

Observations of Beam-Beam Effects at High Intensities in the LHC

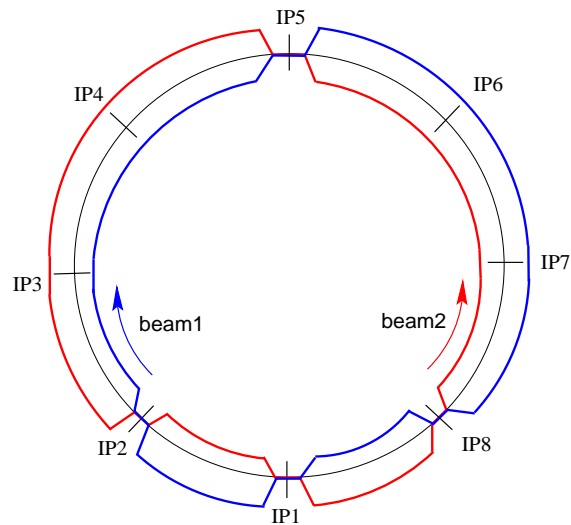
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(for LHC Beam-Beam Studies Team)

Beam-beam effects in the LHC

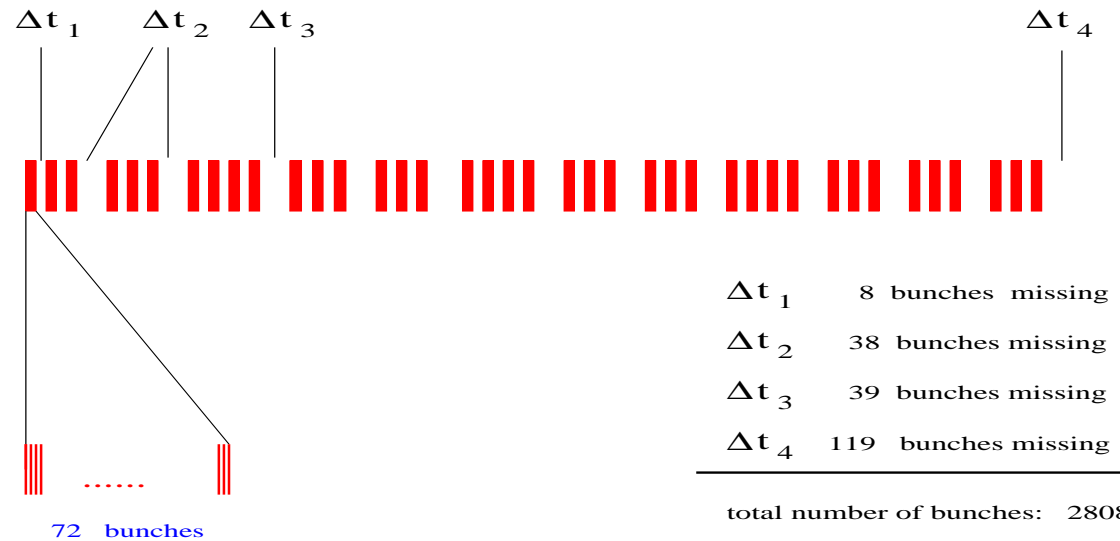
- Some important features of the LHC:
 - Equally charged beams and separate rings
 - Large number of bunches
 - Strong-strong beam-beam interaction
 - Users (experiments) with very different requirements
- All have significant implications for beam-beam effects
- Studied in dedicated tests and during operation
- An overview, details presented in posters

Where it happens: LHC collision layout



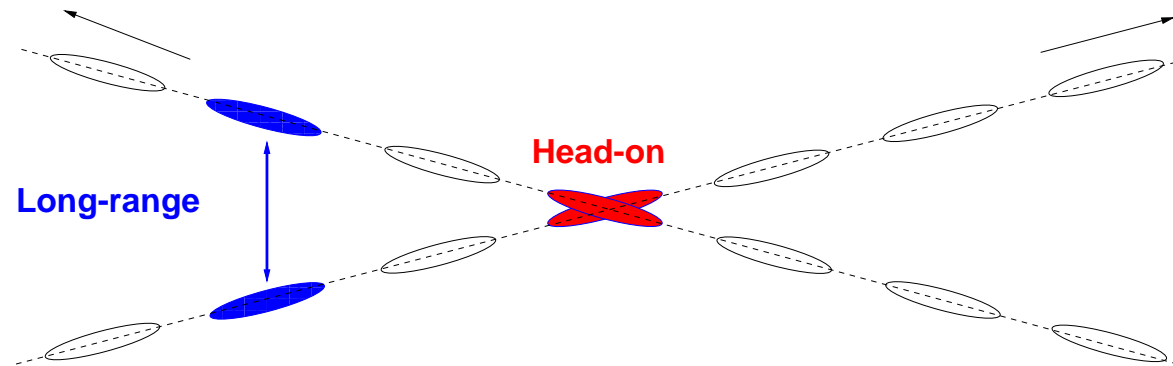
- Two rings with 4 interaction regions (4 experiments)
- High luminosity (strong long range) in IP1 and IP5 (opposite in azimuth)
- "Low" luminosity in IP2 and IP8

