Potential for Stochastic Cooling of Heavy Ions in the LHC

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Outline

- Brief Introduction to Stochastic Cooling

- System and Performance at RHIC

- Data Analysis and Simulations from 2011 and 2013
  - Bunch-to-Bunch Differences
  - Beam Evolution and Tracking Simulations

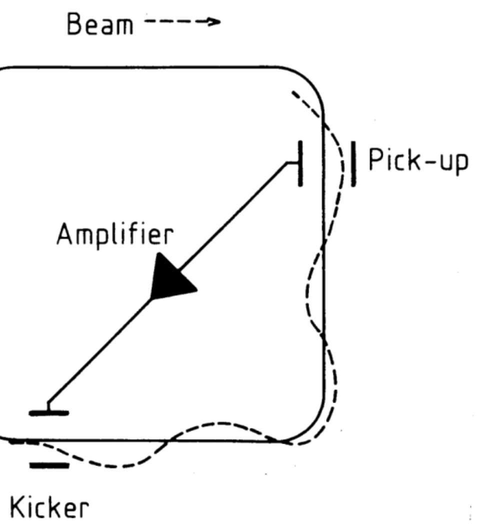
- First Studies for a Stochastic Cooling System at LHC

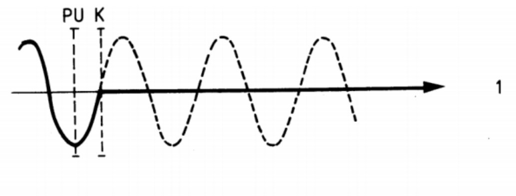
Stochastic Cooling – Basic Principle (1/5)

Cooling aims to reduce the size and energy spread of a circulating particle beam

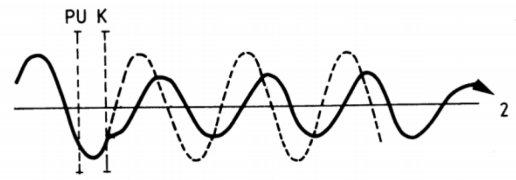
Test particle picture:

- Particle performs betatron oscillations, due to position and angle errors.
- Cooling system is designed to damp these.
- Pick-up measures transverse position at each turn.
- Kicker applies angle correction proportional to position error at pick-up.
  → Synchronism between particle & signal!
  → Phase of pick-up and kicker is chosen to be (λ/4 + n λ/2).
  → Signal has to take a short cut.

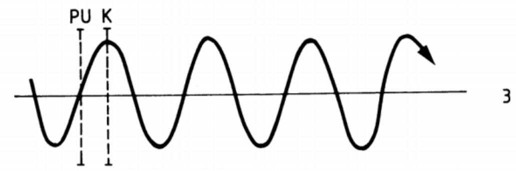




Oscillation completely cancelled.



Oscillation partly cancelled.



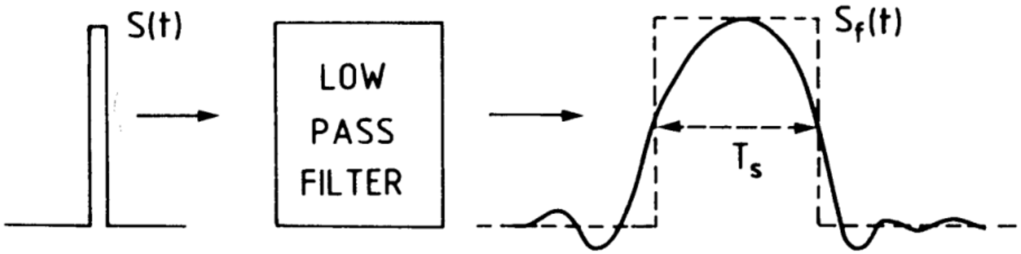
Particle not affected.

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

Stochastic Cooling – Basic Principle (2/5)

Beam samples:

- Off-axis particle passing through pick-up induces short pulse.
- Finite bandwidth (W) of the cooling system.
  → Kicker signal broadened into pulse of length $T_s = 1/(2W)$.



- Test particle passing system at t_0 will be affected by kicks of all particles passing during the time interval $t_0 \pm T_s/2$.

  → Those particles belong to the sample of the test particle.

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

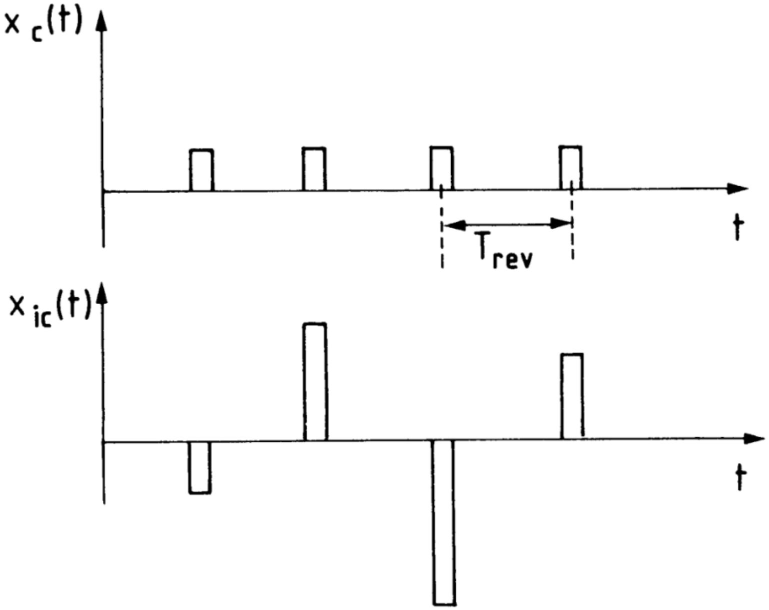
Stochastic Cooling – Basic Principle (3/5)

Test particle picture:

- x is the error of the test particle.
- Corresponding correction at the kicker: $\Delta x = -\lambda x$
  → Corrected error:
  $x_c = x - \lambda x$

- Kicks of other sample members have to be added!

Coherent (systematic) signal of the test particle itself.



Incoherent (random) signal of the other sample particles.
→ Heating!

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

Stochastic Cooling – Basic Principle (4/5)

- Only test particle present:
  → Correction at the kicker: $\Delta x = -\lambda x$
  → Corrected error: $x_c = x - \lambda x$
- Kicks of other sample members have to be added.

$$x_c = x - \underbrace{\lambda x}_{\text{coherent effect}} - \underbrace{\sum_{\text{others}} \lambda_i x_i}_{\text{incoherent effect}}$$

Rectangular kicker pulse:
$\lambda_i = \lambda$

$$x_c = x - \lambda x - \lambda \sum_{\text{others}} x_i$$

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

Stochastic Cooling – Basic Principle (5/5)

- Rewrite the sum to include the test particle.
- Average sample error (the samples centre of gravity): N_s is number of particles per sample.

$$\langle x \rangle_s = \frac{1}{N_s} \sum_{\text{sample}} x_i$$

Test particle picture

Sampling picture

$$x_c = x - \lambda x - \lambda \sum_{\text{others}} x_i \quad \Longrightarrow \quad x_c = x - (N_s \lambda) \langle x \rangle_s$$

Cooling System measures average sample error and applies a correcting kick ($\propto \langle x \rangle_s$) to the test particle!

