Simulations of IBS for Protons at Injection in 2012

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Thanks to John Jowett, Roderik Bruce

Collider Time Evolution (CTE) Program

- Authors: Roderik Bruce, Mike Blaskiewicz and Tom Mertens
- Program to track 2 bunches of **macro-particles** in time in a collider
  - Subroutines act on the bunches on a **turn-by-turn basis**: one simulation turn can correspond to any chosen number of machine turns.
  - Several other input parameter define the initial beams: e.g. particle type, particles per bunch, emittances in X und Y, bunch length, RF voltage…

Starting Conditions used in CTE Simulations

Combinations of simulated beam parameters

Emittances $\varepsilon_{x,y}$ [um rad]
1.9
2.0
2.2
2.5

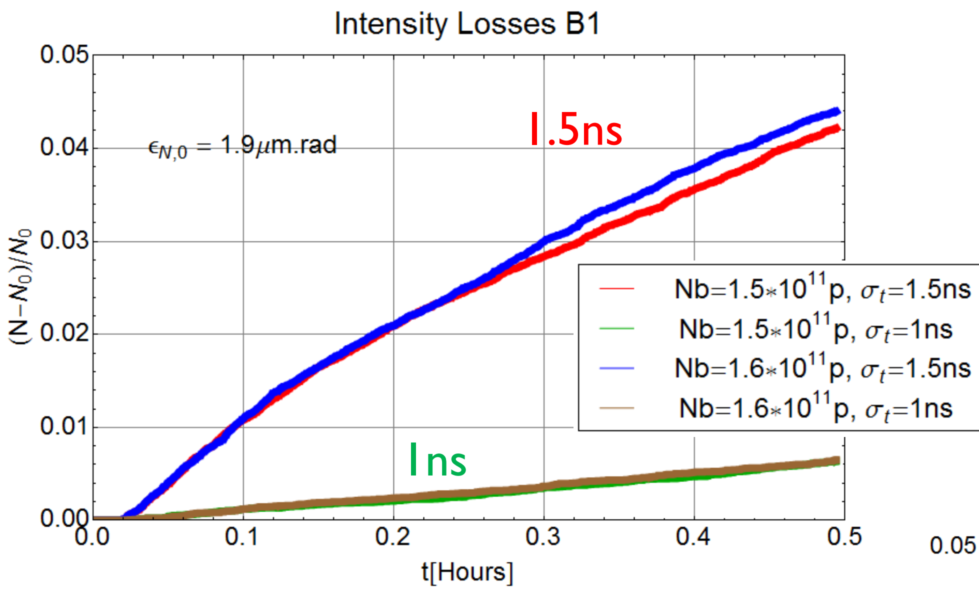
Intensity per Bunch, Nb [10^11 charges]
1.5
1.6

Bunch Length, σ_s (4σ) [ns]
1.0
1.5

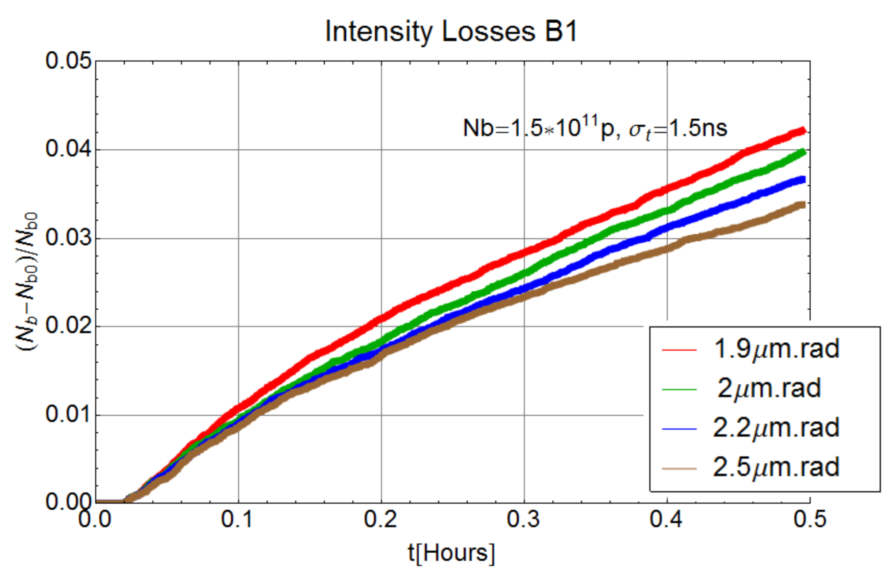
Other important Settings

- injection energy (450GeV)
- 6MV RF-Voltage
- round beams
- uncoupled planes
- beam shape: pseudo-Gaussian, exactly matched
- no collisions
- no collimation

Intensity

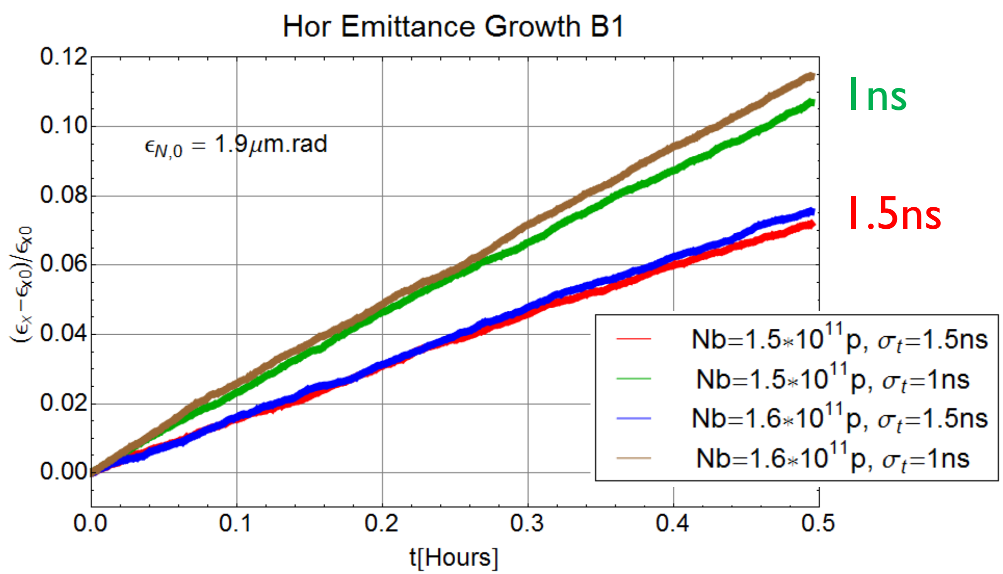


- loss mechanisms
  - particles leave bucket (debunching losses)
  - hit physical aperture (due to dispersion or betatron action)

