Observations of beam-beam effects in the LHC

W. Herr

for Beam-Beam Studies Team

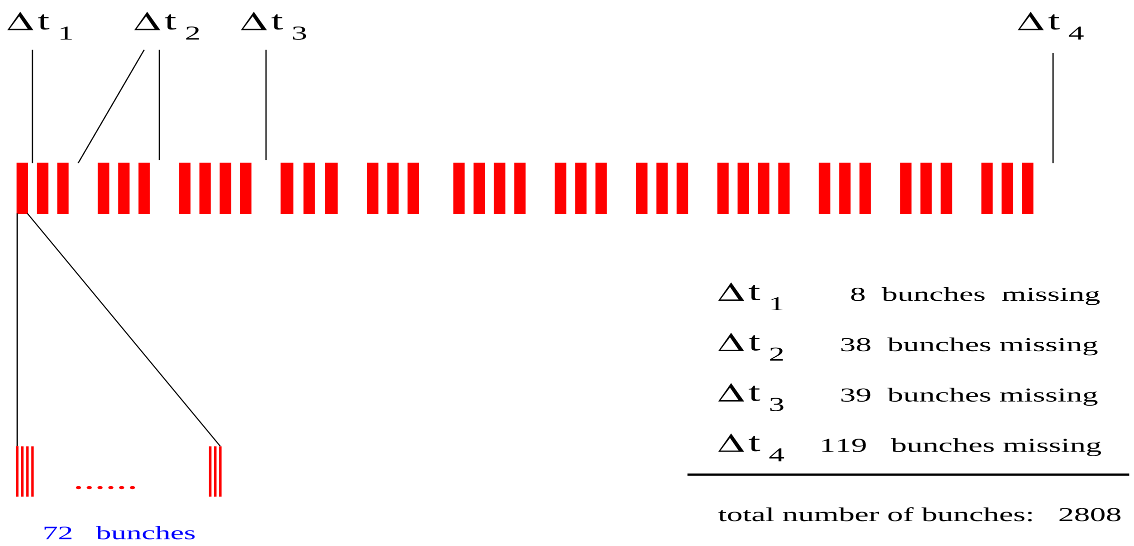
Beam-beam issues in the LHC

- **Relevant questions for crab crossing**

  (with first answers in 2010/2011):

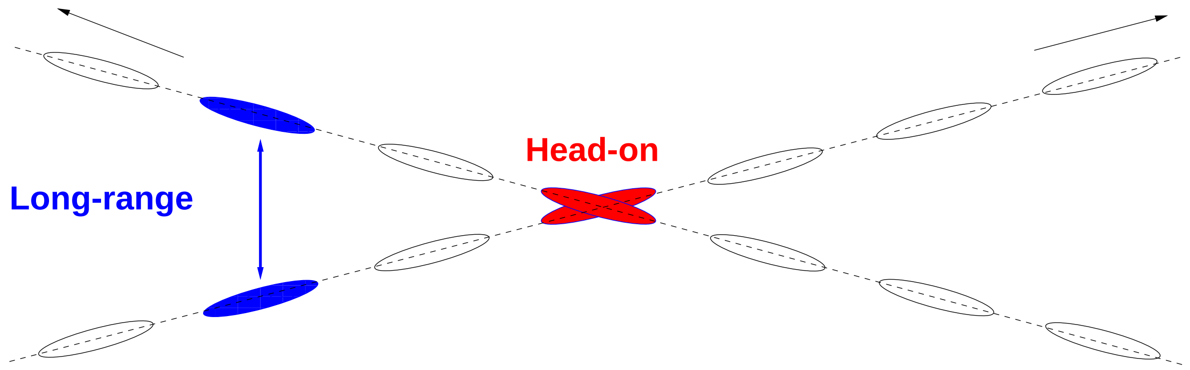
  - **Head-on beam-beam: are we limited ?**
  - **Do we see long range effects ?**
  - **Do we see "PACMAN" effects (i.e. bunch-to-bunch differences) ?**
  - **Can we level the luminosity ?**
  - **What are the main lessons ?**

LHC beam: "nominal" bunch filling pattern



- **Arranged in 39 trains of 72 bunches, spaced by 25 ns, (2808 bunches), with gaps between trains (PACMAN bunches)**
- **In 2011: 50 ns spacing, 1380 bunches per beam**

Large number of bunches



- **Implications :**
  - **Long range interactions**
  - **Crossing angles (horizontal or vertical, $\approx$ 200 - 300 μrad)**
  - **Depending on β^*: small β^* → large angle**
  - **Separation typically 8 - 12 σ**

The "nominal" LHC

- **Parameters relevant for beam-beam:**
  - **Bunch intensity ($1.15 \cdot 10^{11}$ p/bunch)**
  - **Normalized bunch emittance (3.75 μm)**
  - β^* **(0.55 m)**
  - **Crossing angle α ($\approx$ 300 μrad)**
  - **Piwinski ratio $\approx$ 0.66, loss of luminosity $\approx$ 16%**

