Simulations of IBS for Protons 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…
  - IBS effects are simulated but no Beam-Beam

Starting Conditions used in CTE Simulations

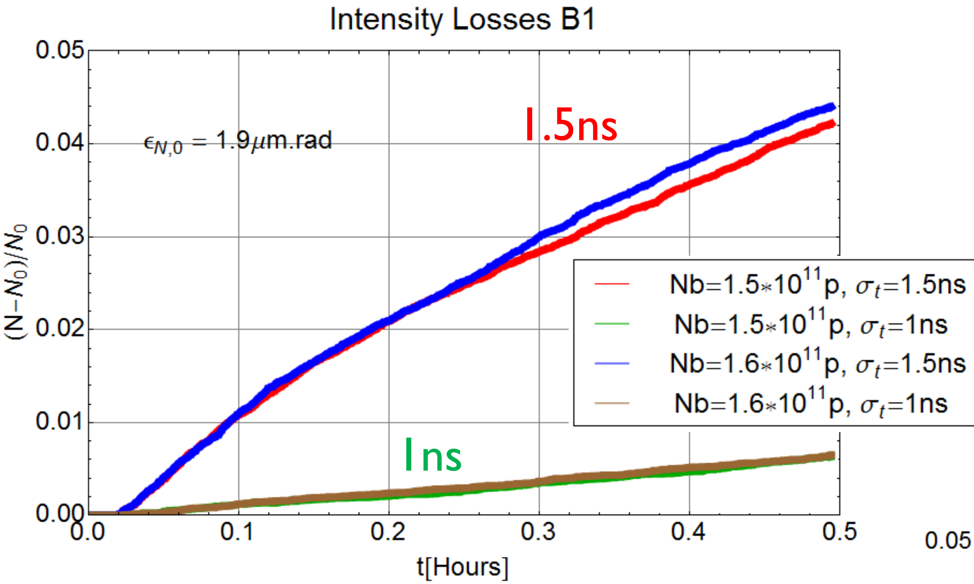
		Unit	@ 450 GeV	@ 4TeV
Emittance	$\varepsilon_{x,y}$	[um rad]	1.9 / 2.0 / 2.2 / 2.5	2.0 / 2.5 / 3.0
Intensity per Bunch	Nb	[10^11 charges]	1.5 / 1.6	1.6
Bunch Length	σ_t (4σ) $= 4\ \sigma_s/c$	[ns]	1.0 / 1.5	1.0 / 1.35 / 1.5

- Other important Settings
  - 6MV@inj, 12MV@4TeV RF-Voltage
  - round beams
  - uncoupled planes (for IBS growth)
  - beam shape: pseudo-Gaussian, exactly matched

Injection

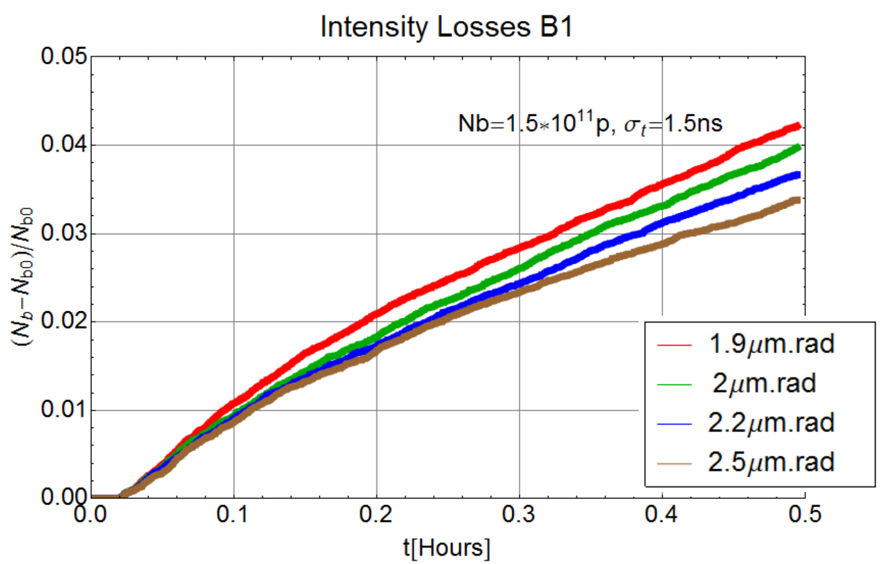
		Unit	@ 450 GeV	@ 4TeV
Emittance	$\varepsilon_{x,y}$	[um rad]	**1.9 / 2.0 / 2.2 / 2.5**	2.0, 2.5, 3.0
Intensity per Bunch	Nb	[10^11 charges]	**1.5 / 1.6**	1.6
Bunch Length	σ_t (4σ) $= 4\,\sigma_s/c$	[ns]	**1.0 / 1.5**	1.0 / 1.35 / 1.5