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

Crude Cooling Rate Approximation (1/2)

$$\Delta x = -(\lambda N_s)\langle x\rangle_s \equiv -g\langle x\rangle_s$$

- g can be interpreted as the fractional correction per turn → g ≤ 1.
- $g = \lambda N_s = 1$ is an estimate for the upper limit.
- Assume incoherent effect averages to zero:

$$\Rightarrow \Delta x = -\frac{1}{N_s} x$$

Assume exponential damping with the number of turns n:

$$x = x_0 \exp(-n/\tau_n)$$

Cooling rate per turn.

$$\Rightarrow \frac{1}{\tau_n} = -\frac{1}{x}\frac{dx}{dn} \cong -\frac{1}{x}\frac{\Delta x}{\Delta n} \underset{\uparrow}{=} -\frac{\Delta x}{x} = \frac{1}{N_s}$$

since Δn = 1 turn

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

Crude Cooling Rate Approximation (2/2)

Cooling rate per turn: $$\frac{1}{\tau_n} = \frac{1}{N_s}$$

For a coasting beam:

Number of samples per beam: $n_s = T_{rev} / T_s$

Number of particles per sample: $N_s = N / n_s = NT_s / T_{rev} = N / (2WT_{rev})$

Cooling rate per second: $$\frac{1}{\tau} = \frac{1}{T_{rev}} \frac{1}{\tau_n} = \frac{2W}{N}$$

For a bunched beam:

→ treat bunch as part of the beam: $N \rightarrow \frac{N_b}{B_f} = N_b \frac{C_{LHC}}{4\sigma_z}$

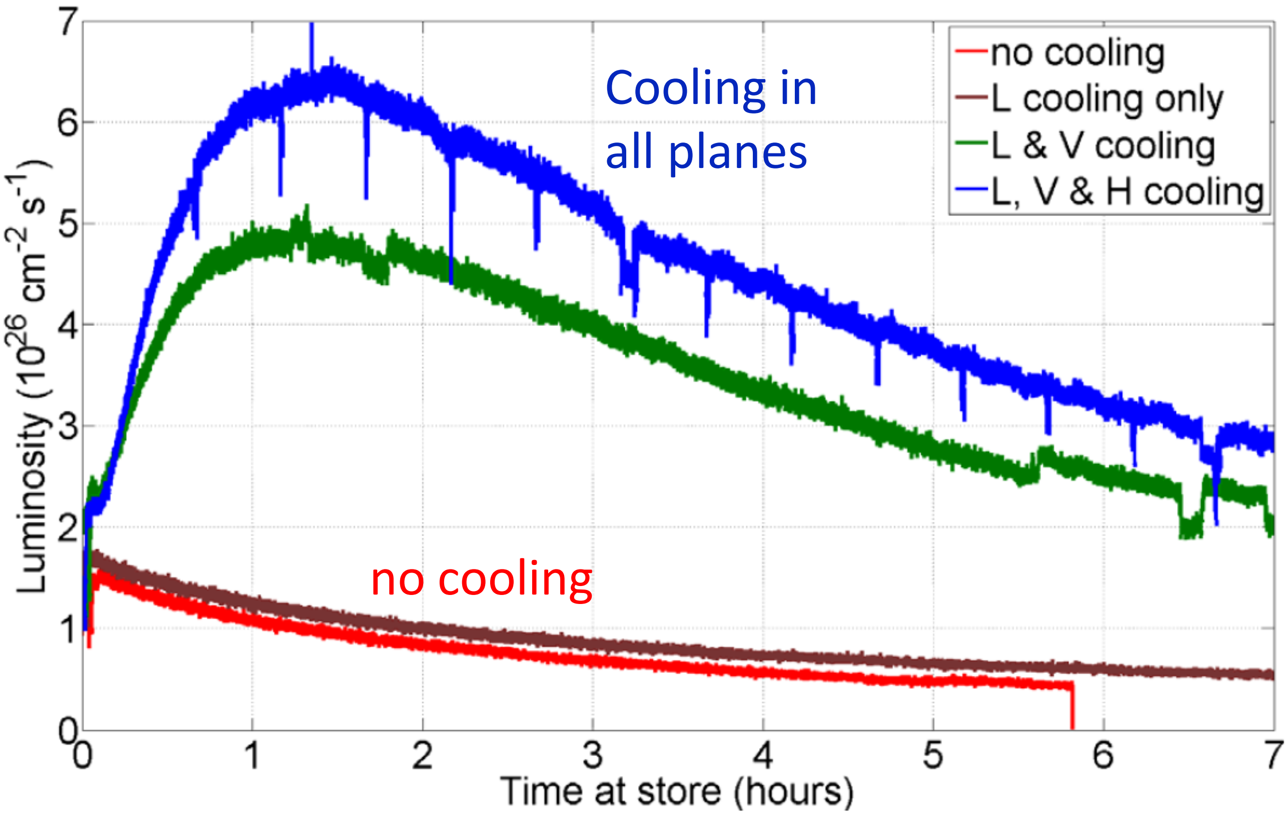
Cooling rate per second: $$\frac{1}{\tau} = \frac{8W\sigma_z}{N_b \, \mathrm{C}_{LHC}}$$

This simple approximation overestimates the optimum cooling rate by only a factor of 2.

Stochastic Cooling for Beginners, D. Moehl, CAS Oct. 1983

Stochastic Cooling of Bunched Beams at RHIC

Luminosity Evolution with and without cooling



Mike Blaskiewicz

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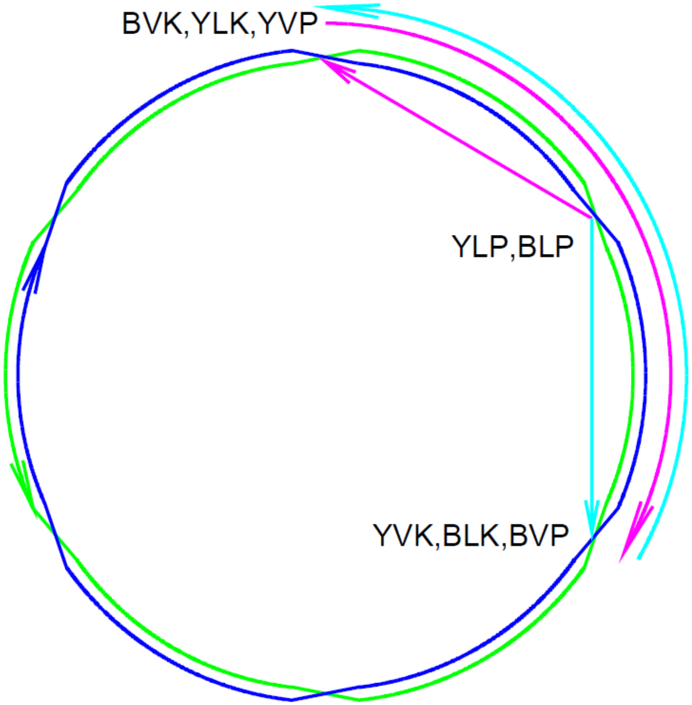
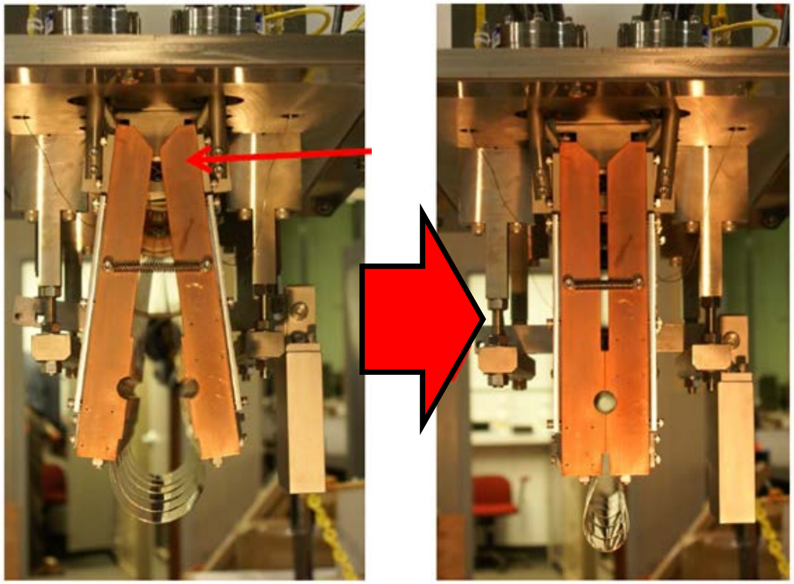
Stochastic Cooling at RHIC

Tunnel Layout:

- Transverse signals run backwards in the tunnel.
- Longitudinal signals are sent via microwave link.



