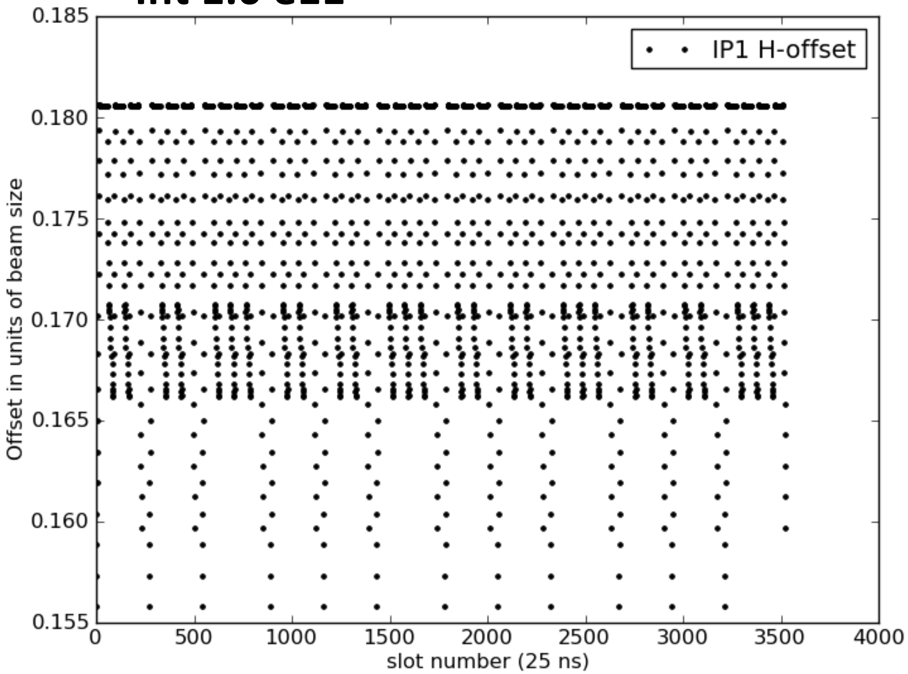
Int 2.2 e11



Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.3 σ at intensities of 2.0-2.2e11 ppb

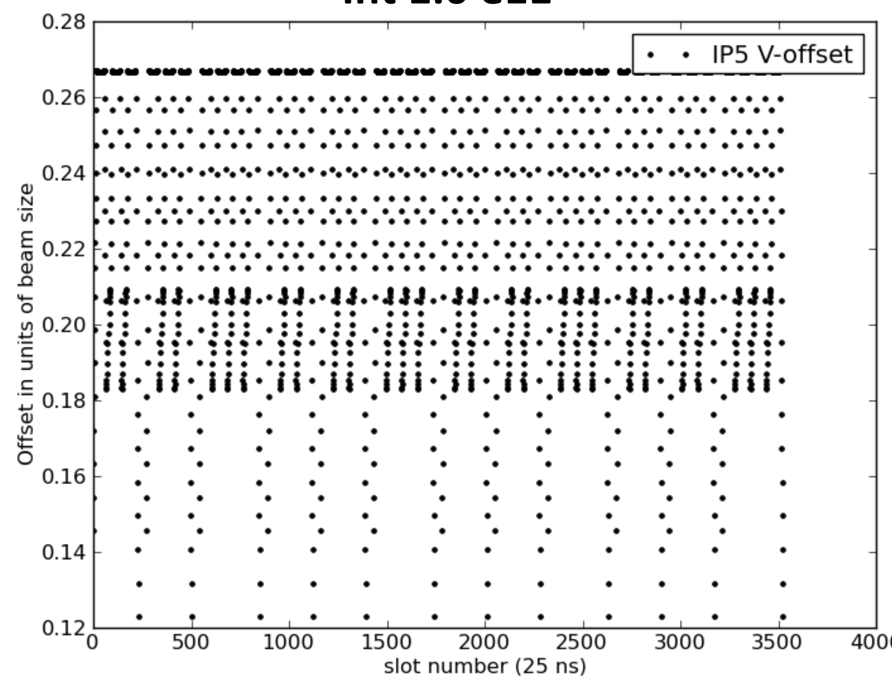
HL-LHC: IP1&IP5 IP1 observation

Int 1.0 e11



- **Intensity 1.0e11 ppb**
- **Emittance 2.5 (7 μm at IP)**
- **ATS optic β* 0.15 collision**
- **15 LR per side of IP**
- **Crossing angle 590 μrad**
- **Nominal LHC filling scheme 25 ns**

Int 1.0 e11



Long ranges lead to offsets in opposite IP in the plane of separation of maximum 0.1 σ at intensities of 1.0e11 ppb

Still on-going understanding and work….

Problems:

- Still to understood asymmetry between b1 and b2 → on-going with Werner and Rogelio (should be easy)
- Sometime the eigenvalue routine fails finding the eigenvalues (Qs and Q'…) → Need to check the convergency of the routine (some ideas)
- Need a careful study on the impact of different collision sets (crossing angles, separation bumps)

Beam-Beam deflection angles and orbit in the LHC: model for round and non-round beams

Deflections: $$\theta_y + i\theta_x = \frac{2r_p}{\gamma} N_p F_0(x, y, \Sigma)$$

$$\begin{cases} \Sigma_{12} = 0 \\ \Sigma_{11} > \Sigma_{22} \\ \Sigma_{11} = \sigma_{x^1}^2 + \sigma_{x^2}^2 \\ \Sigma_{22} = \sigma_{y^1}^2 + \sigma_{y^2}^2 \end{cases}$$

Bassetti-Erskine formula:

$$F_0(x, y, \Sigma) = \frac{\sqrt{\pi}}{\sqrt{(\Sigma_{11} - \Sigma_{22})}} [w(\alpha_1) - w(\alpha_2) \cdot \exp(-\frac{1}{2}(\Sigma_{11}^{-1} x^2 + \Sigma_{22}^{-1} y^2))]$$

$$\alpha_1 = \frac{x + iy}{\sqrt{2(\Sigma_{11} - \Sigma_{22})}} \qquad \alpha_2 = \frac{(\Sigma_{22} x + i\Sigma_{11} y)}{\sqrt{2\Sigma_{11}\Sigma_{22}(\Sigma_{11} - \Sigma_{22})}}$$

$$w(z) = exp(-z^2) erfc(-iz)$$

Closed Orbit effect: $$Orb_{x,y} = \theta_{x,y} \cdot \beta_{x,y} \cdot \frac{1}{2\tan(\pi \cdot Q_{x,y})}$$