Intensity

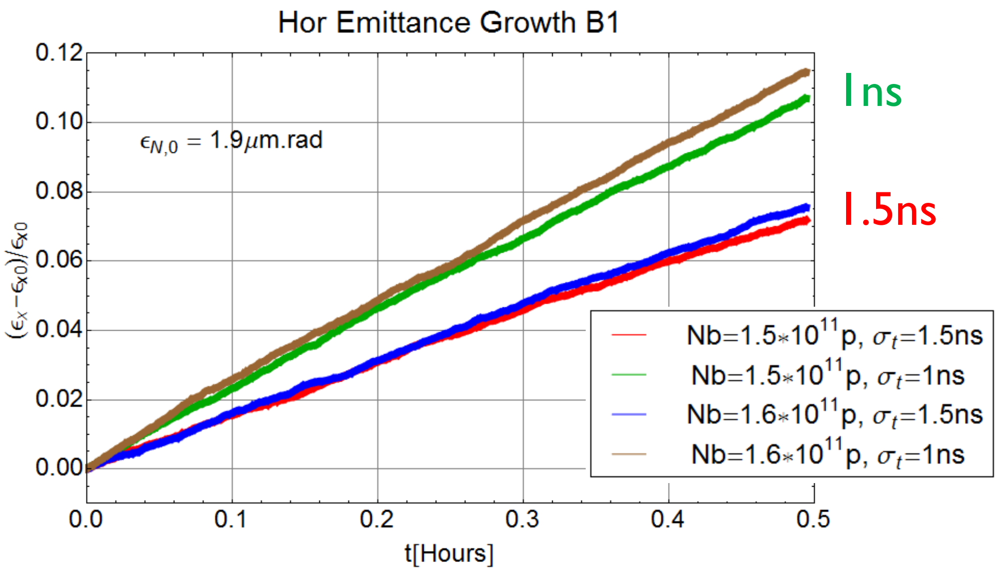


- loss mechanisms
  - particles leave bucket (debunching losses)
  - hit physical aperture (due to dispersion or betatron action)

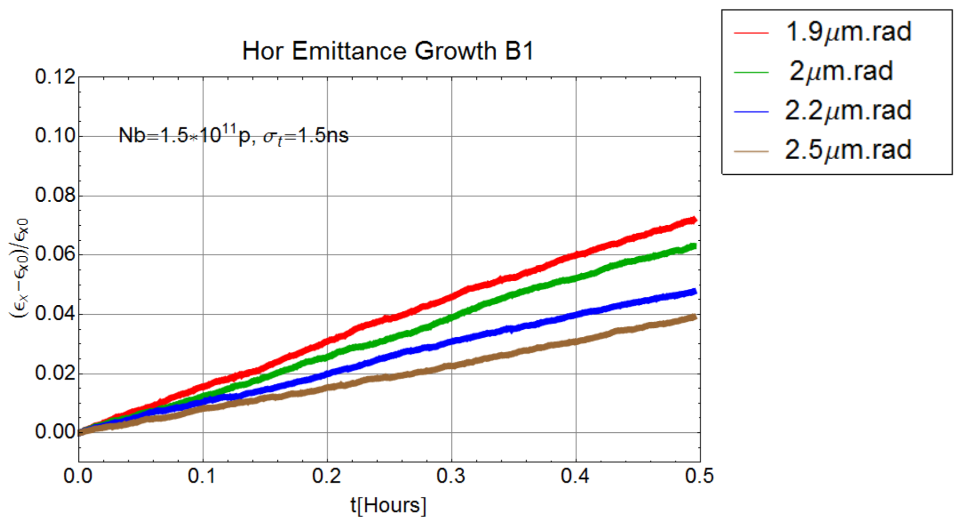
- highest losses for
  - bunches with great bunch length (1.5ns)
  - bunches with small emittance