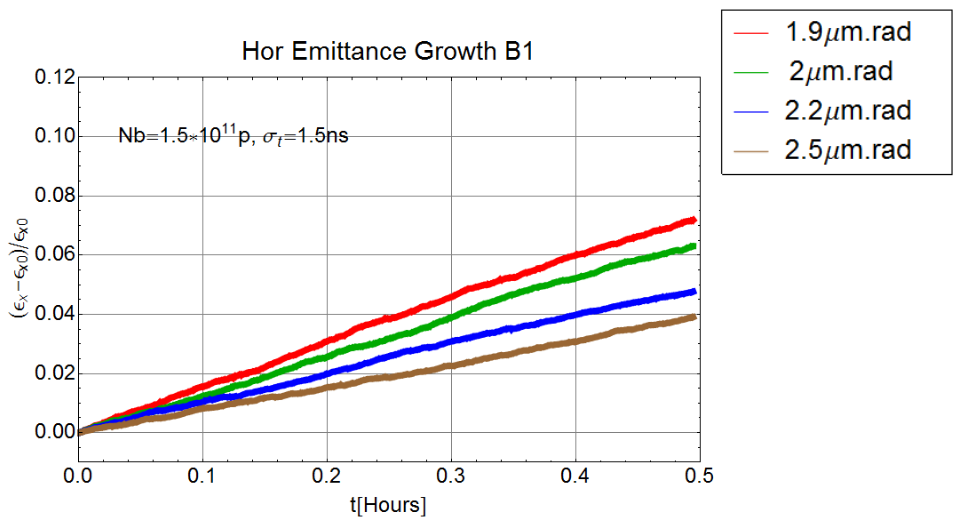


- highest losses for
  - bunches with great bunch length (1.5ns)
  - bunches with small emittance

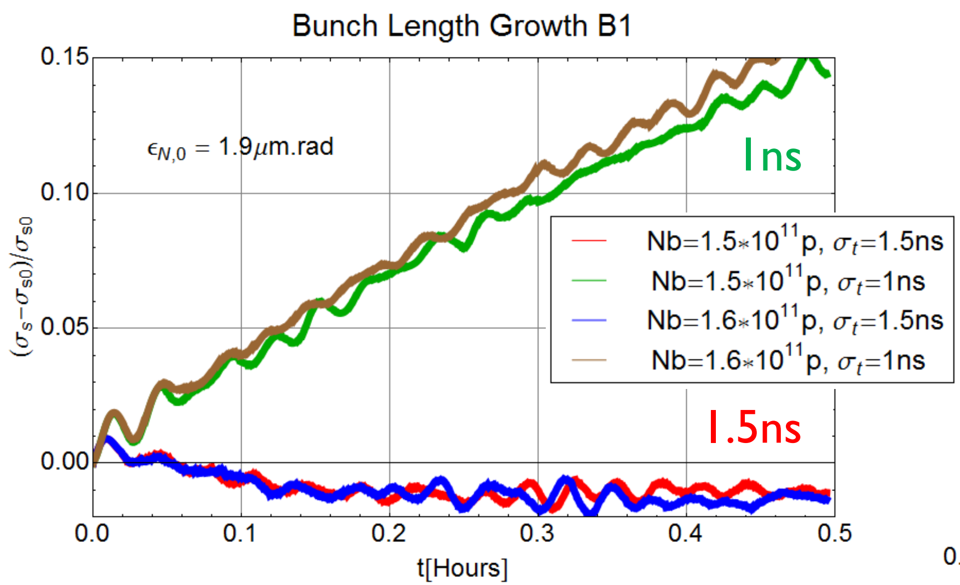
Emittance

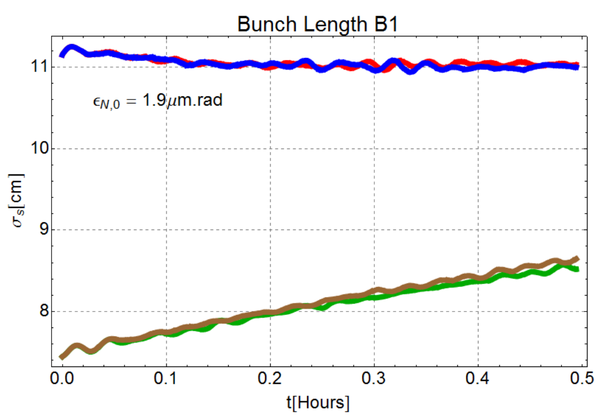


- small initial emittances increase faster
- small initial bunch lengths (1ns) increase faster in transverse emittance
- no big difference for different initial intensities