Transverse kickers have to be opened at injection due to small aperture of 4.8-7.8GHz cavities. → Impedance problems!



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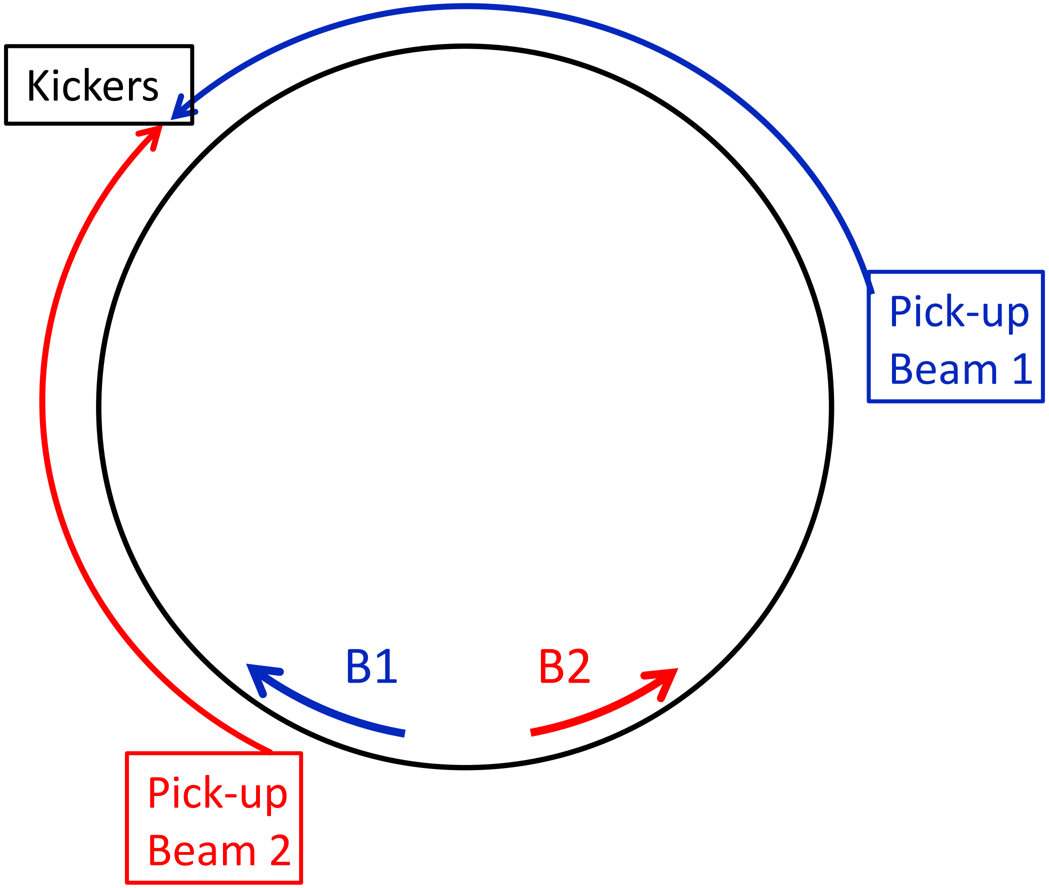
Stochastic Cooling System at LHC

- Consider a system similar to the one in RHIC.
- LHC: 27km circumference & 100m underground:
  → New diagonal tunnel for signal too expensive.
  → Microwave-links on surface difficult, due to long distance and weather conditions.
- Signal has to travel backwards in the tunnel.
- Assume 2/3 turn delay between pick-up and kicker.



Simulations of beam evolution in LHC ring

Simulations include:

- IBS (various models)
- Burn-off from luminosity production
- Radiation damping and quantum excitation
- Stochastic Cooling

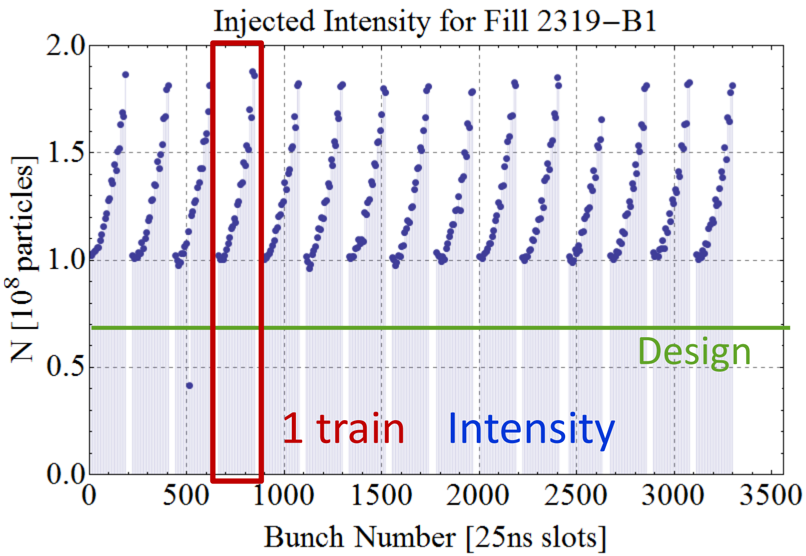
M. Blaskiewicz's Program [1]: developed for RHIC

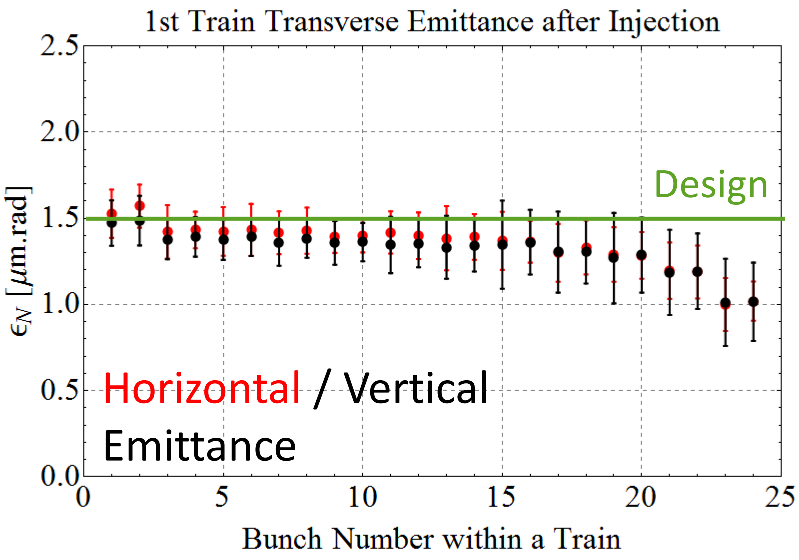
R. Bruce & T. Mertens, Collider Time Evolution (CTE) Program [2]: adapted for LHC application

Simulations require:

- initial beam parameters (from measurements): e.g. particle type, particles per bunch, emittances, bunch length, RF voltage…
- Properties of stochastic cooling system.

Bunch-by-Bunch Differences after Injection (450Z GeV)



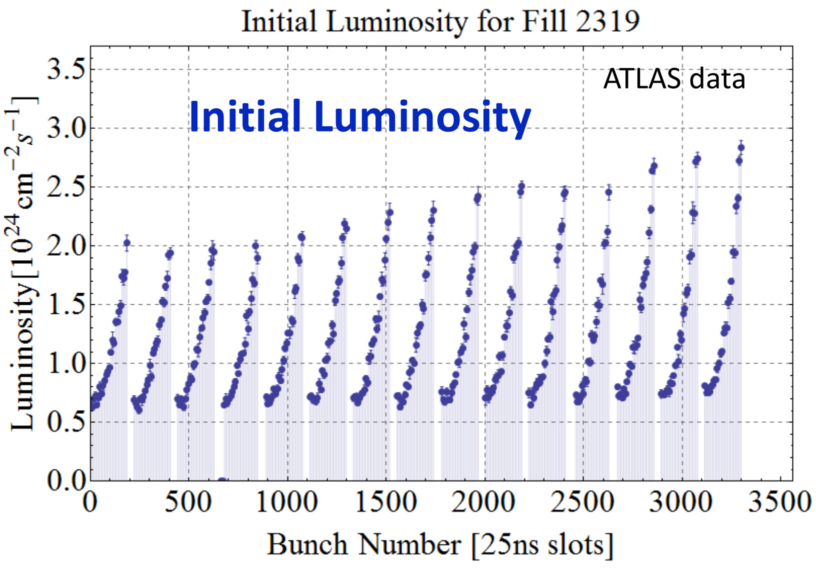


- Structure within a train (1st to last bunch):
    - increase: - intensity
      - bunch length
    - decrease: emittance.