→ **"Nominal" beam-beam parameter: $\xi = 0.0035$**

- **Conservative (not considered as a limit !)**
- **Defined to reach design luminosity: 10^{34} cm^{-2} 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 (later 1.0 m)**
- **Emittances smaller than nominal ($\approx$ 1.5 - 2.5 μm)**
- **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 I

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

Observations: head-on beam-beam effects I

- Dedicated experiment with few bunches
- Test maximum beam-beam parameter (at injection energy) - head-on only
  - Intensity $1.9 \cdot 10^{11}$ p/bunch
  - Emittances 1.1 - 1.2 μm
  - Achieved:
    ξ = **0.017** for single collision ($\approx$ 5 times nominal !)
    ξ = **0.034** for two collision points (IP1 and IP5)
  - No obvious emittance increase or lifetime problems during collisions (maximum ξ not yet found)

⚠ No long range encounters present !

Observations: head-on beam-beam effects II

- **Dedicated experiment with few bunches**
- **Test maximum luminosity per collision (pileup) (at 3.5 TeV, $\beta^* = 1$ m) - head-on, with crossing angle**
  - **Intensity $\approx$ 2.4 $\cdot$ 10^{11} p/bunch**
  - **Emittances 2.5 - 3.0 μm (blown up during injection and ramp)**
  - **Achieved:**
    ξ = 0.018 for two collision points (IP1 and IP5)
    "pileup" $\approx$ 35 per collision, lifetime above 30 hours

Allows very large head-on beam-beam tune shift ! Low noise ?

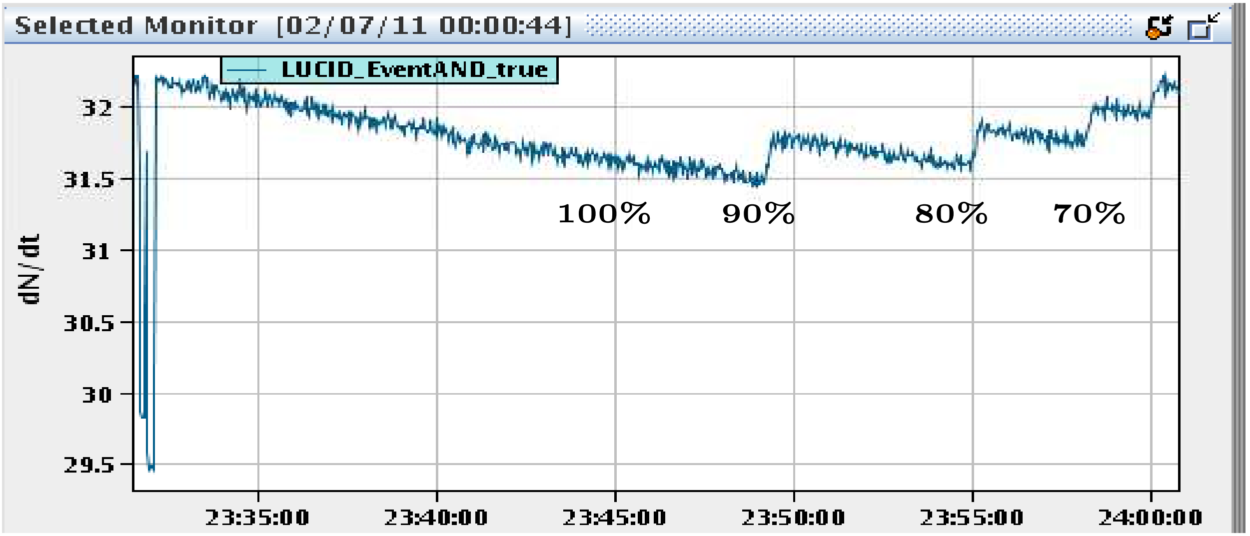
Experimental study of long range beam-beam interactions

- **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 $\approx$ 32 parasitic encounters**
  - **In standard operation (2011): separation is kept at $\approx$ 12 σ (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**