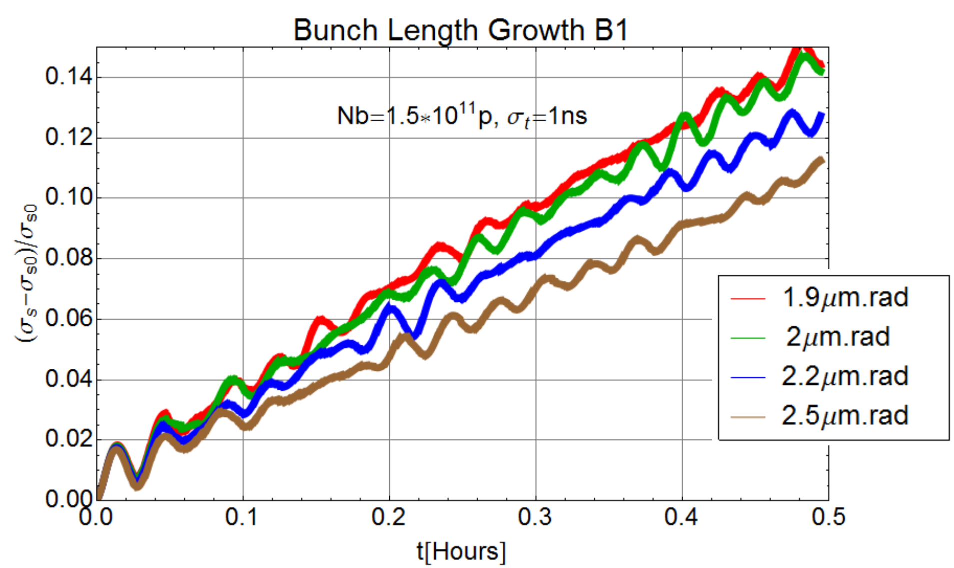


Bunch Length





- small initial bunch lengths (1ns) grow much faster
  - particles fill the bucket
- 1.5ns case actually decreases a bit
  - tails of the distribution are cut when particles leave the bucket
  - RMS of the distribution decreases and Gaussian shape is lost



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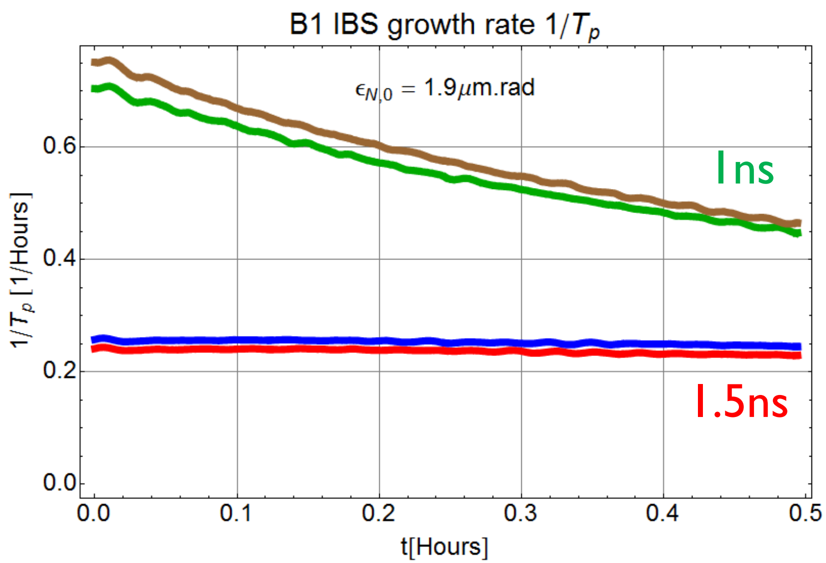
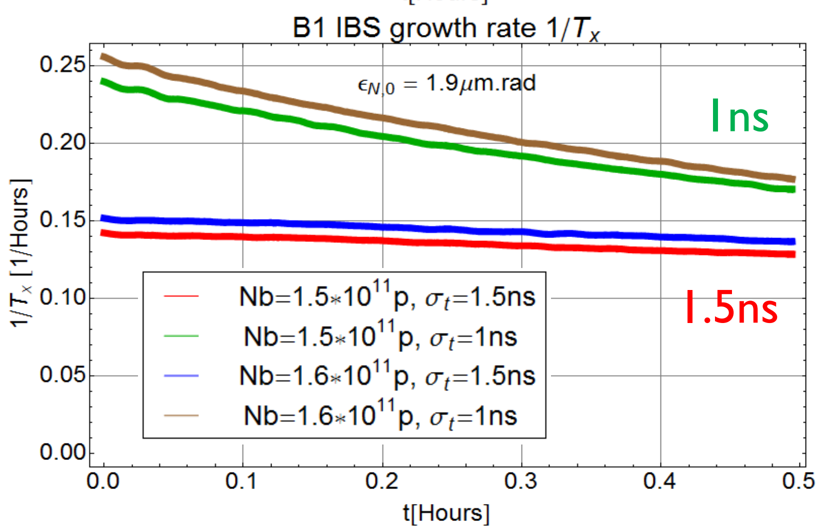
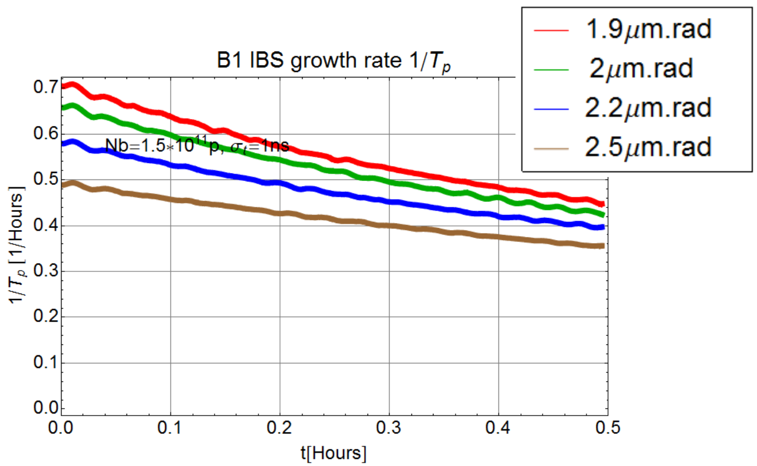
IBS Growth Rates