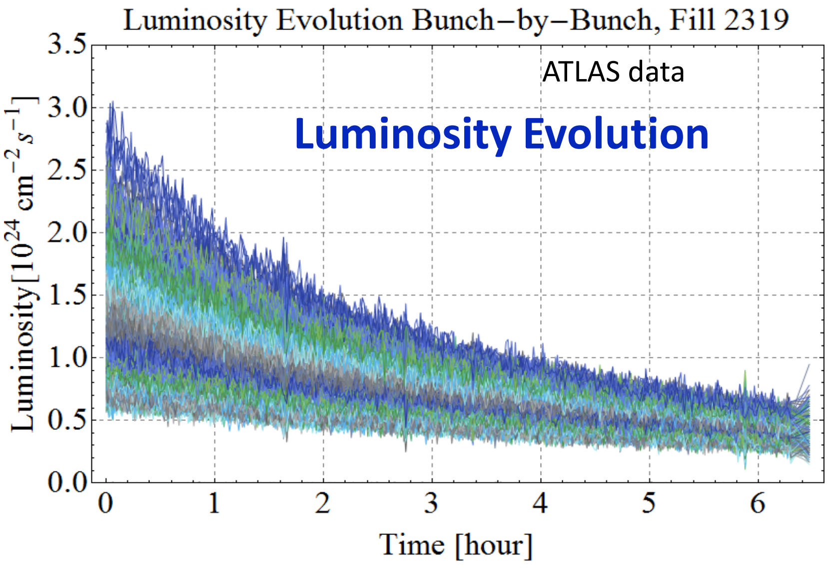
- IBS at the injection plateau of the SPS:
    - while waiting for the 12 injections from the PS to construct a LHC train.

- First injections sit longer at low energy
  → strong IBS,
  → emittance growth and particle losses.

Luminosity



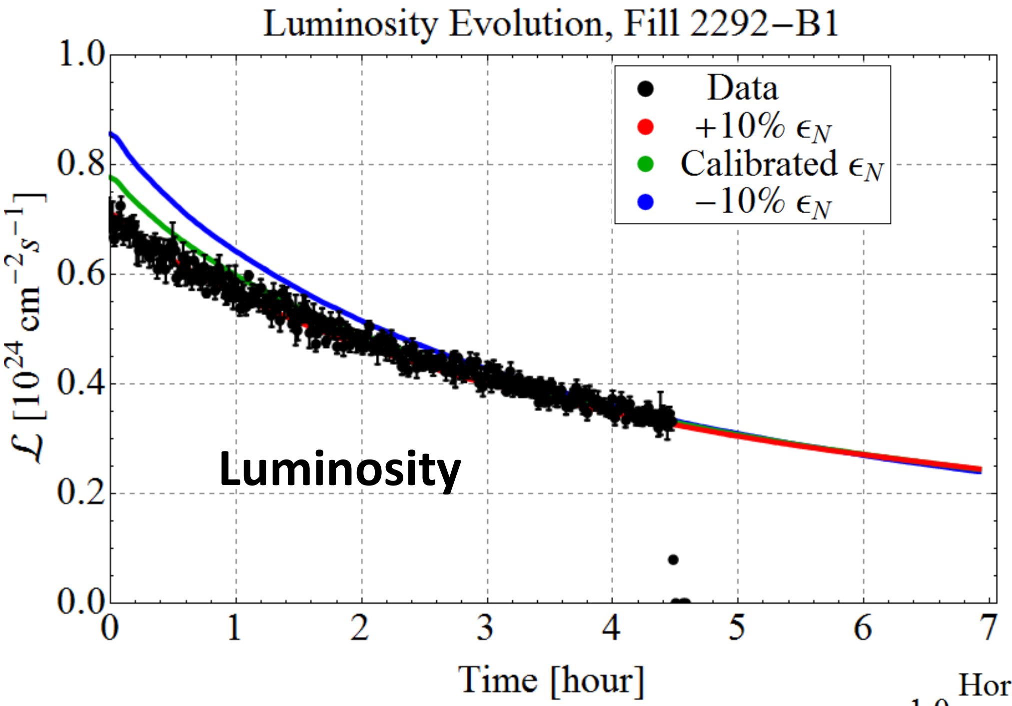
Initial Luminosity for Fill 2319



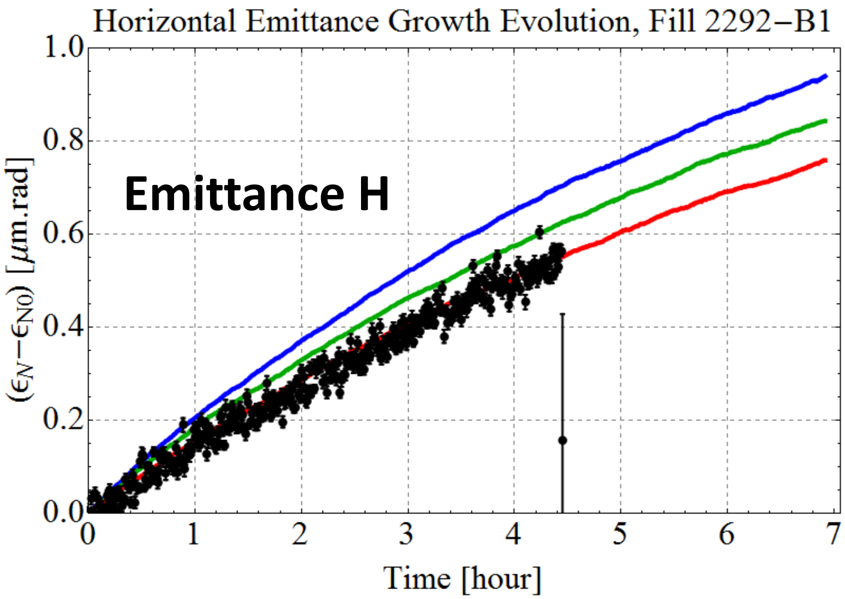
Luminosity Evolution Bunch–by–Bunch, Fill 2319

- Significant bunch-by-bunch structure within a train.
- Initial values differ by a factor 5-6!
- Different speed of decay – high initial luminosities decay very fast.

