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Bunch-by-Bunch Analysis of the LHC Heavy-Ion Luminosity

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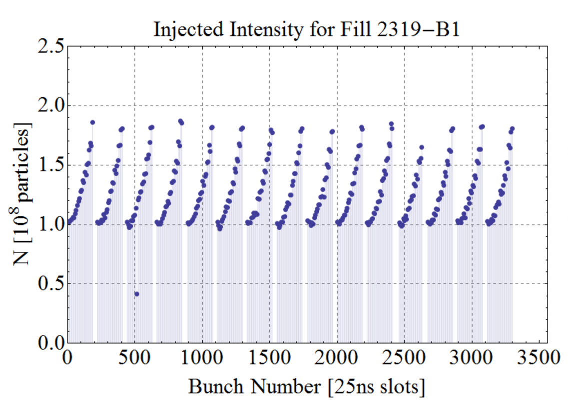
Abstract

After the first run in 2010 [1], the LHC (Large Hadron Collider) continued its heavy-ion operation with collisions of lead nuclei in late 2011. The beam dynamics of those high intensity lead beams are strongly influenced by intra-beam scattering (IBS), especially on the injection plateau. Each train injected from the SPS (Super Proton Synchrotron) spends a different time at injection, introducing significant changes from train to train. Within the trains there is an even larger spread imprinted by the SPS injection plateau. This results in a spread of the luminosity L, produced in each bunch crossing. The luminosity, emittance ϵ_N, intensity N_b, and bunch length σ_z, evolution was analysed bunch-by-bunch and compared with simulations. Based on this analysis, estimates of the potential luminosity performance at 6.5Z TeV, after the present shutdown (LS1), are given.

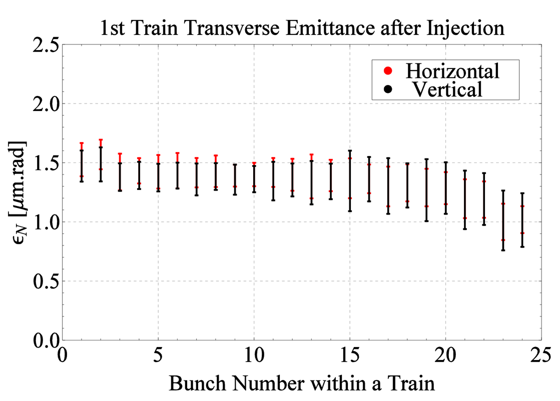
Bunch-by-Bunch Differences

- Pb ions injection chain: source → LINAC3 → LEIR → PS → SPS → LHC.
- Significant bunch-by-bunch pattern within a LHC train builds up at the **injection plateau of the SPS**:
  - → Inject 2 bunches from PS into SPS – 12 injections to construct LHC train.
  - → While waiting for remaining injections form PS, bunches are strongly affected by **IBS ($\propto \gamma^{-3}$) at low energy**.
  - ⇒ Emittance growth and particle losses.

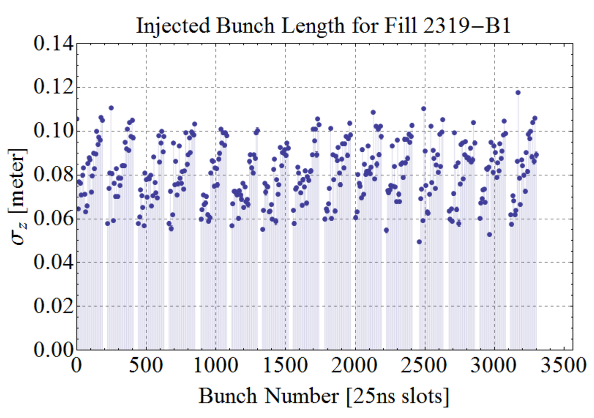
In LHC right after injection



N_b increase from 1st to the last bunch in a train.



ϵ_N decreases from 1st to last bunch in a train.