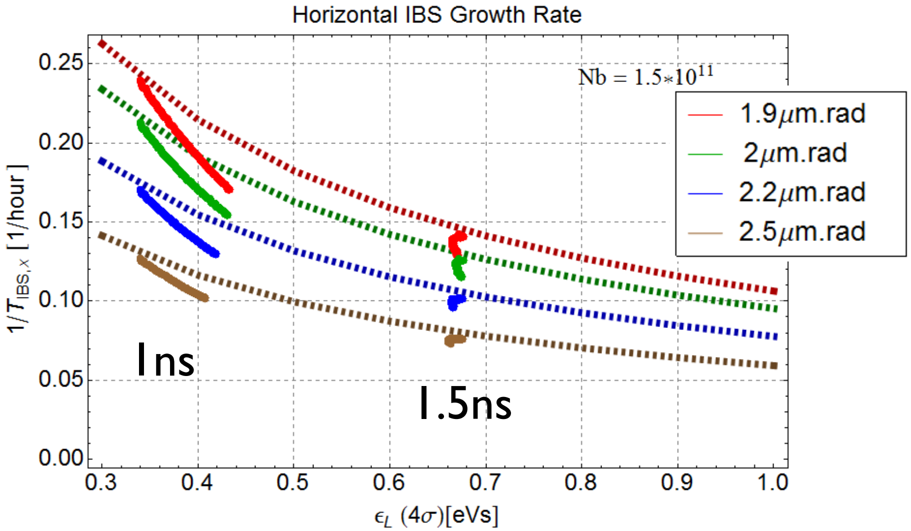


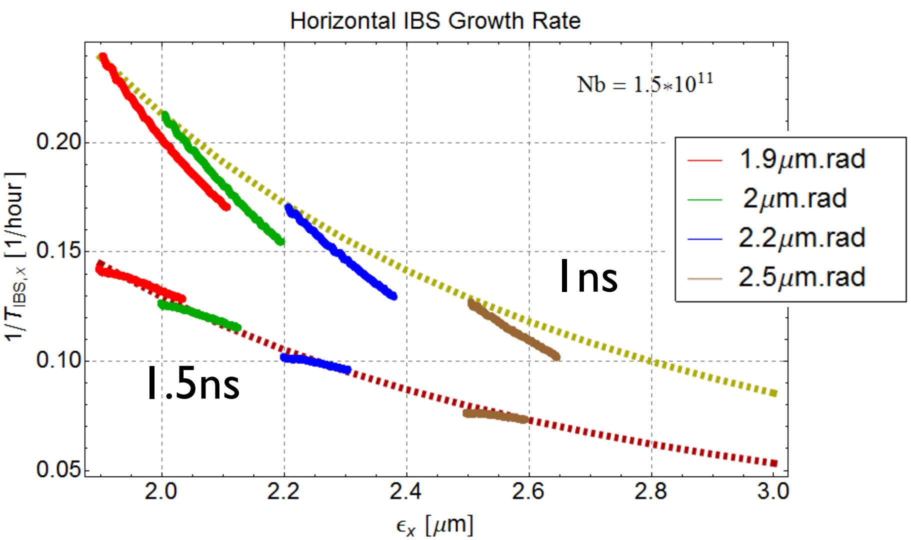


- 1ns growth rates start higher and decreases faster
  - emittances increase faster for small bunch lengths
- 1.5ns growth rates quite stable and much smaller as for 1ns initial bunch length
- initial growth rates increase with smaller initial emittances



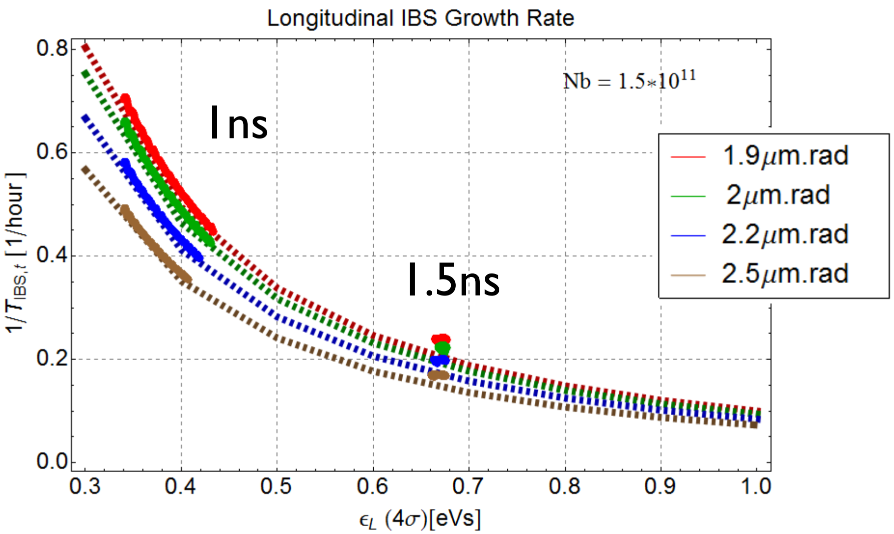
Comparison with MADX Calculations Horizontal Growth Rate