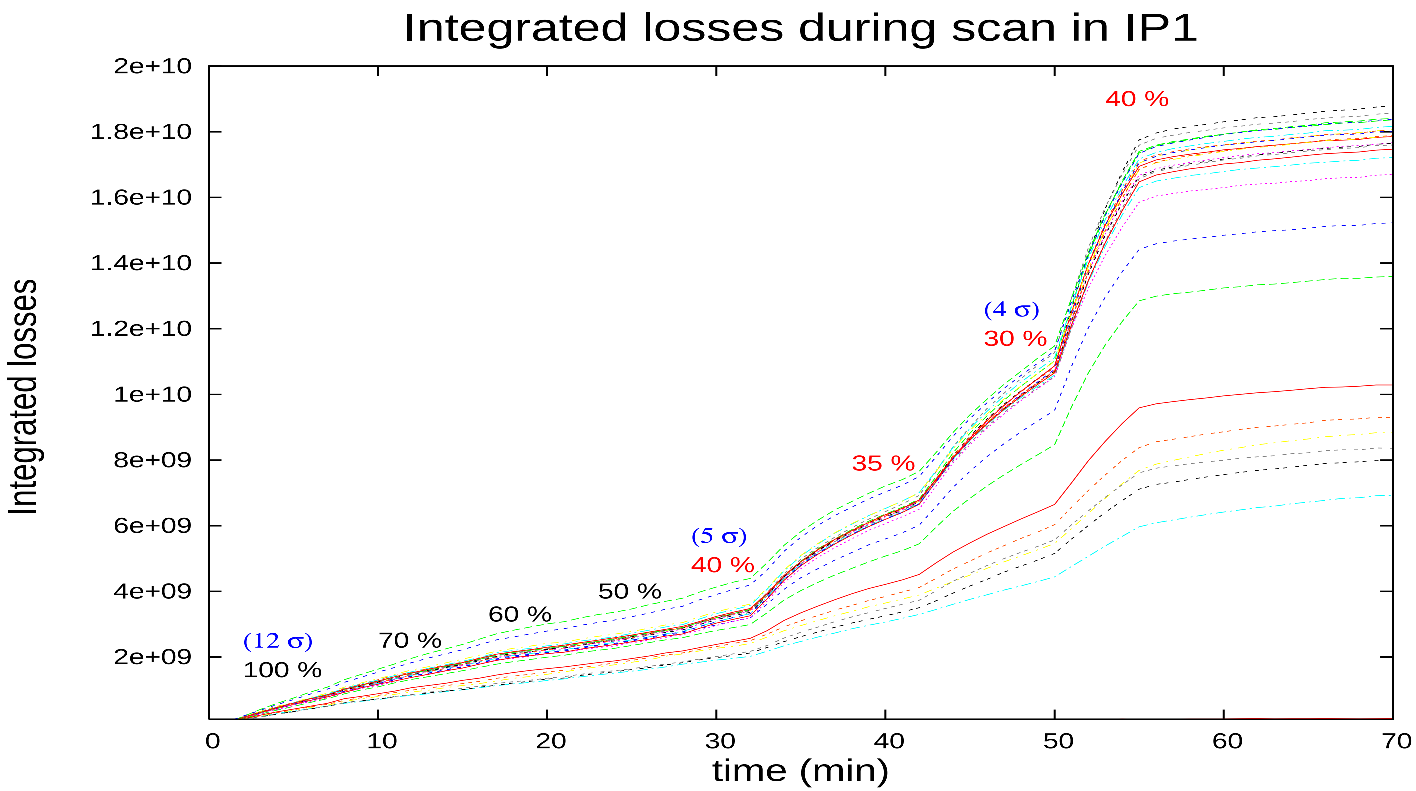
Scan of crossing angle: luminosity



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

BUT: range very small !