LHC bunch filling pattern



- Large number of bunches for high luminosity, (nominal: max. 2808 bunches)
- Arranged in 39 trains of 72 bunches, spaced by 25 ns, with gaps between trains

Large number of bunches

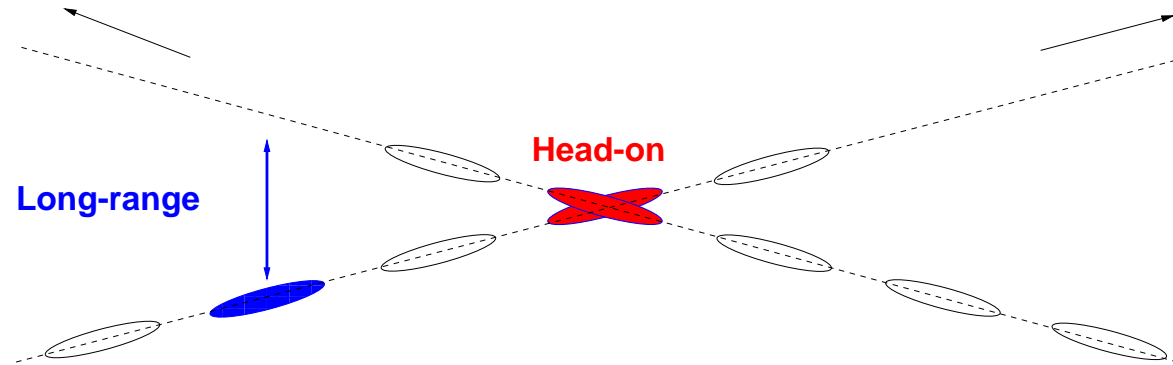


■ Implications :

- Crossing angles (horizontal or vertical, $\approx 200 - 300 \mu\text{rad}$)
- Long range interactions
- Separation typically $8 - 12 \sigma$

■ What about gaps in the train ?

Large number of bunches



■ Due to gaps:

- No head-on or long range interactions when bunches "meet" gaps (once named "PACMAN" bunches)
- Max: 4 head on, 120 long range interactions
Min: 1 head on, 40 long range interactions
- Strong bunch to bunch differences expected

The "nominal" LHC

Parameters relevant for beam-beam:

➤ Bunch intensity ($1.15 \cdot 10^{11}$ p/bunch)

➤ Bunch emittance ($3.75 \mu\text{m}$)

➤ β^* (0.55 m)

➤ Crossing angle α ($\approx 300 \mu\text{rad}$)

➤ Number of bunches (2808 , spaced by 25 ns)

➔ Nominal beam-beam parameter: $\xi = 0.0035$

Can be considered conservative (not as limits !)

Defined to reach design luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

The LHC in 2010/2011

- Energy is 3.5 TeV instead of 7.0 TeV
- Limitations from machine protection, aperture and electron cloud:
 - Bunch spacing 50 ns (max. 1380 bunches)
 - Larger $\beta^* = 1.5$ m
 - Emittances smaller than nominal ($\approx 1.5 - 2.5 \mu\text{m}$)
- In very first collisions at injection energy:
nominal beam-beam parameter/tune shift exceeded !
- How far can we push the beam-beam parameter ?