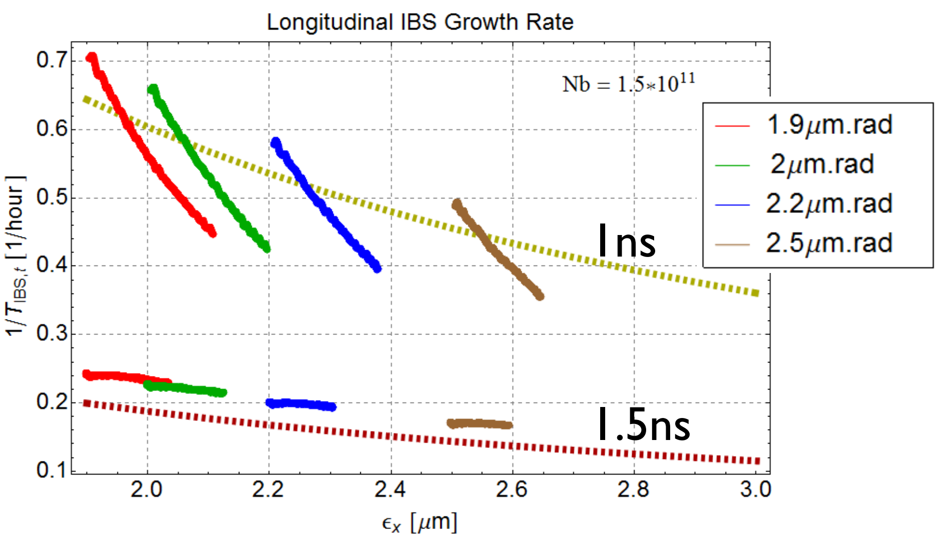




- MADX calculations are shown as the dashed lines
- Growth rate vs. longitudinal emittance ε_l
  - initial points in good agreement
  - lines separate for higher longitudinal emittances
  - MADX calcucation only varies ε_l
  - in the simulation all parameters evolve with time
  - only for initial points, both are expected to agree
- Growth rate vs. transverse emittance ε_{xy}
  - initial points in good agreement
  - for1.5ns initial bunch length, ε_l is almost constant, thus the data agrees for later times as well

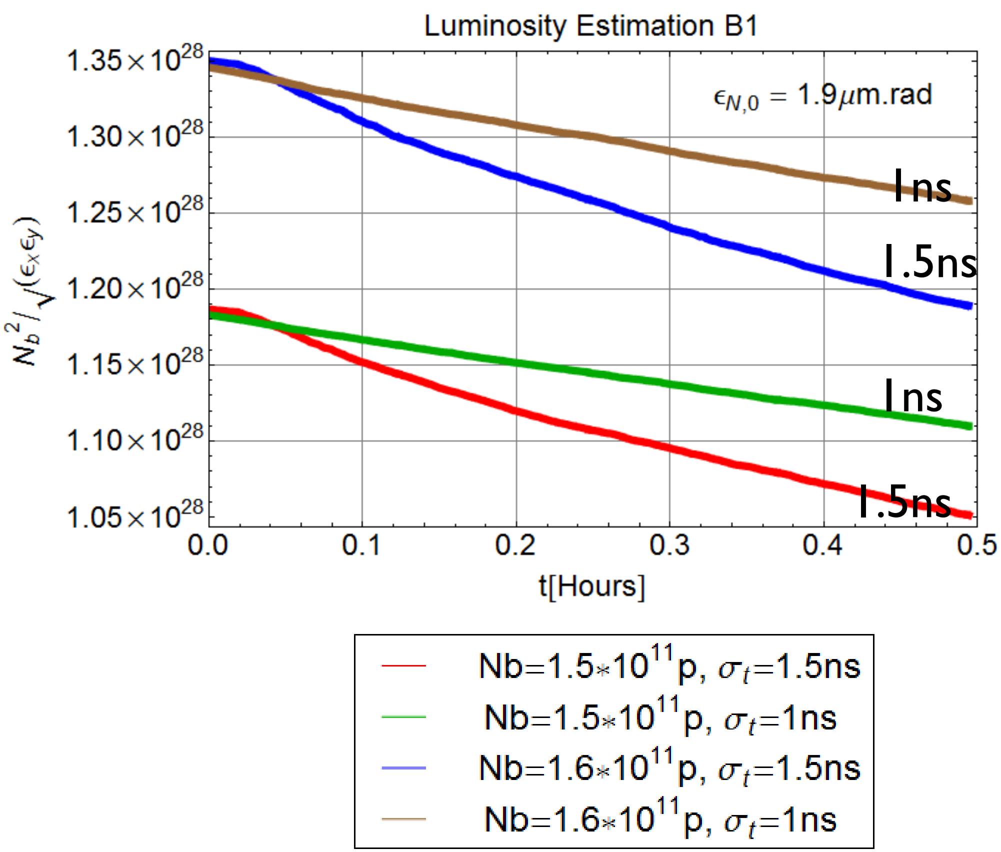
Comparison with MADX Calculations Longitudinal Growth Rate





- MADX calculations are shown as the dashed lines
- Growth rate vs. longitudinal emittance ε_l
  - initial points in good agreement
- Growth rate vs. transverse emittance ε_{xy}
  - offset between MADX and CTE
  - not yet explained

Estimation of the Luminosity



- calculate $N^2/\sqrt{\varepsilon_x \varepsilon_y}$ to get an estimate of what the luminosity would be if collisions are started
- curves for the 1ns initial bunch length cases decrease slower
  - less intensity losses, since the particles fill the bucket before they start to get lost
- the high particle losses of the blown-up bunches decrease the expected luminosity much more, even if their emittance blow-up is slower
- a compromise for the blow-up of the longitudinal emittance has to be found, to optimize the luminosity lifetime