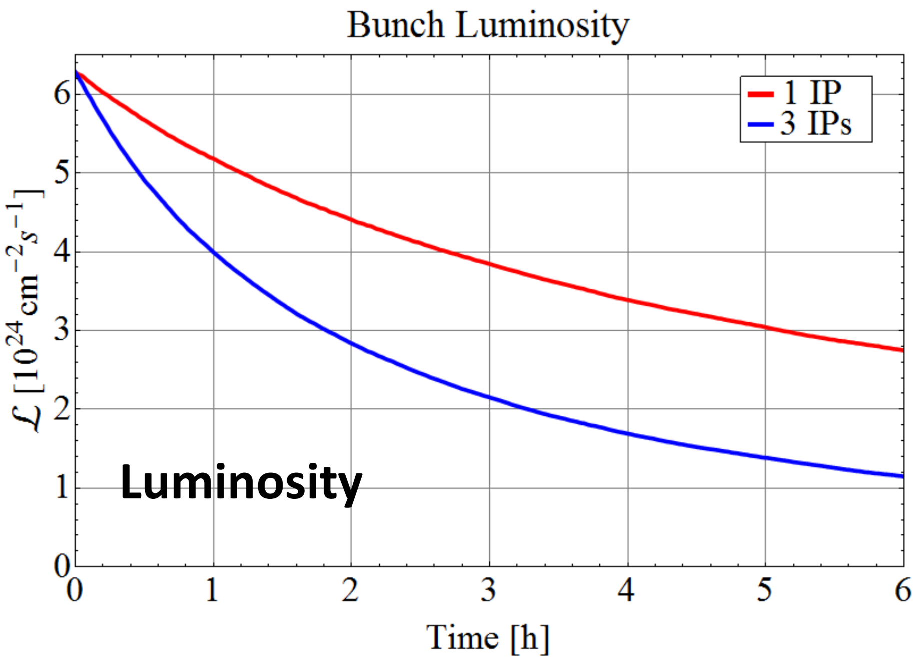
Evolution in Collisions @ 3.5Z TeV



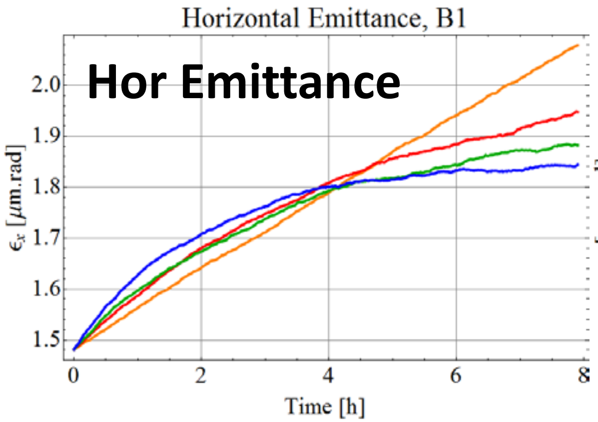
- 2011 Data
- Good agreement between data and simulation.
- Calibration of transverse emittance is difficult.

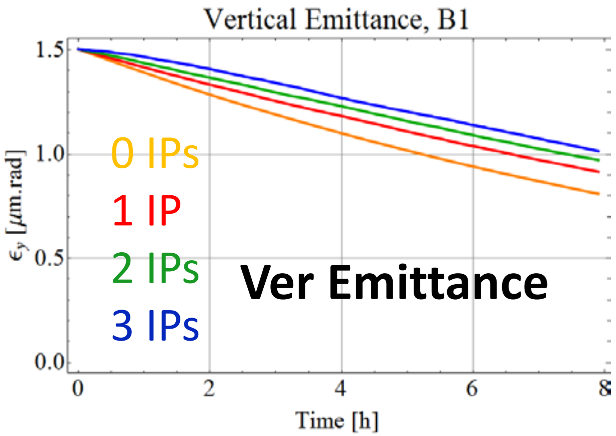


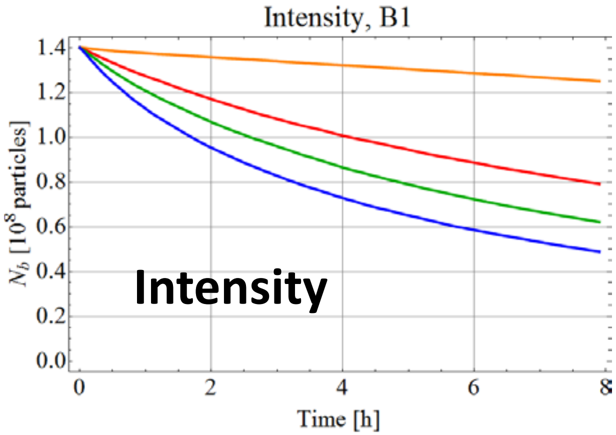
Potential Beam Evolution @ 7Z TeV



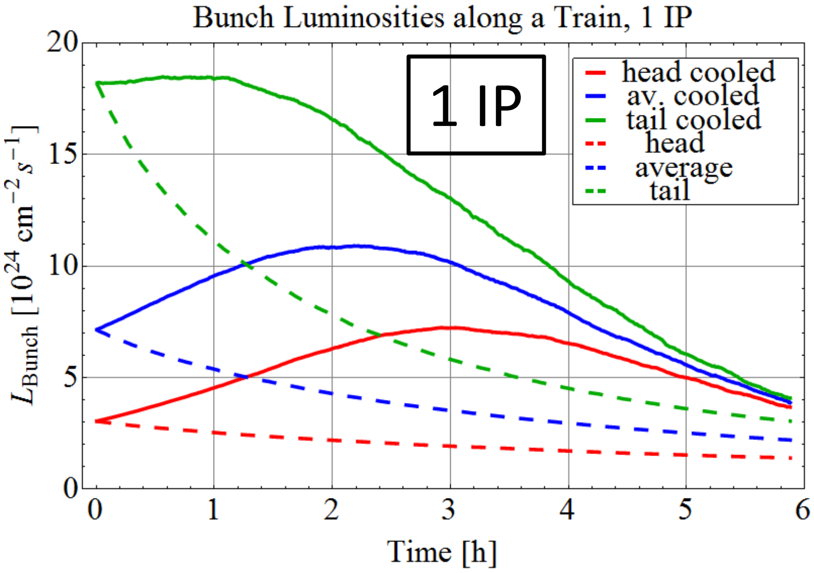
- Simulations [2] with IBS, burn off, radiation damping.
- 3 experiments in collisions lead to very fast burn off: → luminosity ½-life ≈ 2h.
- Turnaround time ≈ 3h.
  → Longer fills are desired.
  → Stochastic cooling as possibility to improve fill lifetime.

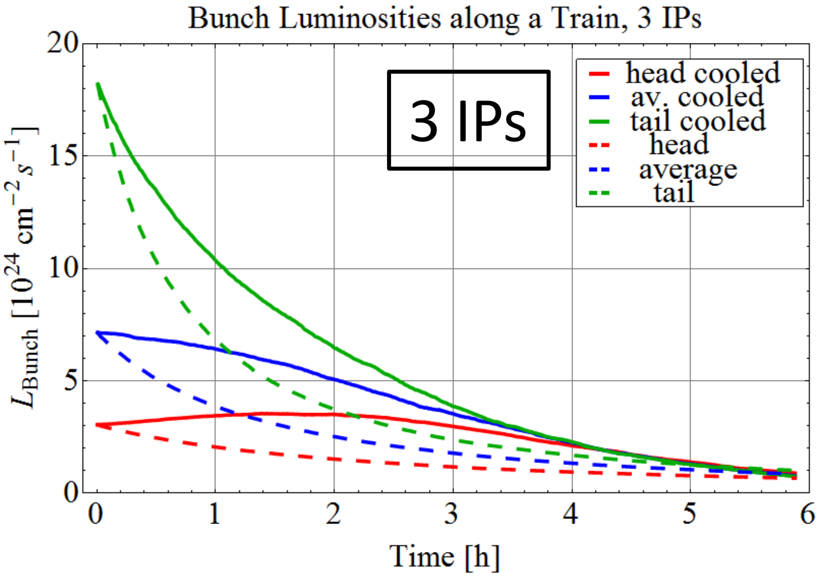






Cooling Simulations





- IBS horizontal growth time ≈ 8h.
- Radiation damping time ≈ 13h
  → radiation damping not included in the simulations on this slide.