Scan of crossing angle: losses

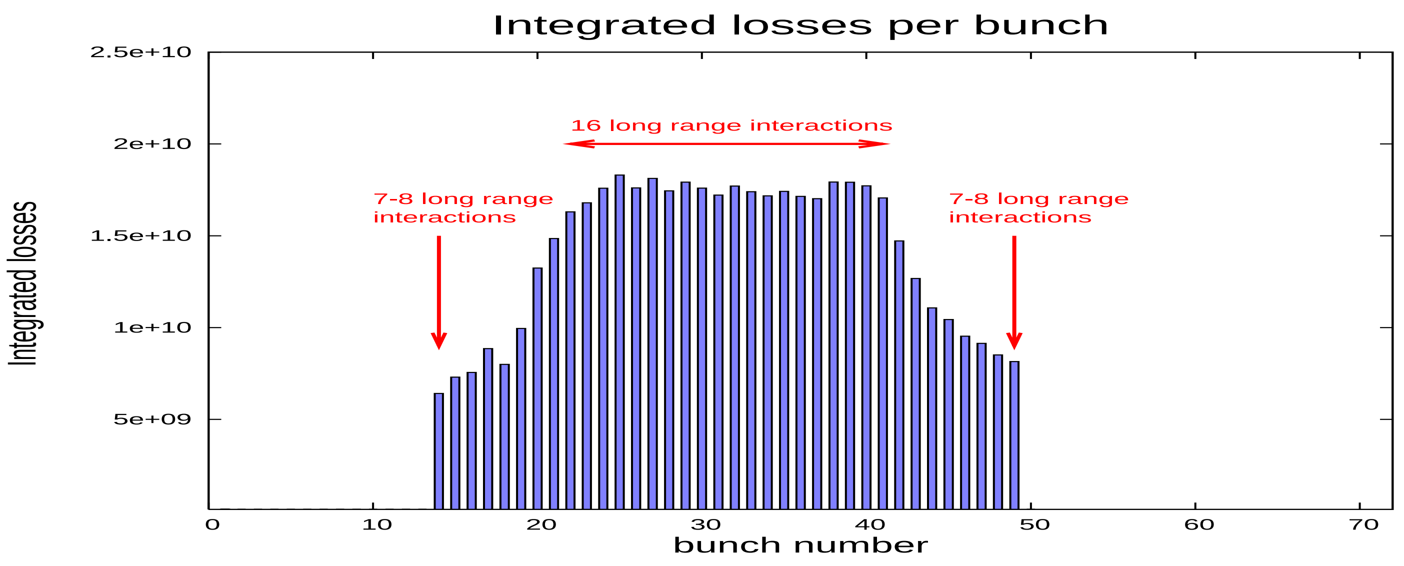


➡ **Bunch by bunch loss as function of crossing angle in IP1**

Scan of crossing angle

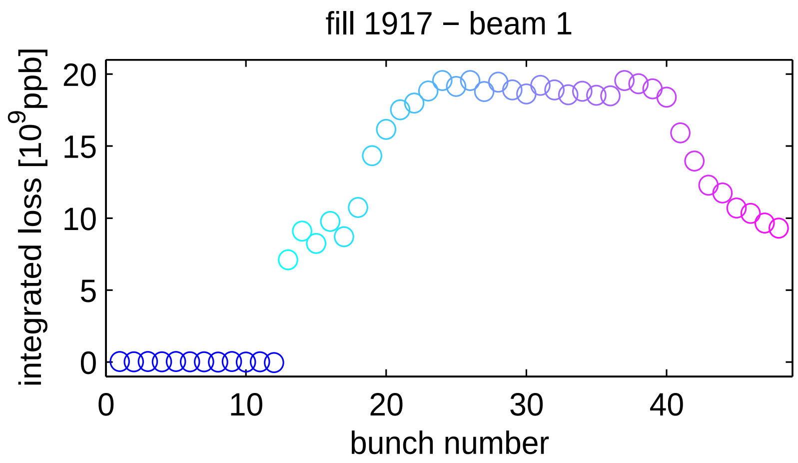
- **Observations:**
  - **Losses start after some threshold (4 - 5 σ separation)**
    remember: 32 parasitic encounters (nominal 120 !)
  - **Smaller separation leads to increased losses (dynamic aperture !)**
  - **Little (if any) effect on emittances**
  - **Different bunches have different threshold !**
  - **Strong evidence for PACMAN effects**

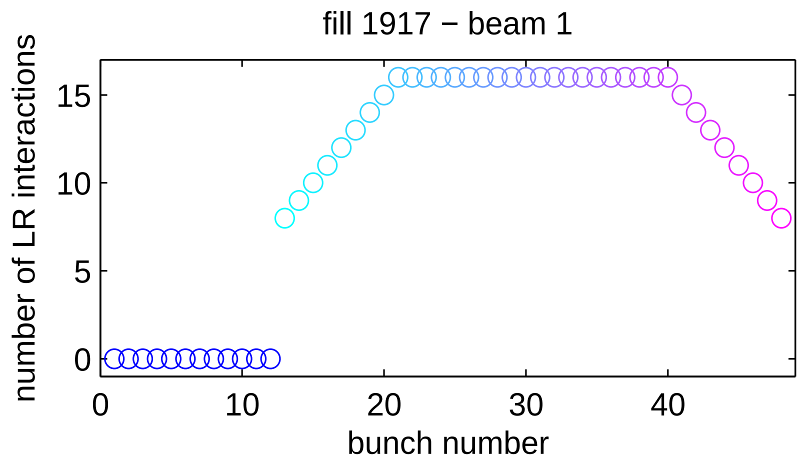
PACMAN effects



- Integrated losses of the bunches in the train (36 bunches)
- Losses depend on position in bunch train

PACMAN effects



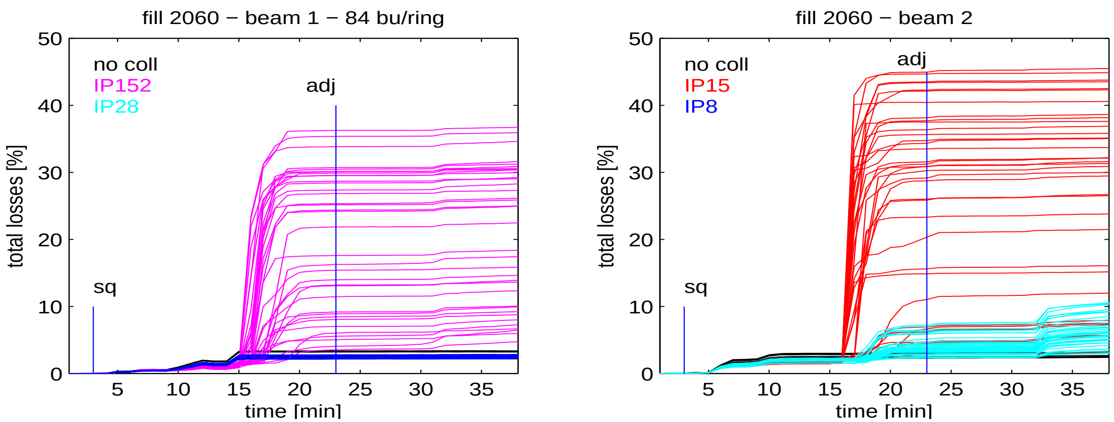


- **Integrated losses and number of long range interactions**
- **Losses directly related to number of long range interactions**