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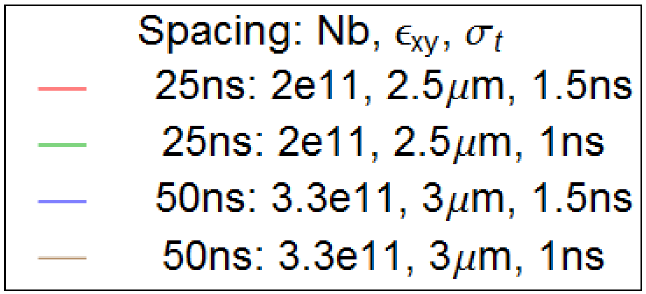
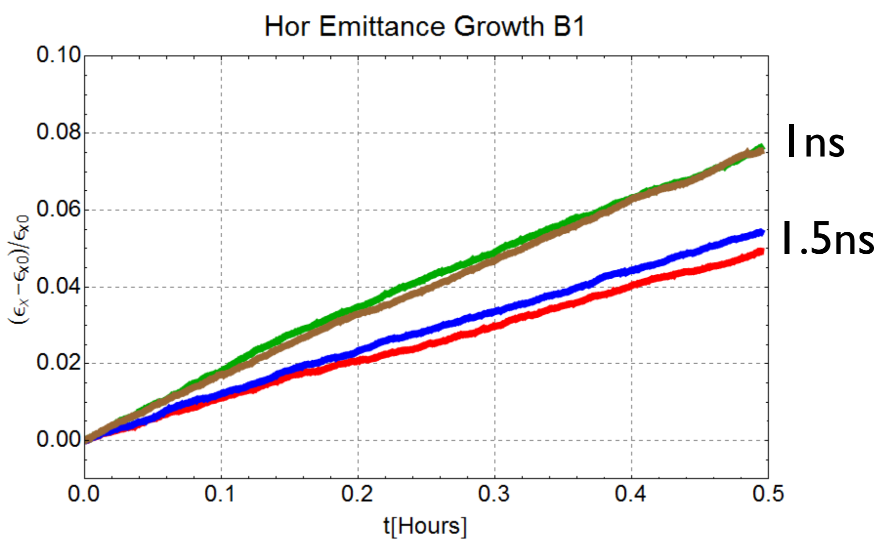
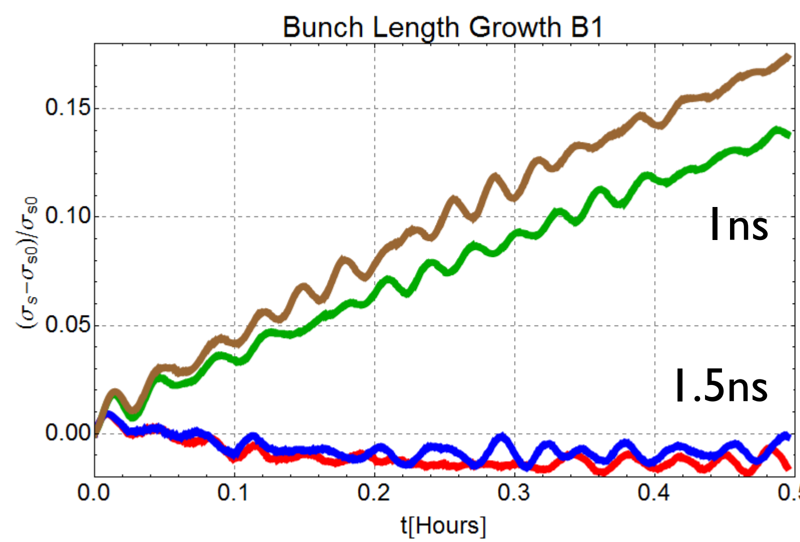
Simulation with HL-LHC Parameters

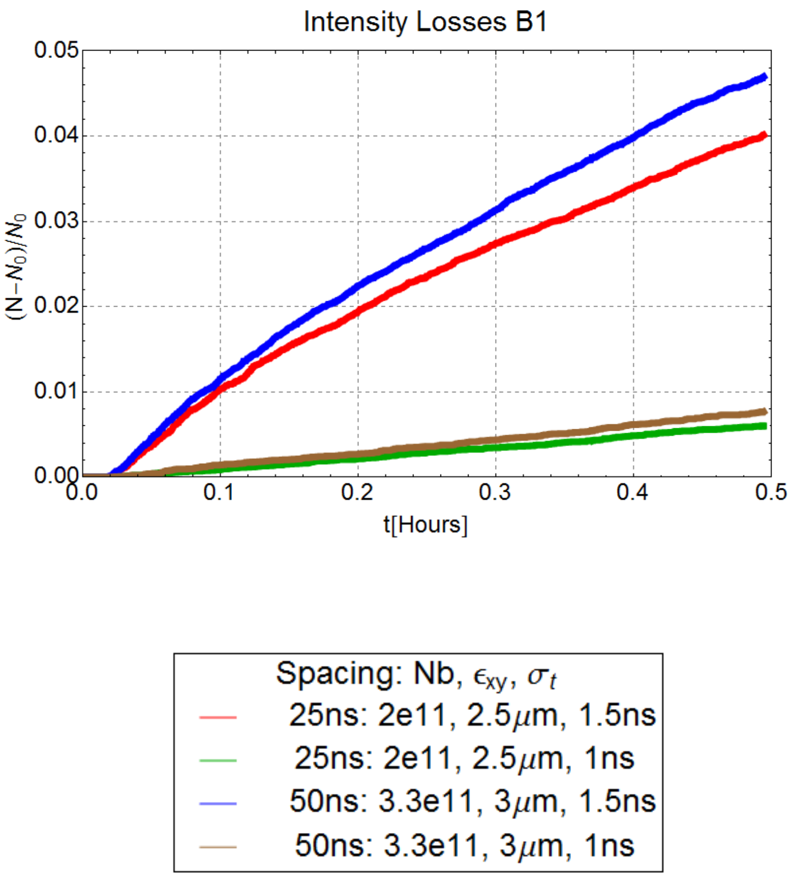


- same picture as for 2012 parameters
- different bunch lengths have big effect on the evolution
- small initial bunch lengths lead to faster growth in transverse and longitudinal plane
- combination 3.3e11ppb/3μm (50ns) and 2e11/2.5μm (25ns) only show small differences for equal initial bunch length
- only one bunch was simulated

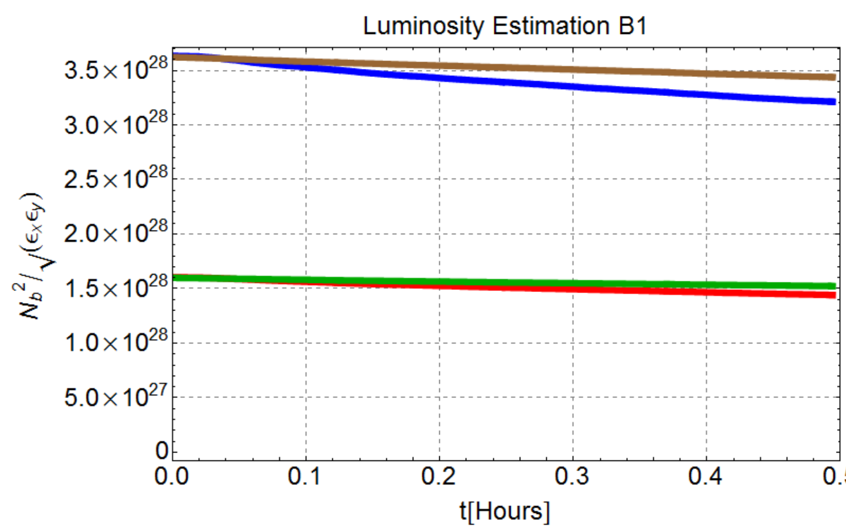




Simulation with HL-LHC Parameters (2)