Observations: head-on beam-beam effects

- Dedicated experiment with fewer bunches
- Test maximum beam-beam parameter achievable (at injection energy), single bunches - head-on only
 - Intensity $1.9 \cdot 10^{11}$ p/bunch
 - Emittances 1.1 - 1.2 μm

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 - Intensity $1.9 \cdot 10^{11}$ p/bunch
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 - Achieved:
 - $\xi = 0.017$ for single collision (≈ 5 times nominal !)
 - $\xi = 0.034$ for two collision points (IP1 and IP5)
 - No obvious emittance increase or lifetime problems during collisions

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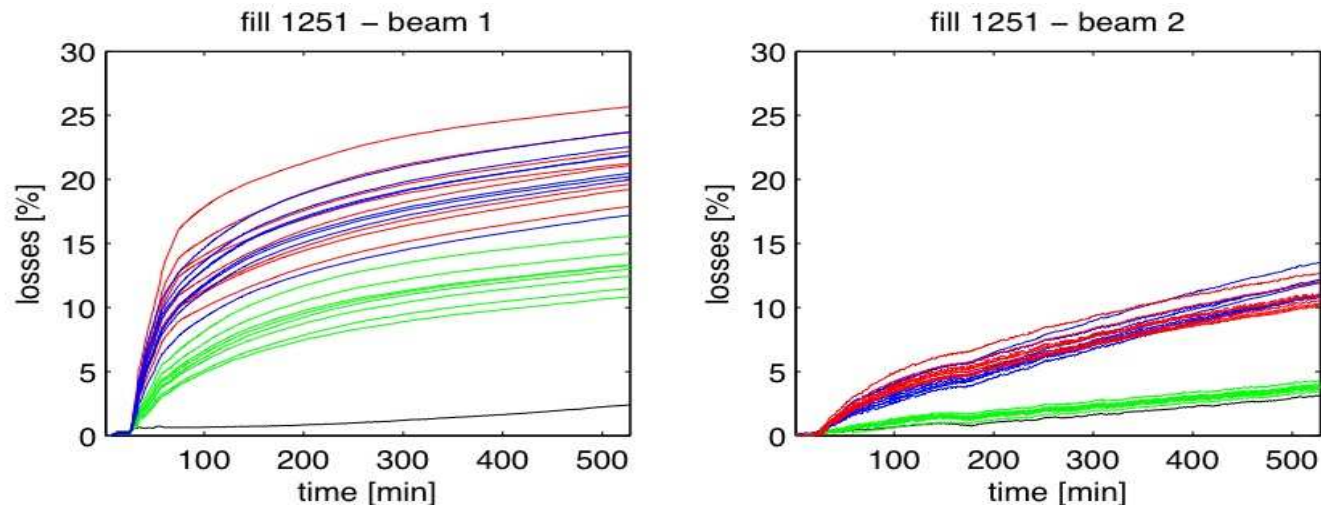
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- ⚠ No long range encounters present !

Head-on beam-beam effects

- Other observations (during normal operation):
 - LHC allows very flexible bunch filling schemes
Many different used (≈ 60 !)
 - Different filling pattern implied different collision pattern
 - Different number of head-on collisions (1 - 4)
 - Overall beam-beam effect very different
 - Differences in lifetime and emittance observed

(details: poster TUPZ023)

Collision pattern effects



- ➔ Different losses of bunches with different collision scheme
- ➔ blue (3 coll), red (2 coll), green (1 coll), black (no coll)
- ➔ Largest effect at start of the collisions !

Luminosity leveling

- LHC has 4 experiments:
 - 2 require highest luminosity,
 - 2 require lower luminosity (up to factor 10^{-4})
- Luminosity leveling required (reduce luminosity and keep constant)
 - Achieved by transversely offset collisions
 - Separation $\approx 4 \sigma$ (IP2) and $\approx 1 \sigma$ (IP8)
 - Routinely done without detrimental effects

(details: poster TUPZ025)

Strong-strong beam-beam interactions

■ (Main) implications expected:

➤ Coherent beam-beam effects

➤ Strong orbit effects

■ Requires self-consistent treatment in many (most) calculations, simple non-linear mapping insufficient

➔ Self-consistent: many bunches, many particles, "real" collision pattern

➔ Required new tools and techniques

Strong-strong: coherent modes

- Coherent beam-beam modes have been observed colliding few bunches
- Provide high degree of symmetry
 - Demonstrated by analysis of sum and difference signals between bunches
 - Symmetry breaking suppresses modes as expected
 - More detailed studies foreseen
- But not a problem for operation

(details: poster TUPZ029)

Experimental study of long range beam-beam interactions

- Test long range interactions with present machine in dedicated experiment, collisions only in 2 experiments
- Colliding in IP1 (vertical crossing) and IP5 (horizontal crossing), alternating planes for partial, passive compensation
- One train of 36 bunches per beam, full complement of long range interactions (50 ns)
 - Provides ≈ 32 parasitic encounters
 - In standard operation (2011): separation is kept at $\approx 12 \sigma$ (normalized)