→ **So-called 'PACMAN' bunches have <u>better</u> life time !**

→ **'PACMAN' effects clearly visible**

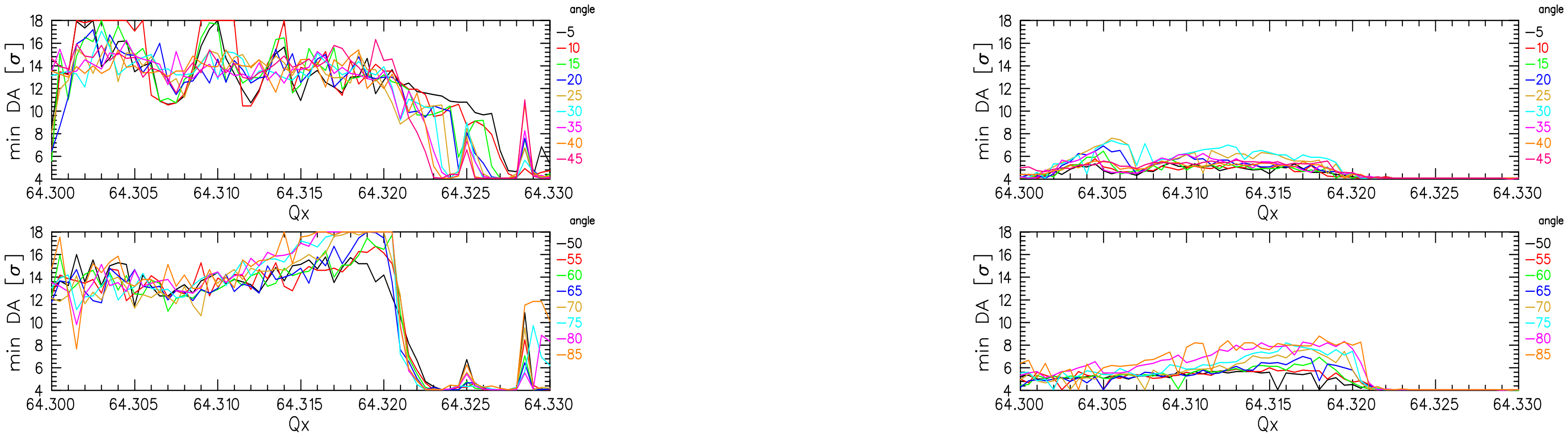
Observations: Losses due to long range



(Courtesy G. Papotti)

- **First attempt with $\beta^* = 1$ m, reduced (!) crossing angle**
- **Bunches colliding in IP1 and IP5: too small separation**
- **Bunches colliding in IP2 and/or IP8: sufficient separation**

Predictions: dynamic aperture due to long range



- Predicted dynamic aperture, tune scan (2007-2008, nominal machine with different crossing angles)

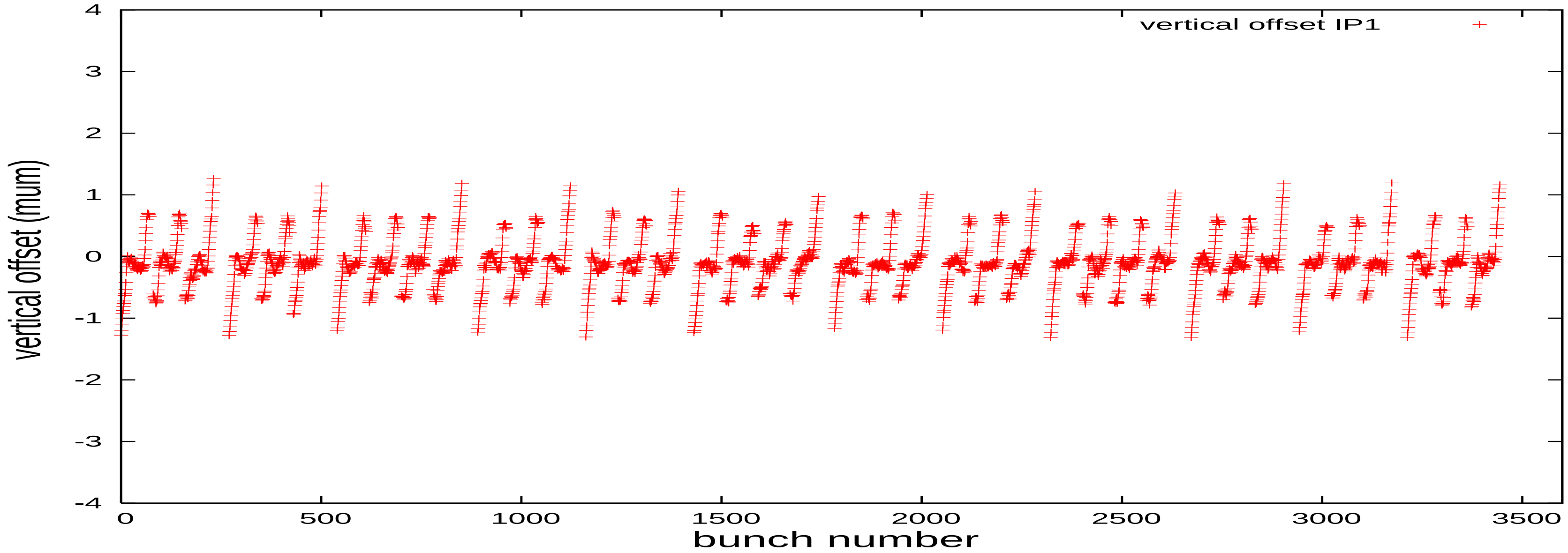
  (LHC Project Note 416, W. Herr, D. Kaltchev)