- higher initial bunch lengths lose more particles
- particle losses affect the potential luminosity more than smaller emittance growth
- luminosity decreases faster for higher initial bunch length
- a compromise has to be found for the longitudinal blow-up to optimise the luminosity lifetime



Conclusion

- Simulations were done for a single bunch at injection.
- The beam conditions are shown as a function of time at injection: this gives an estimation of the spread between early and late injected bunches.

- Higher initial bunch lengths blow-up the transverse and longitudinal plane slowly but show high particle losses due to debunching.
- Small changes in the initial intensity do not have a significant effect.
- The estimation of the potential luminosity shows a great dependency on the losses due to debunching: the blow-up of the longitudinal emittance has to be optimised to find a compromise between smaller transverse emittance blow-up and higher particle losses.

- The IBS growth rates decrease fast with increasing bunch length and emittance
- The calculations of MADX and CTE are in good agreement for the initial parameters.

- A frist estimation of the HL-LHC parameter sets was shown.

BACK- UP

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

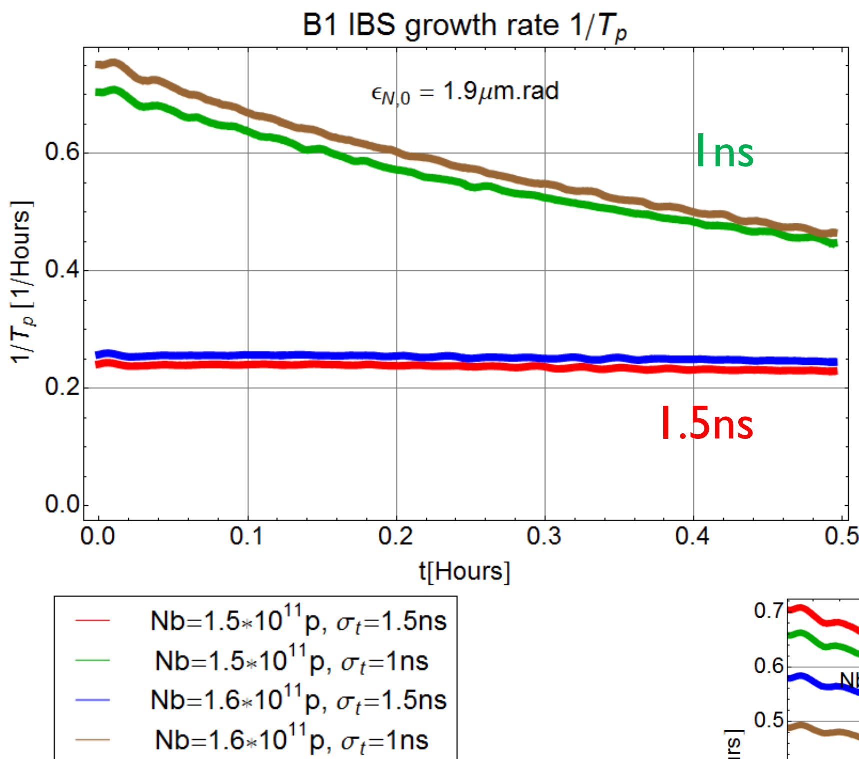
Collider Time Evolution (CTE) Program

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

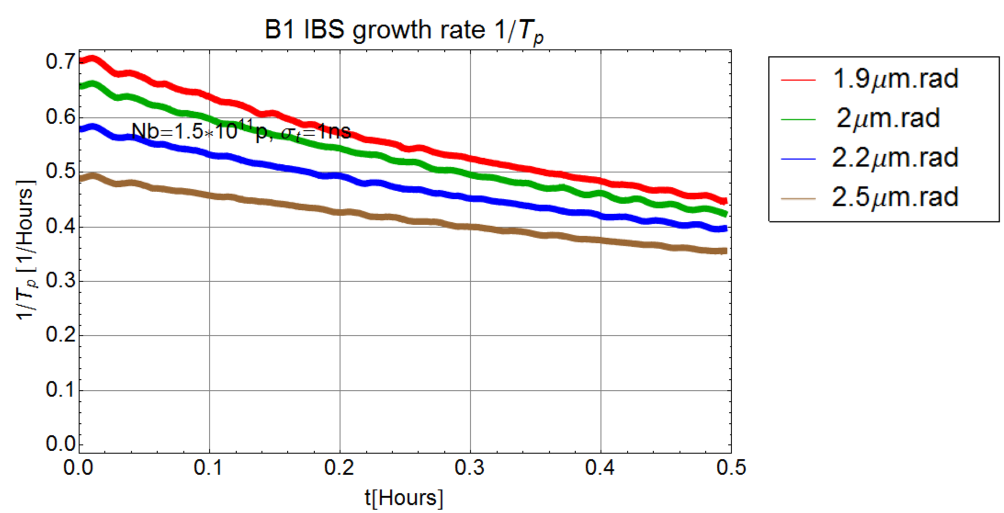
Not Implemented

- Betatron noise from feedback
  - emittance blow-up
- RF noise
- Elastic and inelastic beam gas scattering
  - particle loss and emittance blow-up