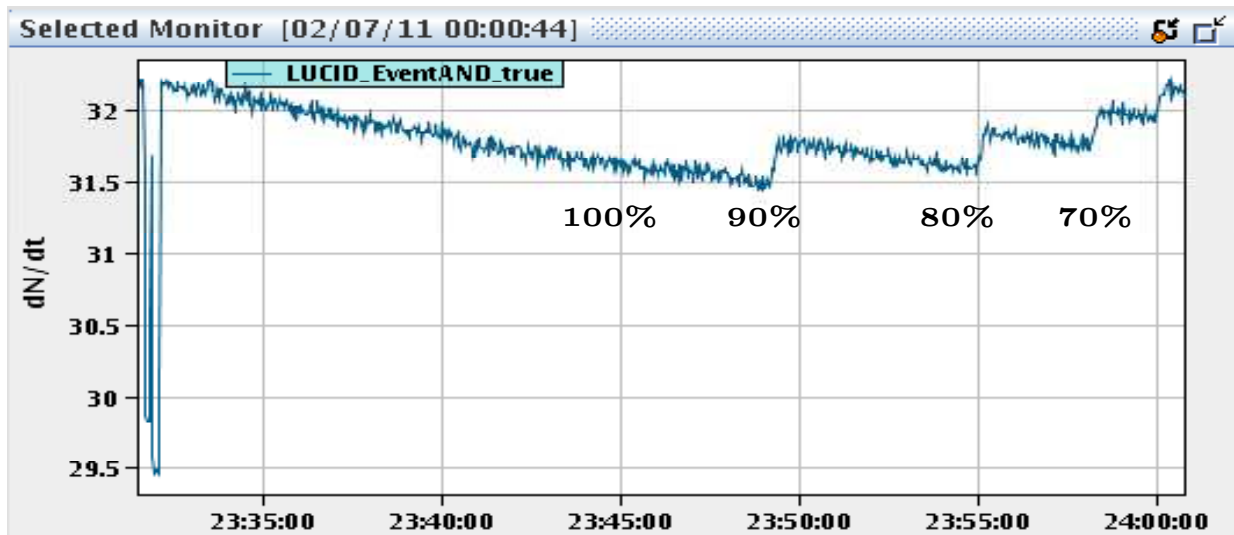
Experimental study of long range beam-beam interactions

■ Procedure:

- Reduce crossing angle (separation) in one IP (IP1) in steps until effect on losses, life times or emittances
- At reduced separation in IP1: reduce crossing angle in second IP5 (crossing in other plane)