- Different case, but comparable separation to standard (2011) and reduced separation

Beam-beam Orbit effects

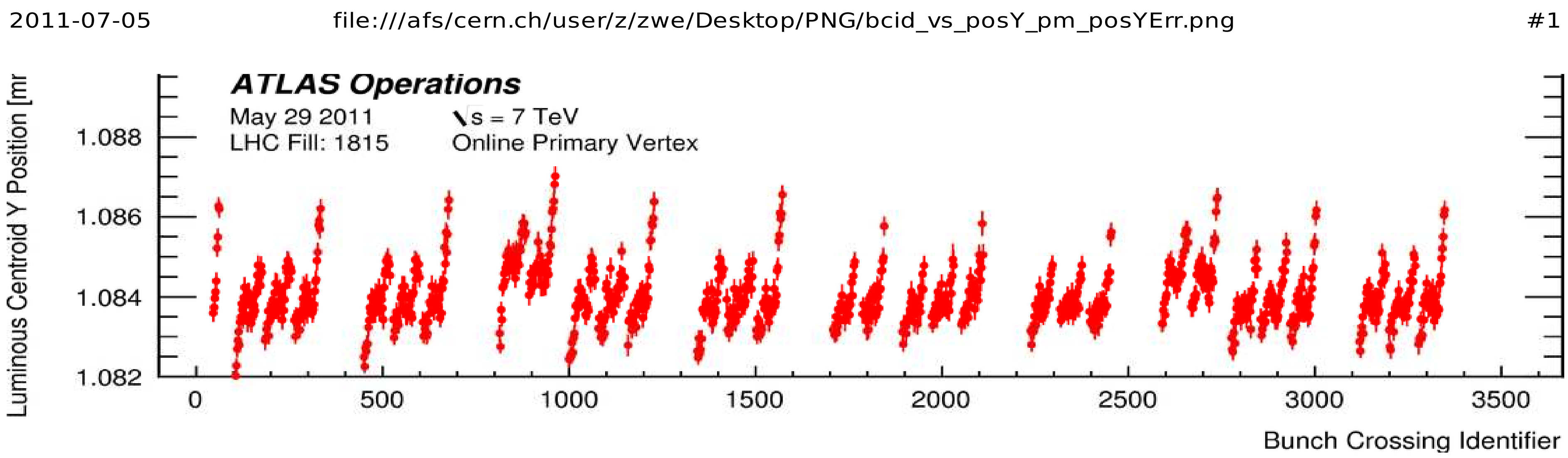
- **Strong beam-beam interaction with static offset produces dipole kick**
  - **Orbit changes due to beam-beam kick**
  - **Used for LEP: deflection scan**
- **What about orbits for PACMAN bunches ?**
  - **Different kicks - different orbits**
  - **Cannot be fully compensated by alternating crossing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