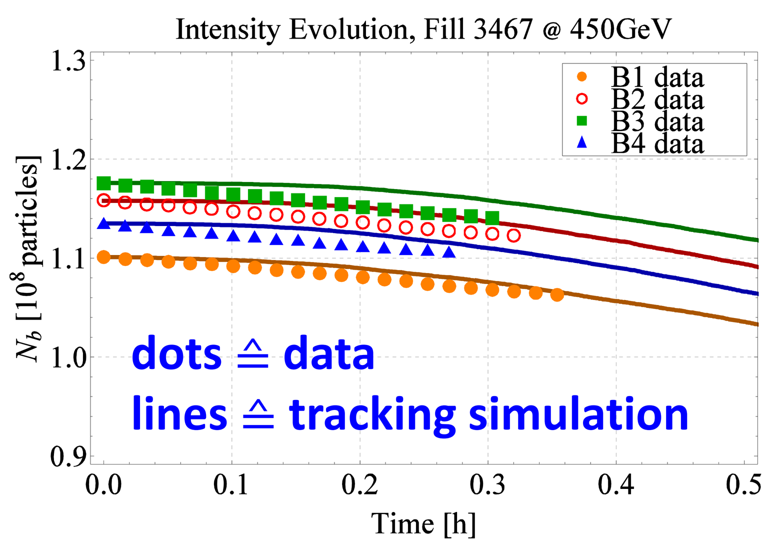


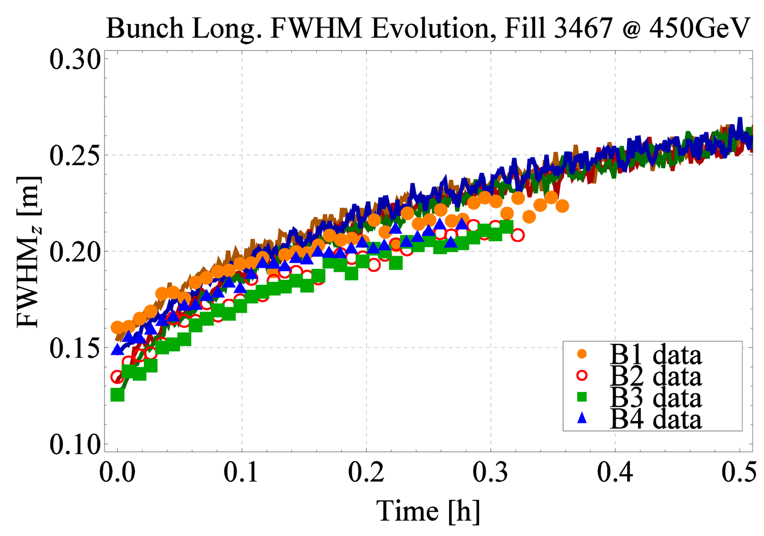
σ_z shows similar behaviour as **N_b**.

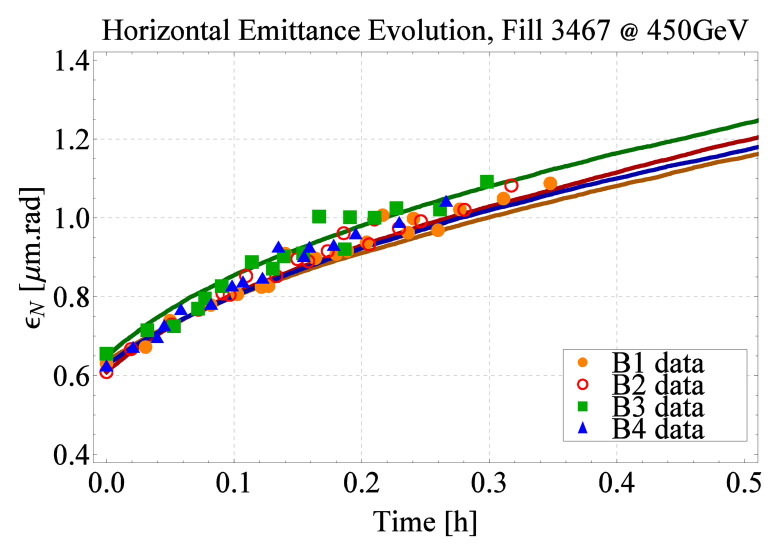
Single Bunch Evolution at Injection

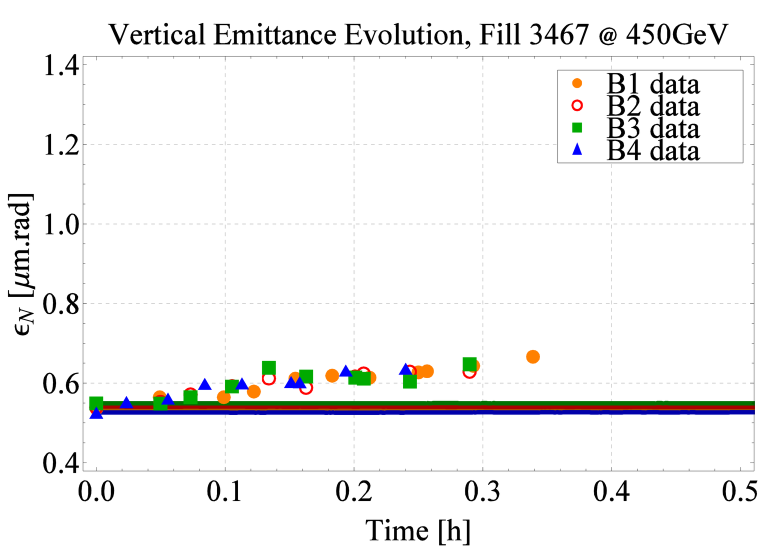
- *Simulation Code: **Collider Time Evolution (CTE)** [2].*
- *Tracking of 2 bunches of macro-particles in time in a collider.*
- *Simulation of IBS, radiation damping, but, eg, no beam-beam.*