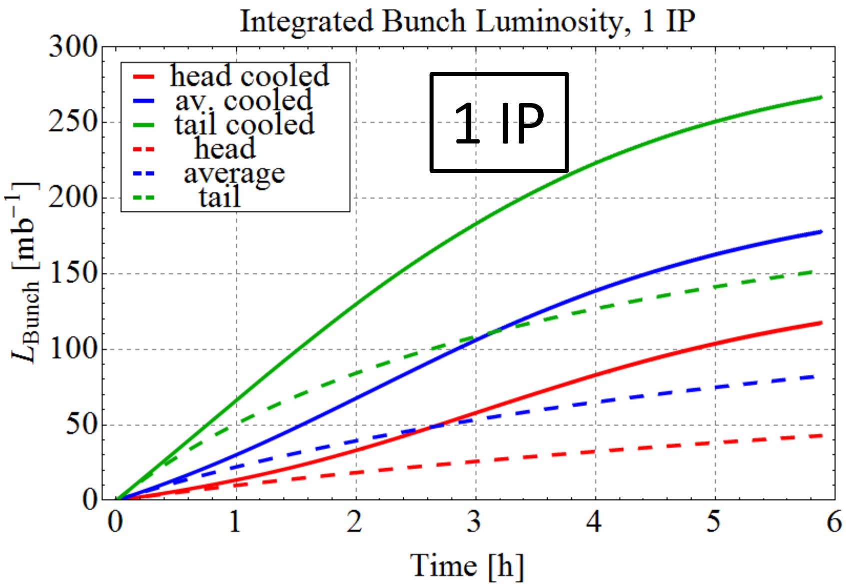
- Assuming a stochastic cooling system with a 5-20GHz bandwidth and average 2013 Pb bunches [4]:

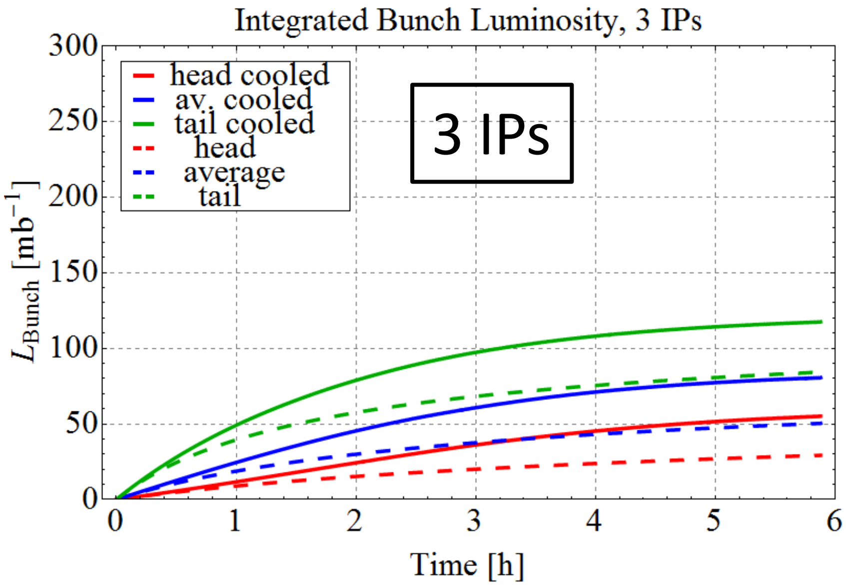
$$T_{\text{cool}} = \frac{N_b C_{\text{LHC}}}{4\sigma_z W}\left[\frac{M+U}{(1-\tilde{M}^{-2})^2}\right] \approx 1.8\,\text{h}$$

- First estimate for RMS voltage per cavity (assuming a system with 16 cavities as in RHIC):

$$V_{cavity} = 2\,\text{kV}$$

Cooling Simulations





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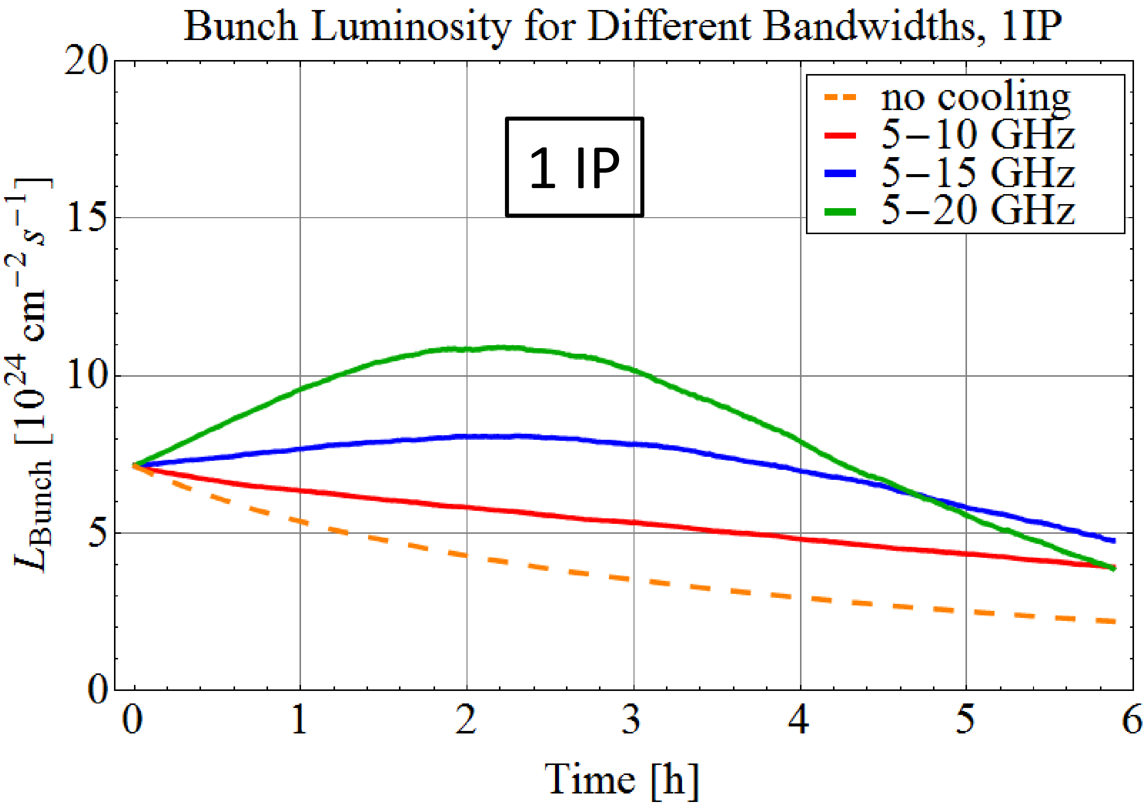
- First estimate for RMS voltage per cavity (assuming a system with 16 cavities as in RHIC):

$$V_{cavity} = 2\,\text{kV}$$

- Integrated luminosity could be increased by a factor ~2.

Cooling Simulations

Larger bandwidth and higher upper frequency, lead to higher integrated luminosity.



Things to be done…

- Find potential locations in the LHC tunnel.
- More detailed simulation and calculations to define required system properties.
- Hardware design challenges to be addressed:
  - Large bandwidth and high upper frequency .
  - Small aperture required → Impedance problems?
  - Compatibility with the proton operation.
- …

Conclusions

- Strong IBS at all energies leads to emittance growth and particle losses.
  → Significant bunch-by-bunch differences.

- Short fills, due to the high burn off rate with 3 experiments in collisions.

- Stochastic cooling could equalise bunches and obtain smaller emittances → higher integrated luminosity.

- First simulation results look promising, studies have just started and are on-going.
  - Challenges in hardware design.

THANK YOU
FOR YOUR ATTENTION

References:

[1] M. Blaskiewicz et al., WEM2I05, COOL07 (2007).

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

[3] J. Bjorken, S. Mtingwa, Part. Acc. 13, pp. 115-143 (1983).

[4] D. Möhl, Lecture Notes in Physics 866, Springer (2013).

[5] M. Schaumann et al., TUPFI025, IPAC13 (2013).

[6] M. Schaumann et al., TUPM1HA02, COOL'13 (2013).