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

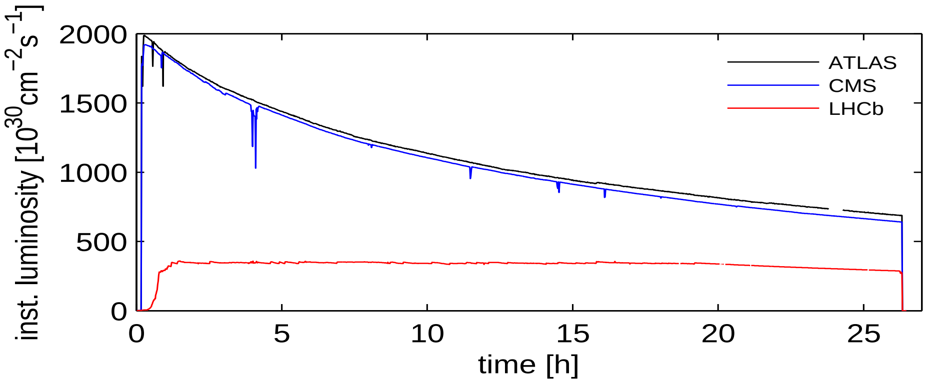


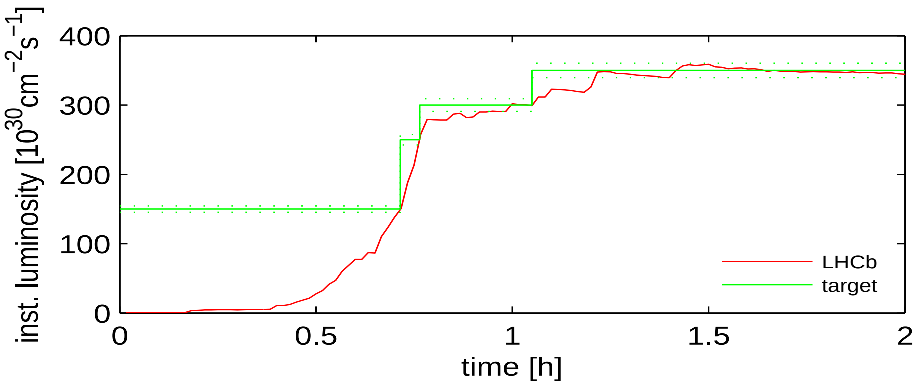
- **Measurement of vertex centroid by ATLAS (IP1)**
- **Qualitatively: follows exactly predicted behaviour**
- **Must be kept under control (sufficient separation) !**

Luminosity levelling

- **LHC has 4 experiments:**
  2 require highest luminosity,
  2 require lower luminosity (up to factor 10^{-4})
- **Luminosity levelling required already in 2011 (reduce luminosity and keep constant)**
  - **Achieved by transversely offset collisions (simple to do, very large range)**
  - **Separation $\approx$ 4 σ (IP2) and $\approx$ 0.5 - 1.5 σ (IP8)**
  - **Routinely done without detrimental effects**

Luminosity levelling - standard operation





- **Luminosity in LHC experiments during levelling**
- **Luminosity very constant in IP8, no effect on other IPs**

Summary of observations

- **Obtained large head-on tune shifts above nominal**

  In daily operation: twice "nominal" value is standard

- **Effect of long range interactions clearly visible (losses, dynamic aperture), no data yet on 25 ns spacing ..**

- **Number of head-on and/or long range interactions important for losses**

- **All observations in excellent agreement with expectations and well understood (so far)**

- **Beam-beam effects should allow higher than nominal luminosity (with 2808 bunches, at 7 TeV)**

LESSONS

- **Beam-beam is a critical issue in LHC, but (so far) under control, well understood and no surprises**
- **For higher luminosities:**
  - **Aim at high head-on beam-beam parameter:**

    high brightness, avoid noise or modulations

    very unlikely to be the limit for high luminosities
  - **Avoid increase of long range beam-beam effects:**

    provide sufficient separation (large crossing angle - don't touch it !), avoid large number of long range
  - **Minimize PACMAN effects and bunch-to-bunch fluctuations (source of noise !)**

CONSEQUENCES FOR LEVELLING

- **Must be independent for all experiments**
- **Transverse offset works without problems (so far), large range**

  → **can only reduce luminosity !**
- **Crossing angle and** β^*

  → **change long range behaviour,** $\rightarrow$ **limited range**
- **Crab crossing**

  → **limited range but can recover geometric factor**

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  - → **limited range but can recover geometric factor**
  - → **for small** β^* **...**