- Evolution of **4 single Pb bunches at injection** (E = 450GeV).
- Horizontal IBS growth stronger than vertical due to horizontal dispersion, → no vertical dispersion in model (for speed).
- Additional growth in vertical ϵ_N due to coupling.

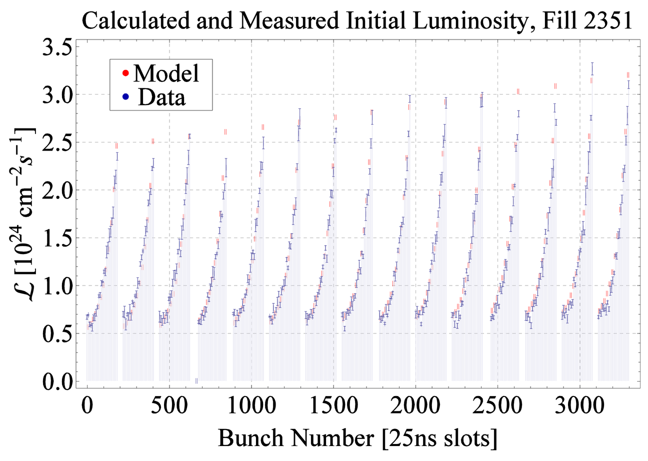


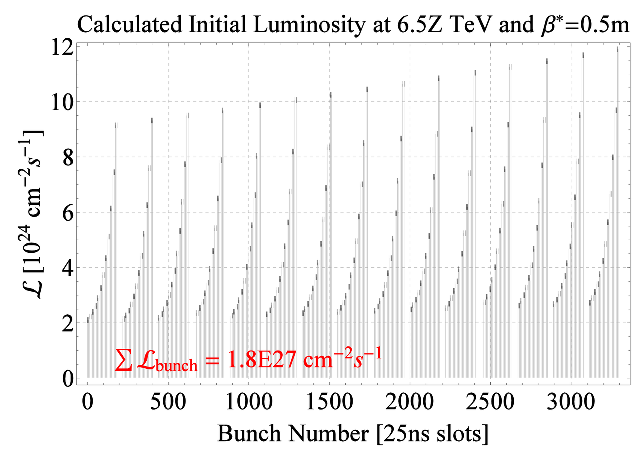






Projections for after LS1





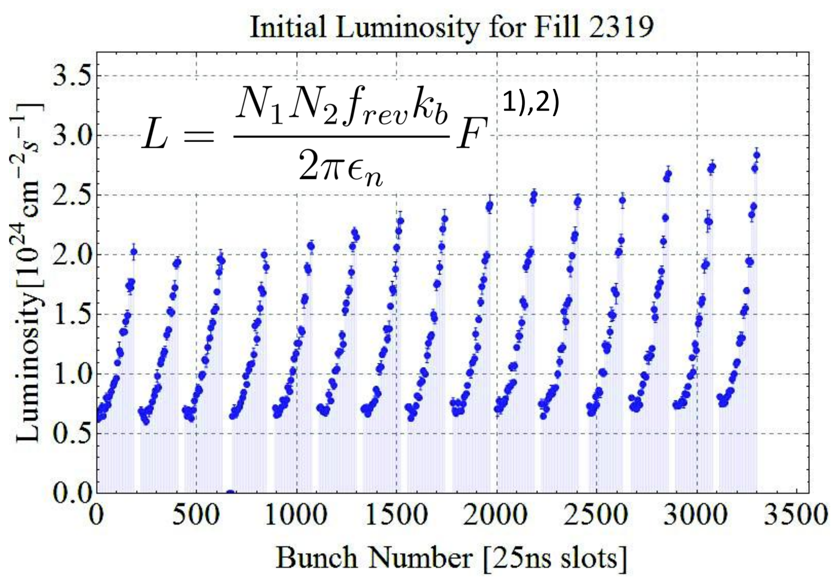
- Running conditions after LS1:
  → higher **E = 6.5Z TeV** and lower **β^* = 0.5m**.
- Estimate peak luminosity at start of collisions:
  → Model based on 2011 bunch-by-bunch luminosity, predicts peak L_{Bunch} as a function of position inside the beam.
  → Assumptions: - 2011 beam conditions,
  - 2011 filling scheme.
  → Scaling to E = 6.5Z TeV yields