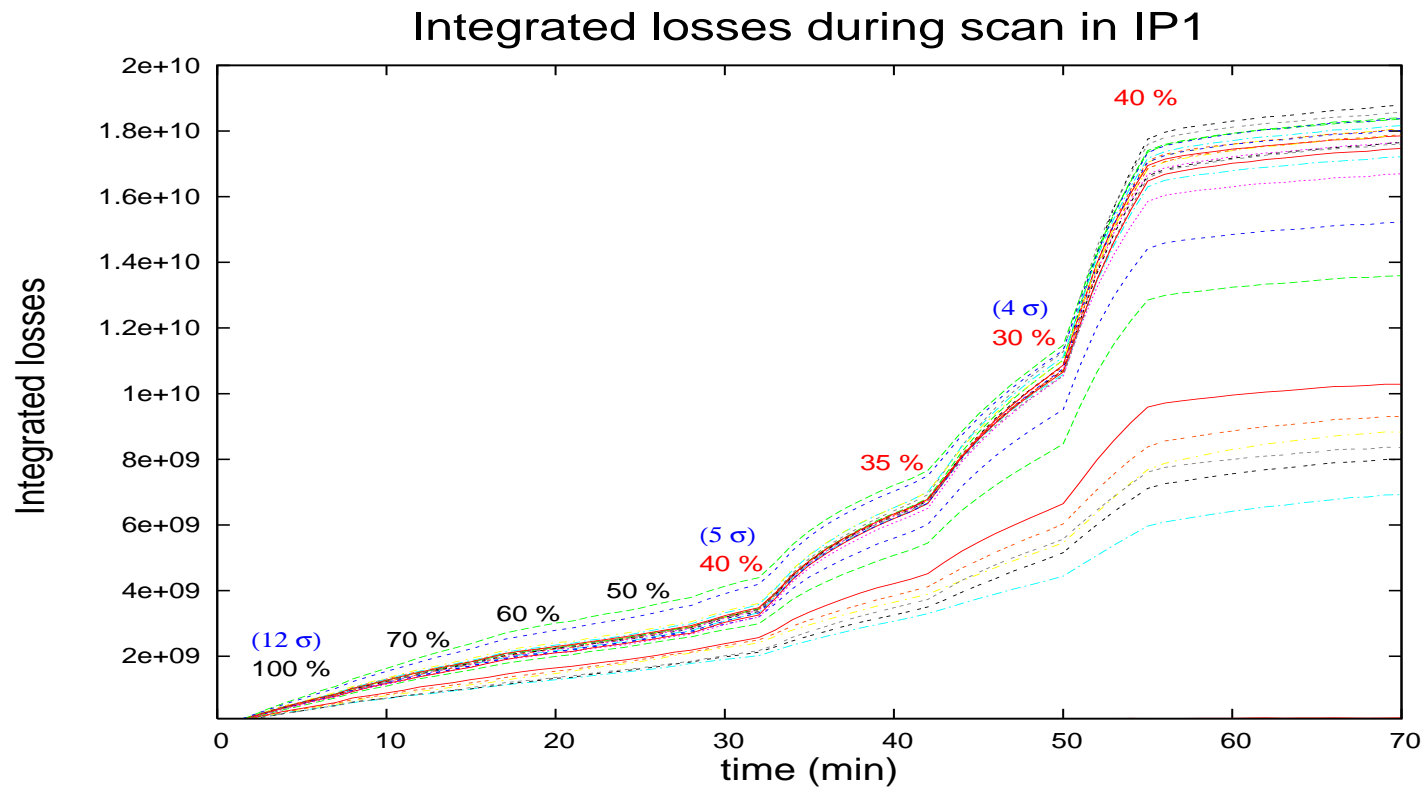
■ From simulations: expect effect on dynamic aperture, i.e. increased losses, but little effect on emittances

Scan of crossing angle: luminosity



- Luminosity in IP1 as function of crossing angle in IP1
- Reduction factor exactly as calculated !
- "Leveling" with crossing angle, no effect on 2nd IP

Scan of crossing angle: losses



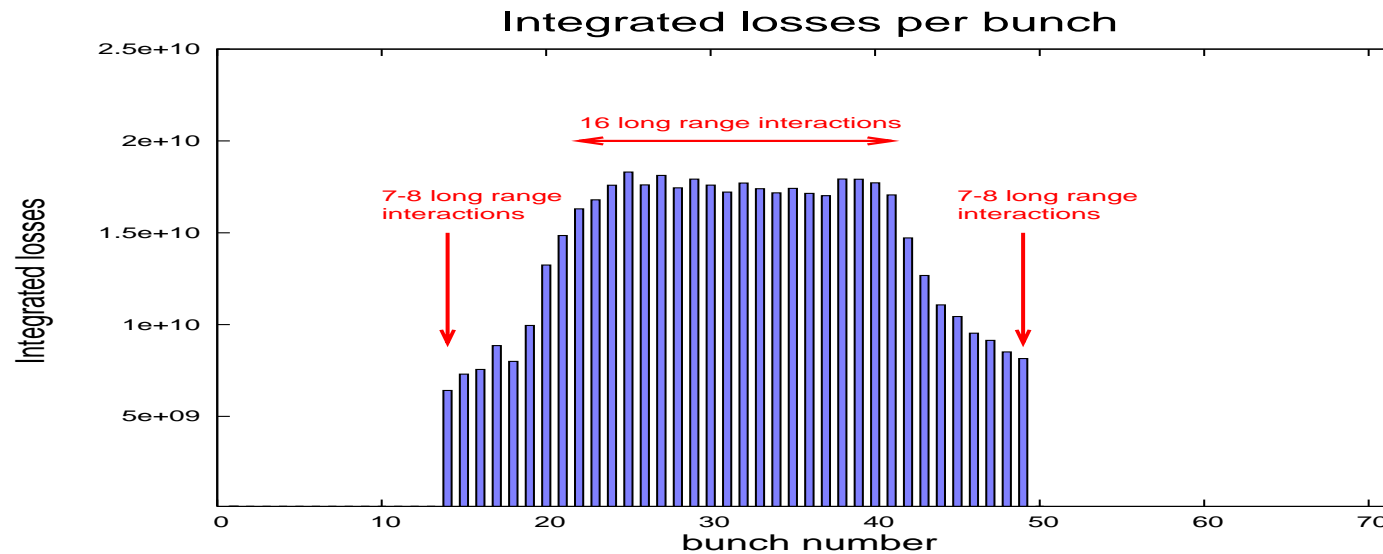
➡ Bunch by bunch loss as function of crossing angle in IP1