[7] M. Blaskiewicz, CERN A&T Seminar 6/6/2013.
http://indico.cern.ch/conferenceDisplay.py?confId=254917

Design & Current Performance

	Collision (Design)	**Injection (2011)**	**Collision (2011)**	**Injection (2013)**	**Collision (2013)**
Beam Energy [Z GeV]	7000	450	3500	450	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	$\mathbf{1.40 \pm 0.27}$
Transv. normalised emittance $[\mu\mathrm{m.rad}]$	1.5	---	1.7 ± 0.2	$\mathbf{1.3 \pm 0.2}$	---
RMS bunch length $[\mathrm{cm}]$	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	9.8 ± 0.1
Peak Luminosity $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	---	$\mathbf{0.4 \pm 0.1}$	---	p-Pb

Collider Time Evolution (CTE) Program

Processes taken into account:

- COLLISIONS
  - user can choose between 2 collision routines:
    - very slow, integrates interaction probability for every particle by sorting particles in opposing beam in discrete bins. **No assumptions on the shape of the beam distribution**.
    - fast routine, **assumes Gaussian transverse distribution** and calcualtes interaction probability from transverse distribution analytically and uses **global reduction factor** (hourglass and crossing angle) for all particles. **No assumptions on longitudinal distribution**.
- IBS
  - rise time calculated using a standard method and modulated to account for non-Gaussian longitudinal profiles
  - user can choose between the following methods:
    - Nagaitsev full lattice
    - smooth lattice Piwinski
    - full lattice Piwinski
    - full lattice modified Piwinski
    - full lattice Bane *(not good at injection)*
    - interpolation from tabulated risetimes in external file at given points in emittance-space
- BETATRON MOTION
- SYNCHROTRON MOTION (particles outside RF bucket are lost)
- RADIATION DAMPING and QUANTUM EXCITATION
- transverse aperture cut from COLLIMATION

Collider Time Evolution (CTE) Program

- Output on a turn-by-turn basis
  - IBS rise times
  - Intensity
  - Transversal and longitudinal emittances
  - Luminosity

- Not Implemented
  - Beam-Beam effects
  - Betatron noise from feedback
    - emittance blow-up
  - RF noise
  - Elastic and inelastic beam gas scattering
    - particle loss and emittance blow-up

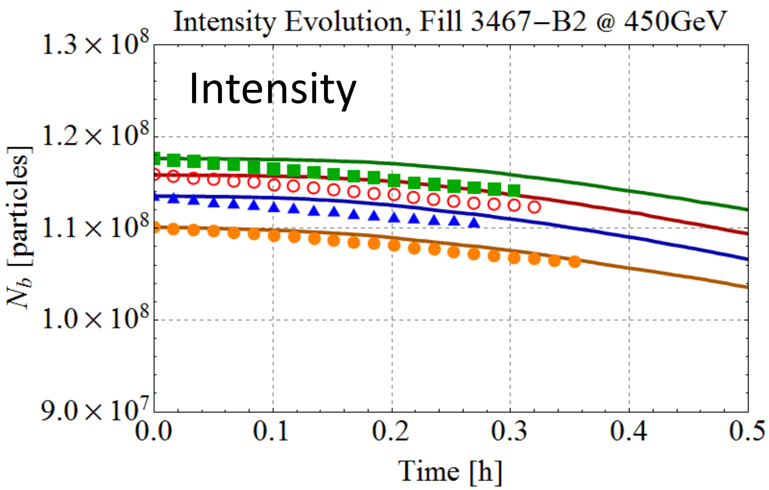
Beam Evolution at Injection (450Z GeV)

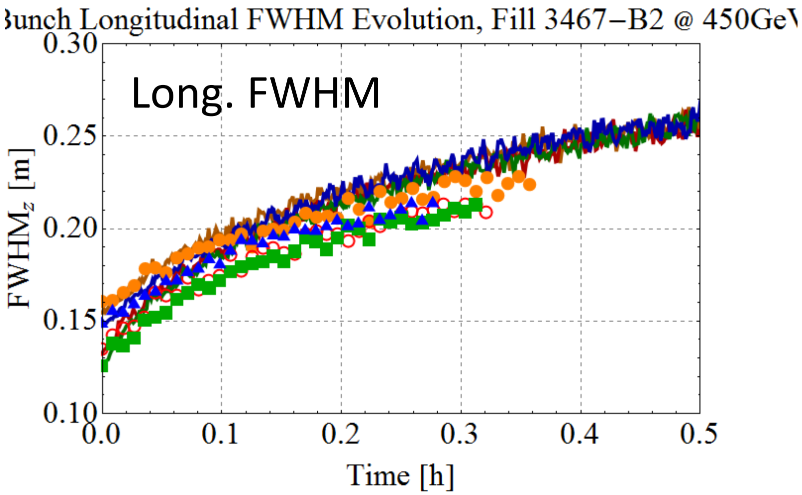
Beams suffer **from strong intra-beam scattering (IBS)**

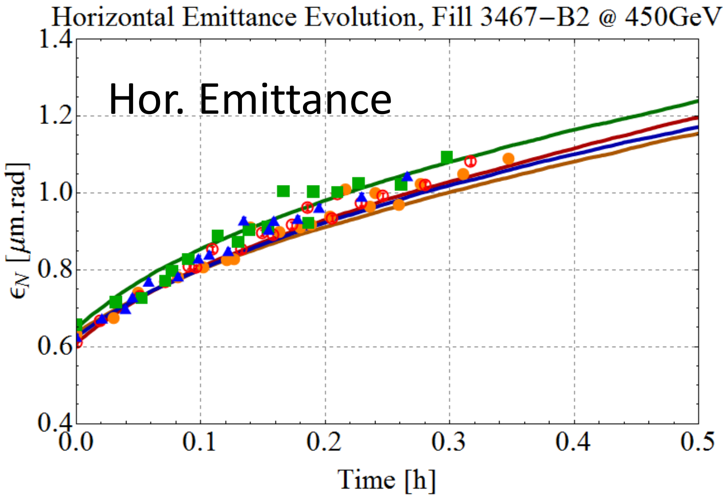
→ Emittance growth and debunching losses

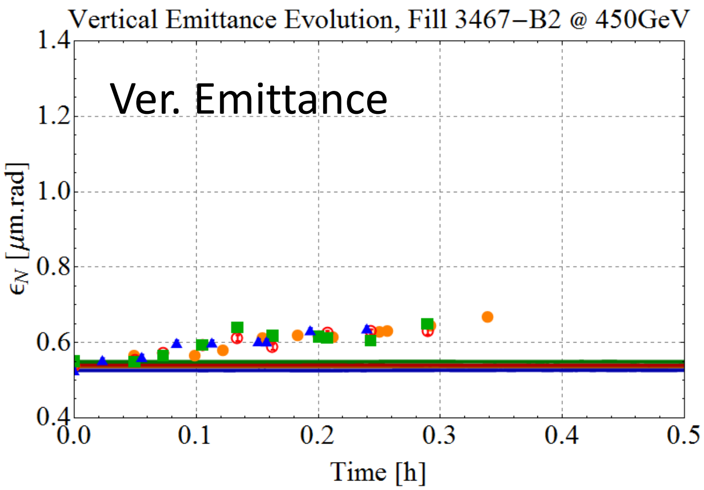
Simulations and data are mostly in good agreement.