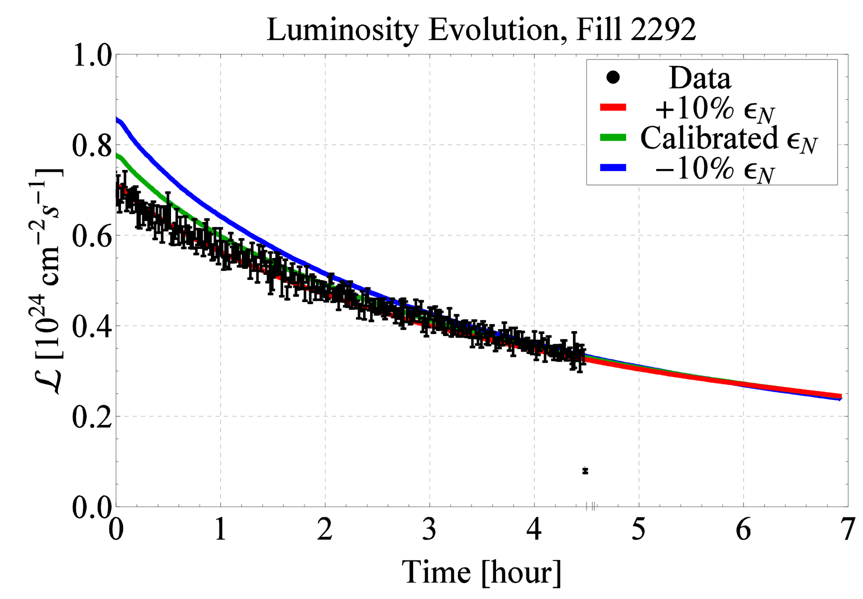
$$L_{\mathrm{Peak}} = 1.8 \times 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1} = 1.8\, L_{\mathrm{Design}}.$$

- In 2013 p-Pb run **N_b could be increased by 30%.**
- Alternating 200/100ns bunch spacing to increase total number of bunches.

⇒ Possible to reach $L > 2 \times 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Luminosity