Scan of crossing angle

Observations:

- Losses start after some threshold (4 - 5 σ separation)
remember: 32 parasitic encounters !
- Smaller separation leads to increased losses (dynamic aperture !)
- Little (if any) effect on emittances
- Different bunches have different threshold !
- Strong evidence for PACMAN effects

PACMAN effects



- Integrated losses of the bunches in the train (36 bunches)
- Losses directly related to number of long range interactions
- ➡ So-called 'PACMAN' bunches have better life time !
(more in: poster TUPZ023)

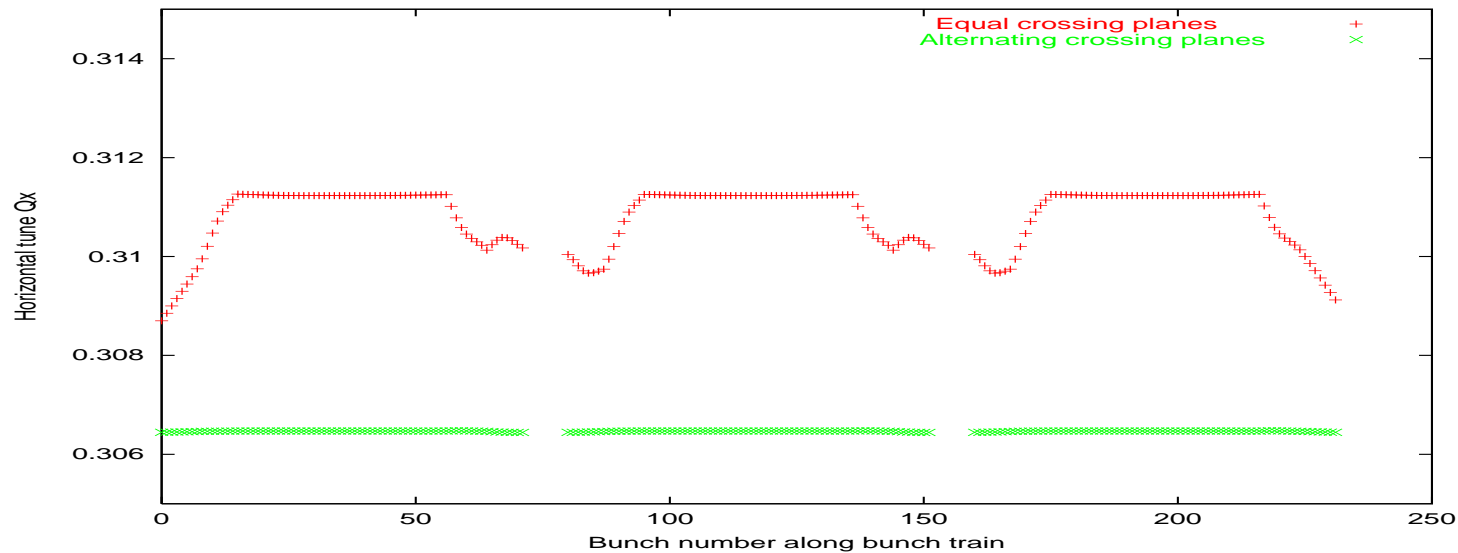
PACMAN effects

- Due to different number of long range collisions expected:
 - Systematic tune differences between nominal and PACMAN bunches
 - Could have reduced lifetimes when machine is optimized for nominal bunches
 - Bunches at head and tail of train would be lost first (origin of the name)

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- In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation