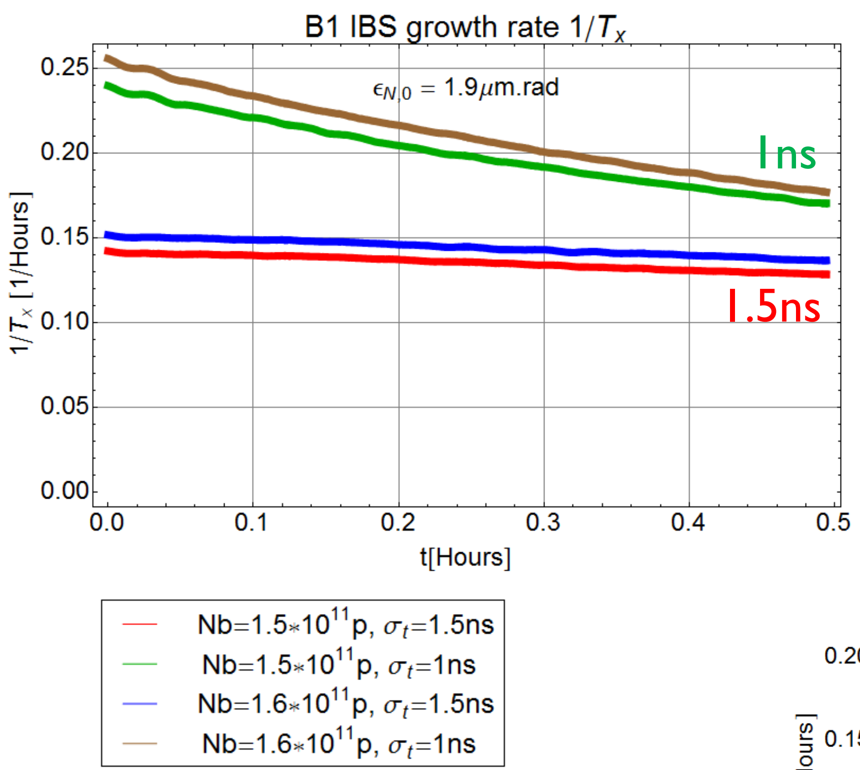
Longitudinal IBS Growth Rates



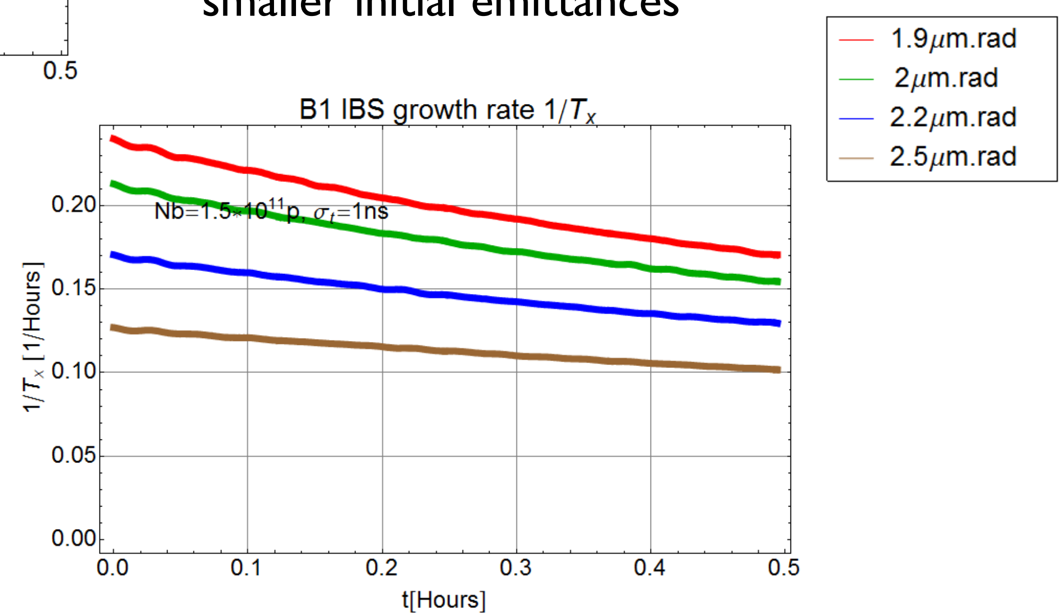
- 1ns growth rate starts higher and decreases faster
  - bunch length grows faster
- 1.5ns growth rate quite stable and much smaller as for 1ns initial bunch length
- initial growth rate increases with smaller initial emittances



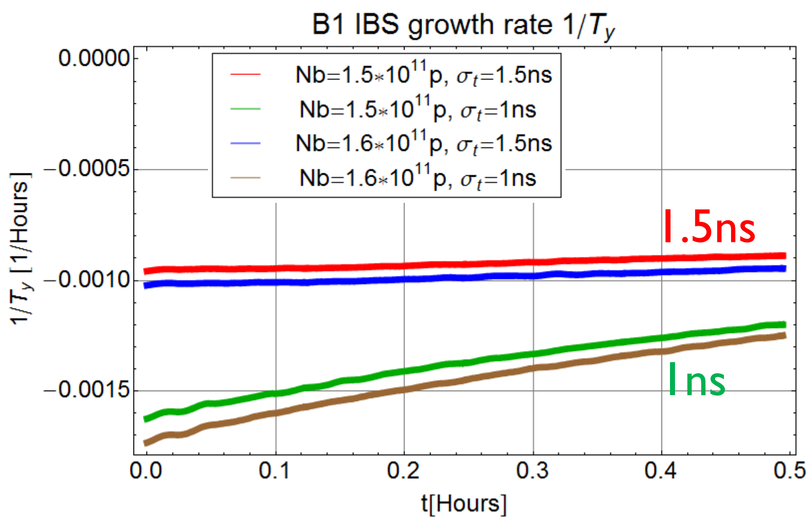
Horizontal IBS Growth Rate



- same picture as for the longitudinal growth rate, but lower amount
- 1ns growth rate starts higher and decreases faster
  - horizontal emittance growth faster
- 1.5ns growth rate quite stable and much smaller as for1ns initial bunch length
- initial growth rate increases with smaller initial emittances



Vertical IBS Growth Rate



- Simulation was done for uncoupled transverse planes
- vertical growth rate very small and negative
  - vertical emittance shrinks very slowly due to IBS