dots = data
lines = simulation

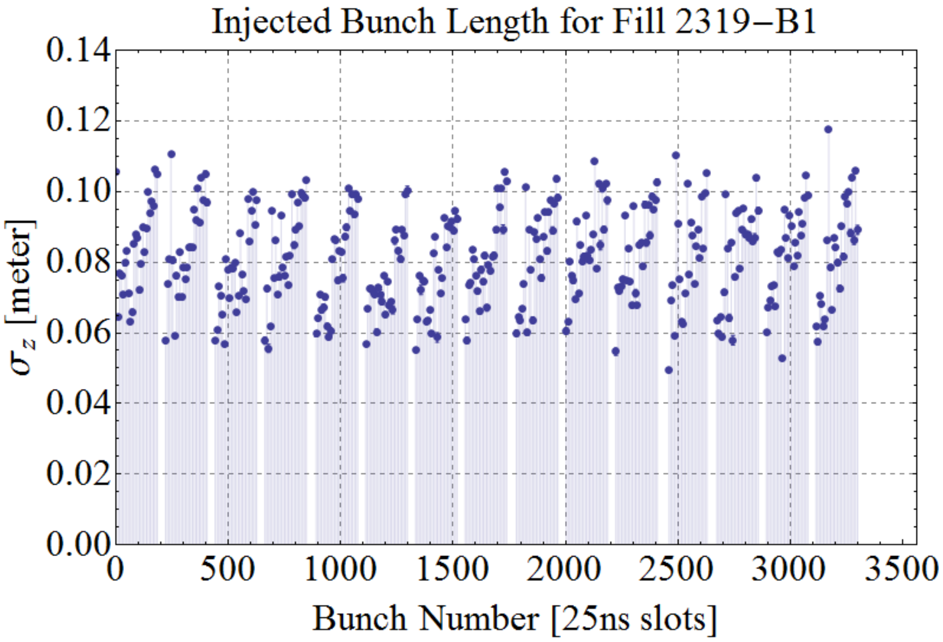

Intensity Evolution, Fill 3467–B2 @ 450GeV

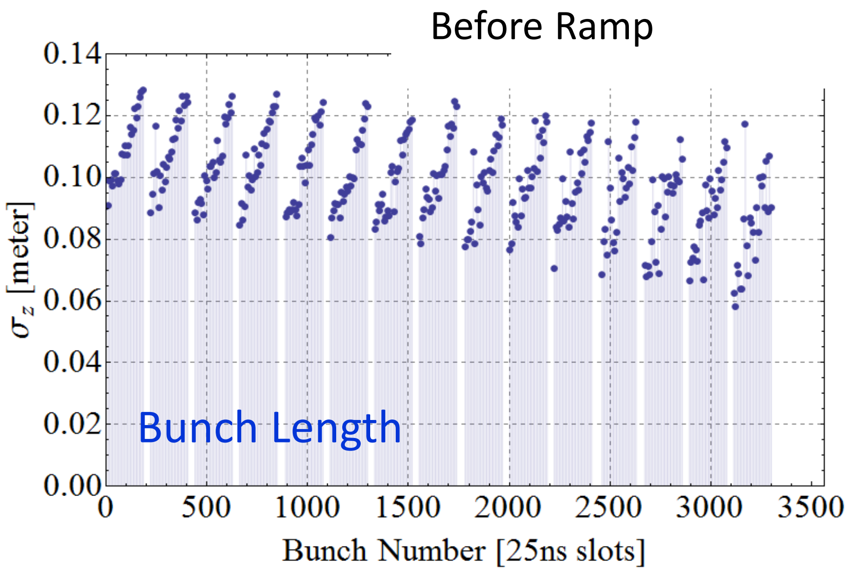

unch Longitudinal FWHM Evolution, Fill 3467–B2 @ 450Ge


Horizontal Emittance Evolution, Fill 3467–B2 @ 450GeV

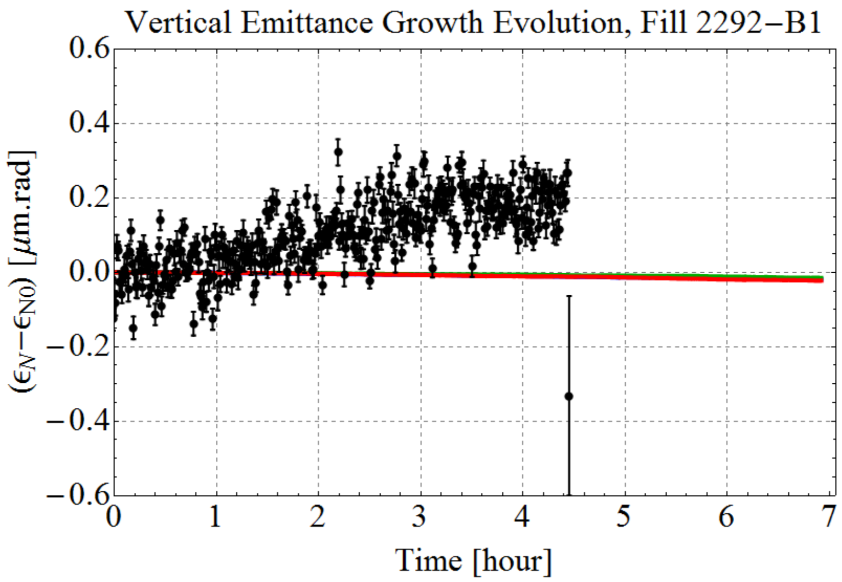

Vertical Emittance Evolution, Fill 3467–B2 @ 450GeV

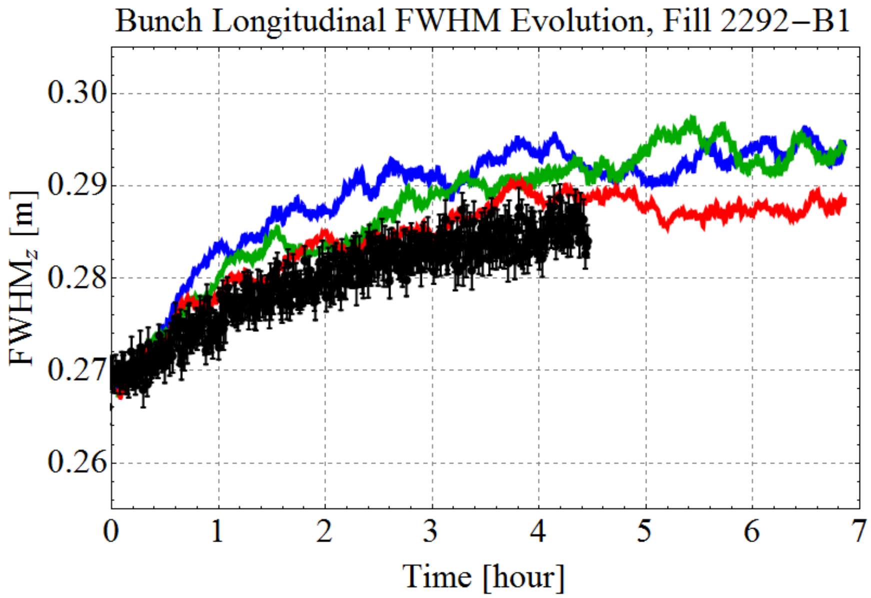
Bunch-by-Bunch Differences after Injection (450Z GeV)

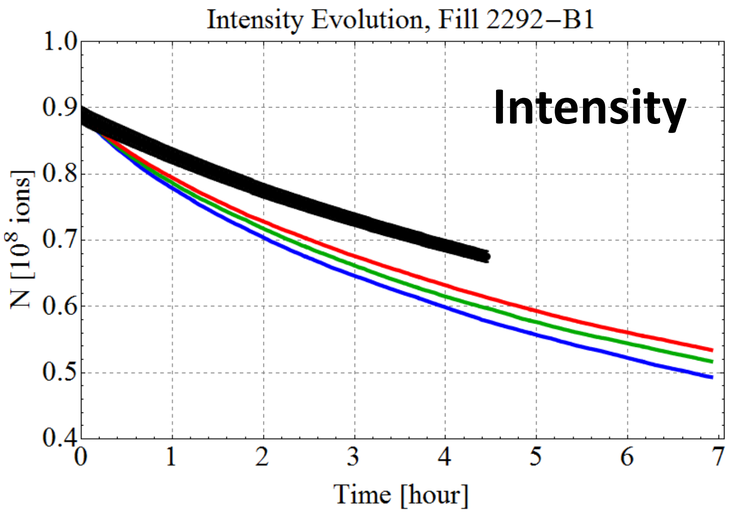




Evolution in Collisions @ 3.5Z TeV







Potential Beam Evolution @ 7Z TeV