PACMAN tune effects: calculation



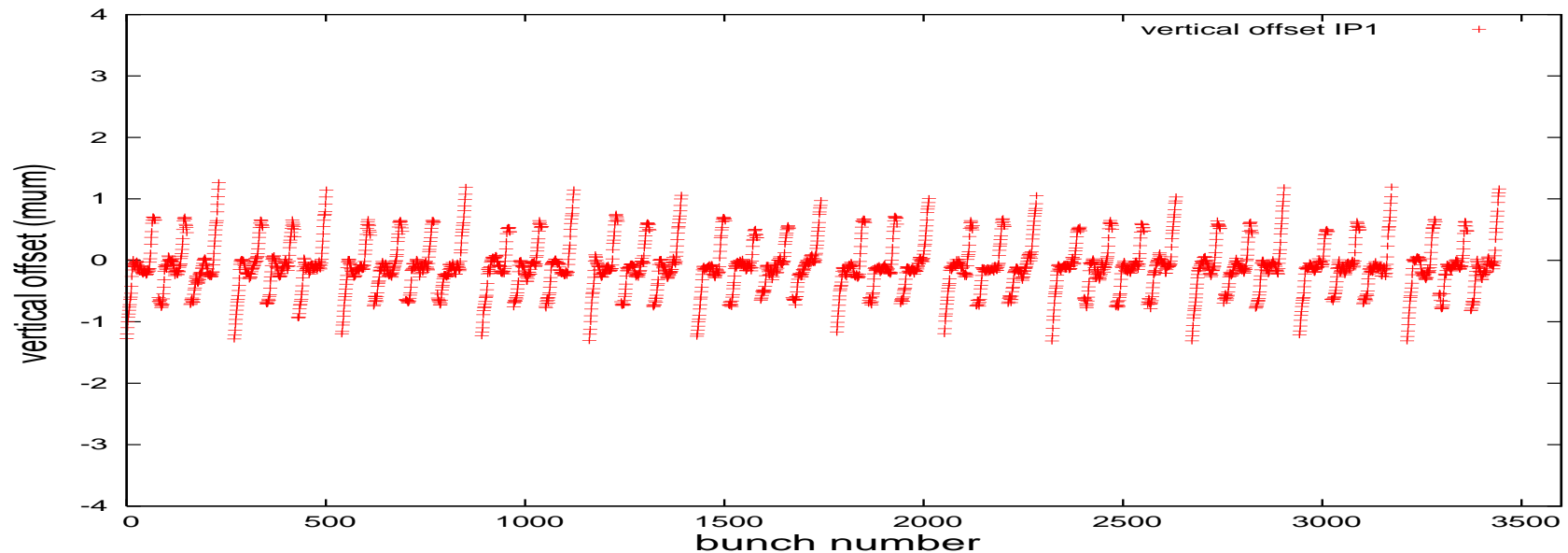
- ➔ Horizontal tune along bunch trains **with** and **without** alternating crossing
- ➔ Predicted tunes from self-consistent computation

Beam-beam Orbit effects

- Strong beam-beam interaction with static offset produces dipole kick
 - Orbit changes due to beam-beam kick
 - Used for LEP: deflection scan
- What about orbits for PACMAN bunches ?
 - Different kicks - different orbits
 - Cannot be fully compensated by alternating crossing schemes !

(details: poster WEPC081)

PACMAN Orbit effects: calculation



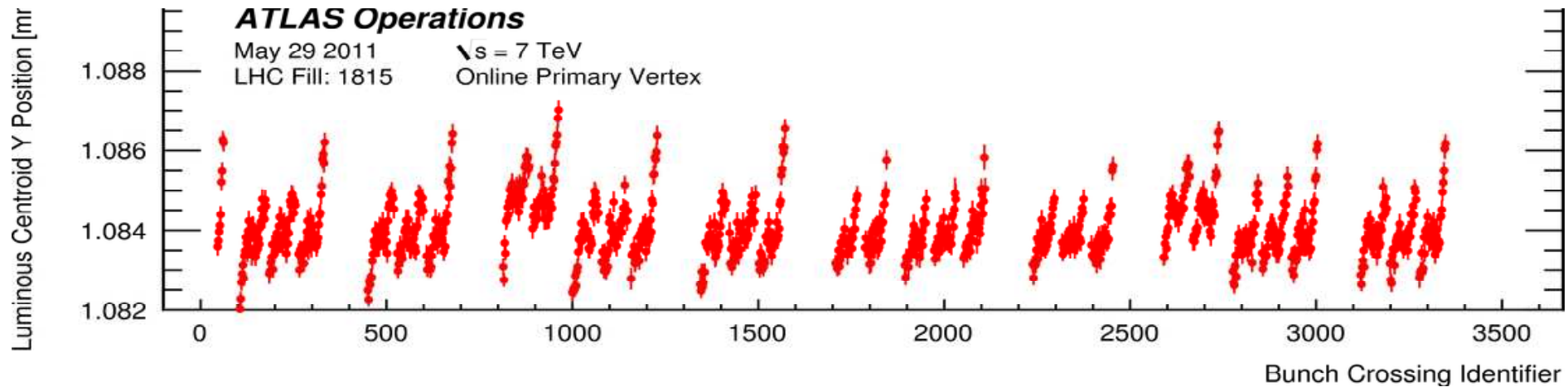
- ➔ Vertical offset expected at collision point in IP1
- ➔ Predicted orbits from self-consistent computation (2003)
- ➔ Cannot be resolved with beam position measurement, but ..