- BACKUP SLIDES -

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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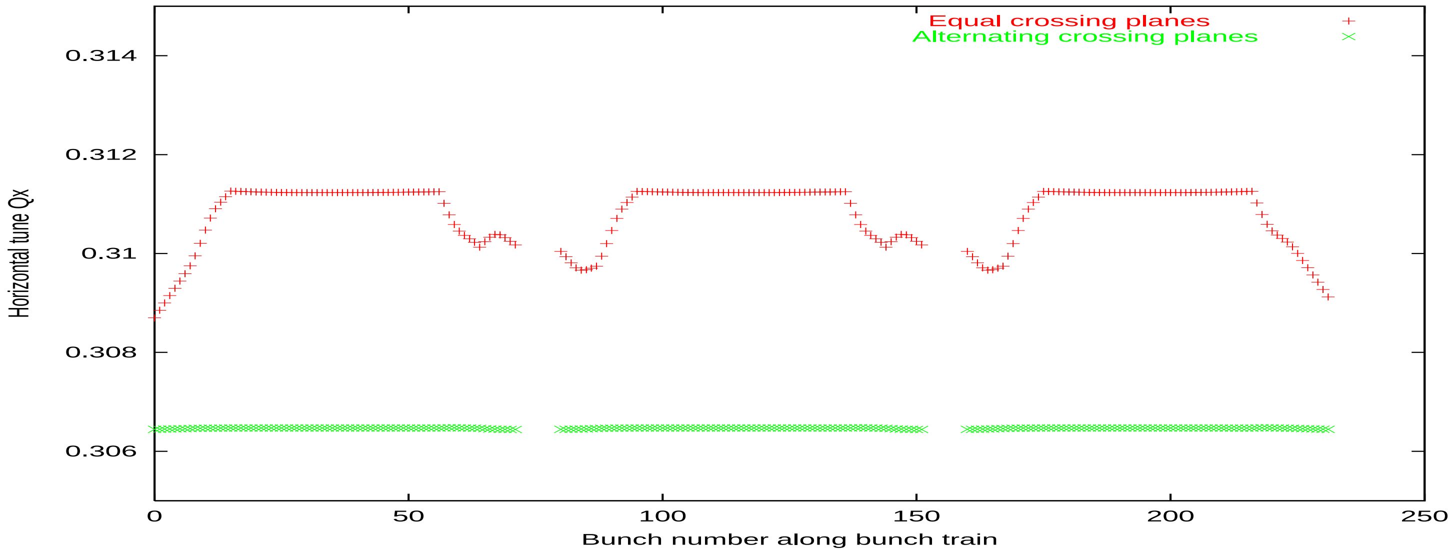
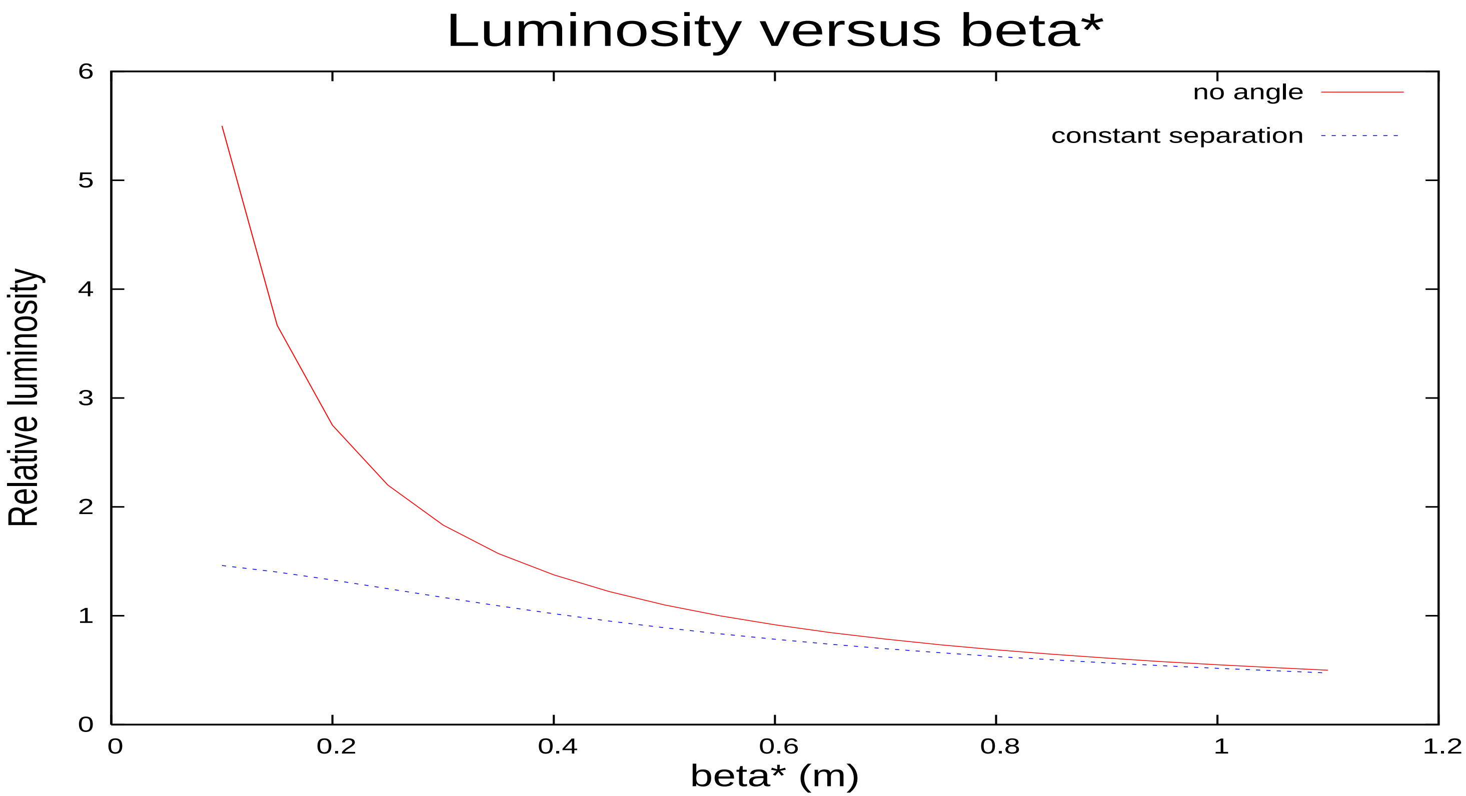
  - **Bunches at head and tail of train would be lost first (origin of the name)**
- **In LHC: alternating crossing scheme (horizontal and vertical crossing planes) removes tune difference by compensation**

PACMAN tune effects: calculation



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

Luminosity versus β^*



➡ **Luminosity versus β^* for constant separation**