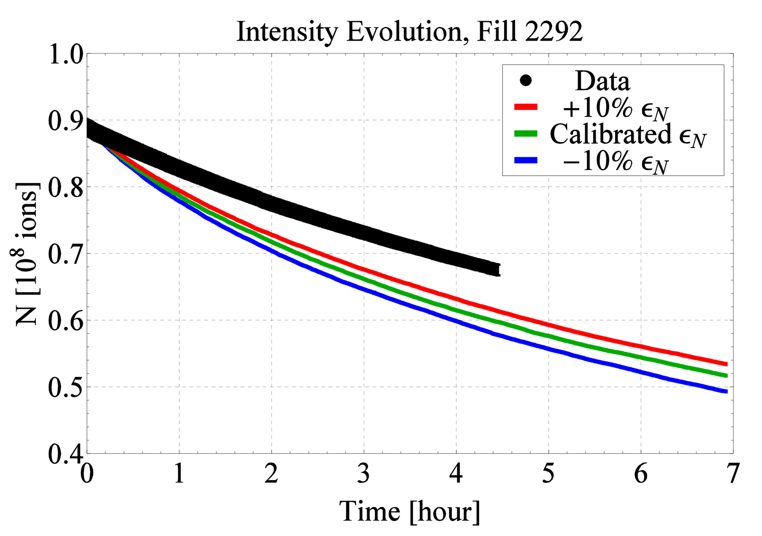


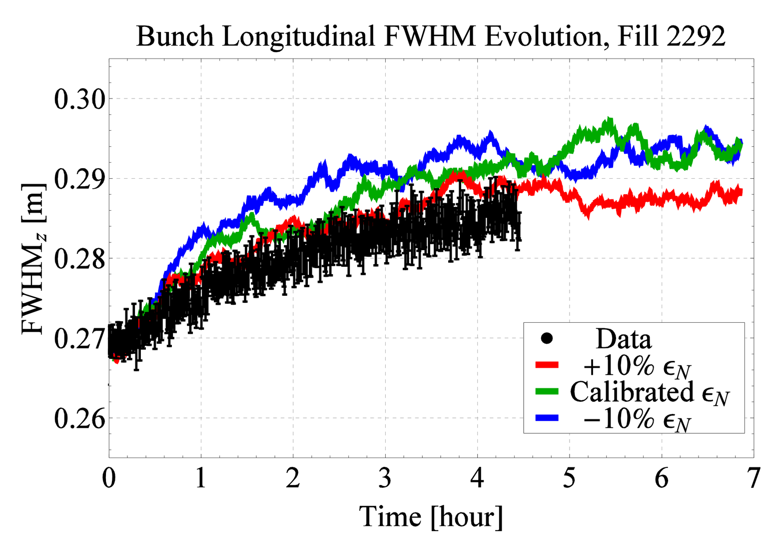


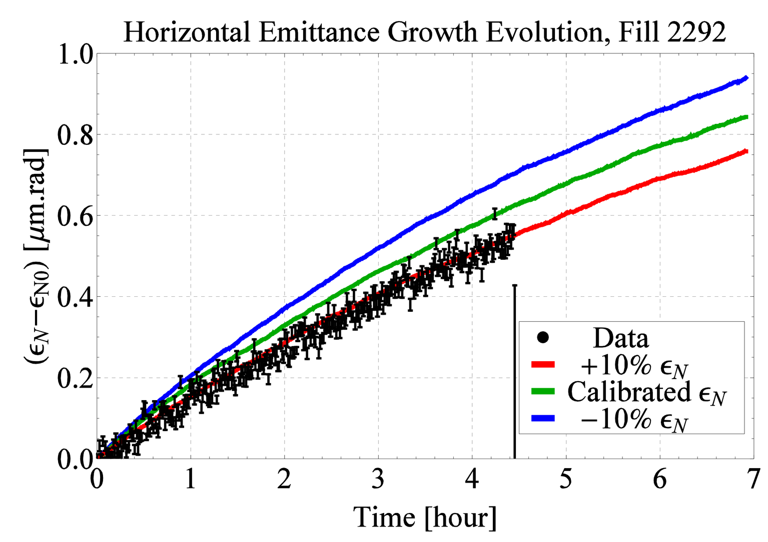
- Collisions of equivalent bunches (with similar N_b and ϵ_N).
- L_{Bunch} varies by a factor 6 along a train - introducing different lifetimes.
- Slope between last bunches of trains introduced by IBS at LHC injection plateau.
- Particle losses during collisions are dominated by nuclear EM processes,
  → leading to non-exponential N_b decay and short lifetimes at E = 3.5Z TeV.

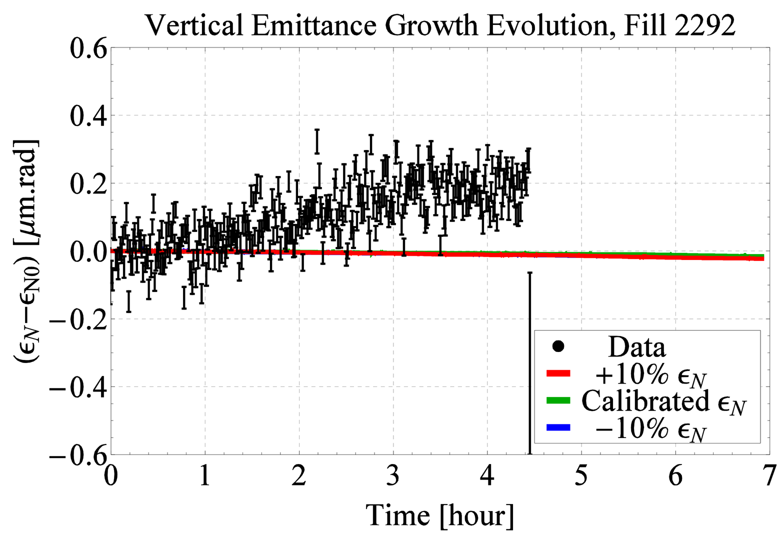
Evolution of Colliding Bunches

- *3 simulation runs with varying initial ϵ_N to account for calibration uncertainties.*
- Losses in N_b are overestimated by the simulation, due to assumption of Gaussian longitudinal profile.
- The calibrated ϵ_N seems to be underestimated by about 10%.
- **L, ϵ_N and σ_z fit very well to the simulation for +10% initial ϵ_N.**









Footnotes: 1) $F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$

2) $\epsilon_n = \frac{\gamma}{\beta^*}\sqrt{\sigma_{x1}^2 + \sigma_{x2}^2}\sqrt{\sigma_{y1}^2 + \sigma_{y2}^2}$

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References:

[1] T. Mertens *et al.*, TUPZ017, IPAC 2011, (2011).

[2] R. Bruce *et al.*, Phys. Rev. ST Accel. Beams **13**, 091001 (2010).

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