PACMAN Orbit effects: observation

2011-07-05

file:///afs/cern.ch/user/z/zwe/Desktop/PNG/bcid_vs_posY_pm_posYErr.png

#1



- ➔ Measurement of vertex centroid by LHC experiments (ATLAS)
- ➔ Qualitatively: follows exactly predicted behaviour

SUMMARY

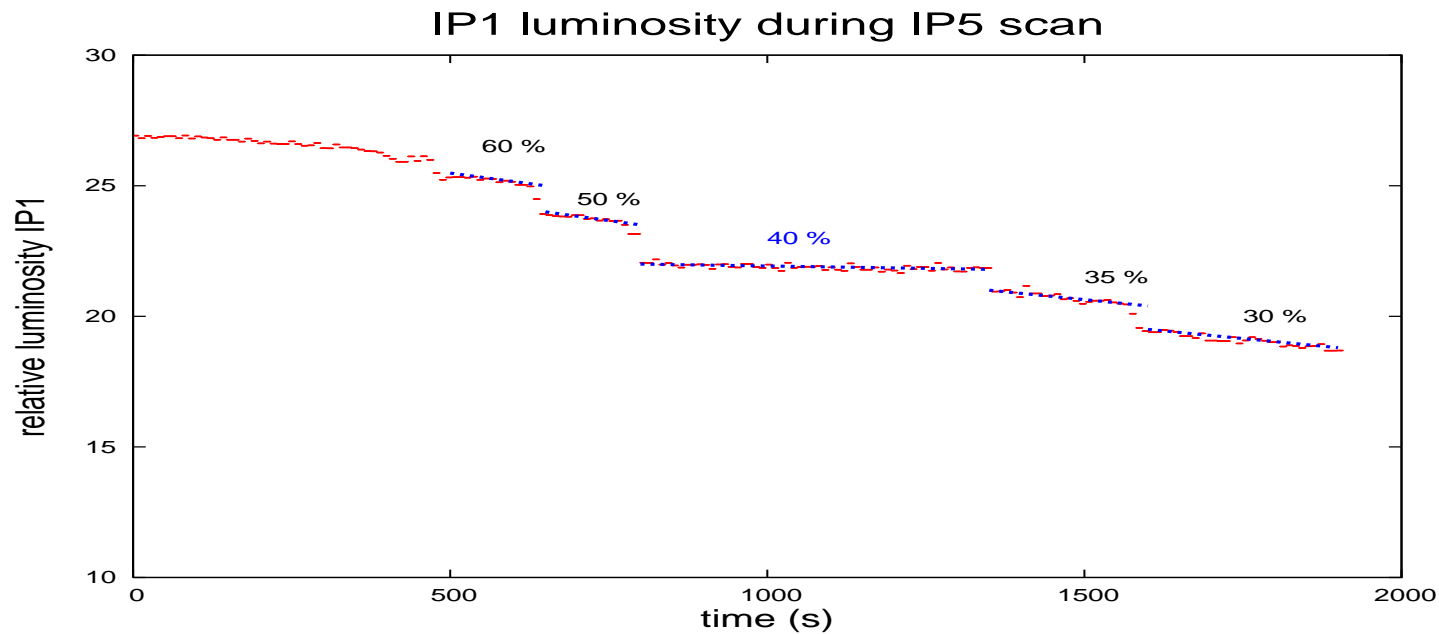
- First clear beam-beam observations in the LHC are presented
- Obtained large head-on tune shifts above nominal
- Effect of long range interactions clearly visible
- Number of head-on and/or long range interactions important for losses
- All observations in excellent agreement with expectations and well understood
- Beam-beam effects should allow nominal luminosity (with 2808 bunches, at 7 TeV)

Back up

- backup slides -



Other signs of compensation ?



- ➡ Luminosity in IP1 during crossing angle scan in IP5
 - ➡ Separation in IP1 kept constant at 40%
 - ➡ Life time best for equal crossing angles in both IPs
- More studies needed