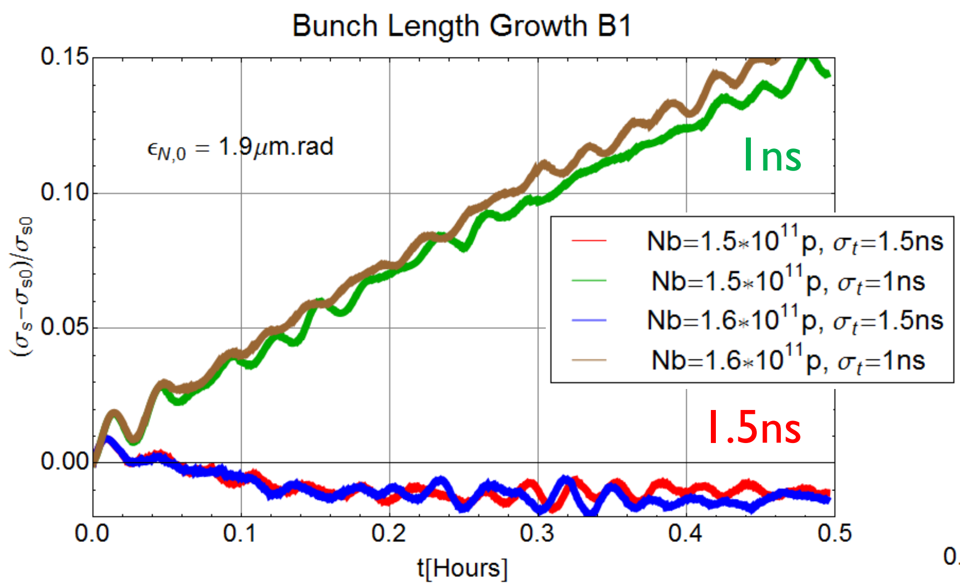
Emittance



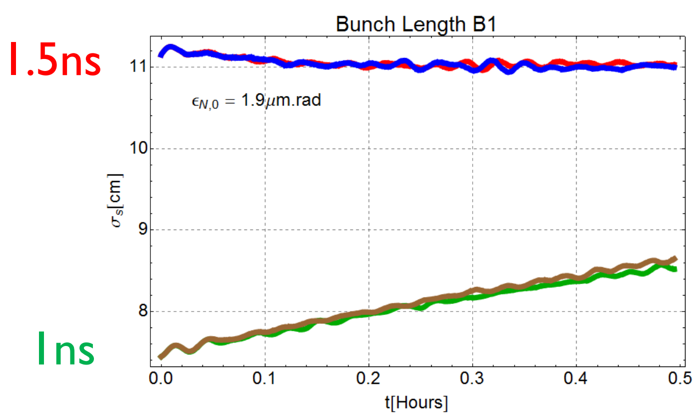
- small initial emittances increase faster
- small initial bunch lengths (1ns) increase faster in transverse emittance
- no big difference for different initial intensities

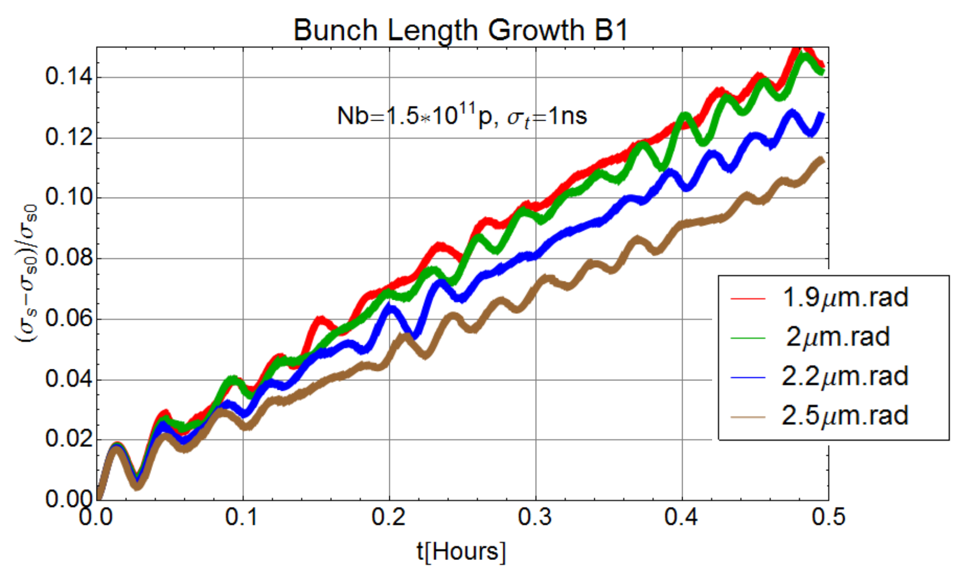


Bunch Length

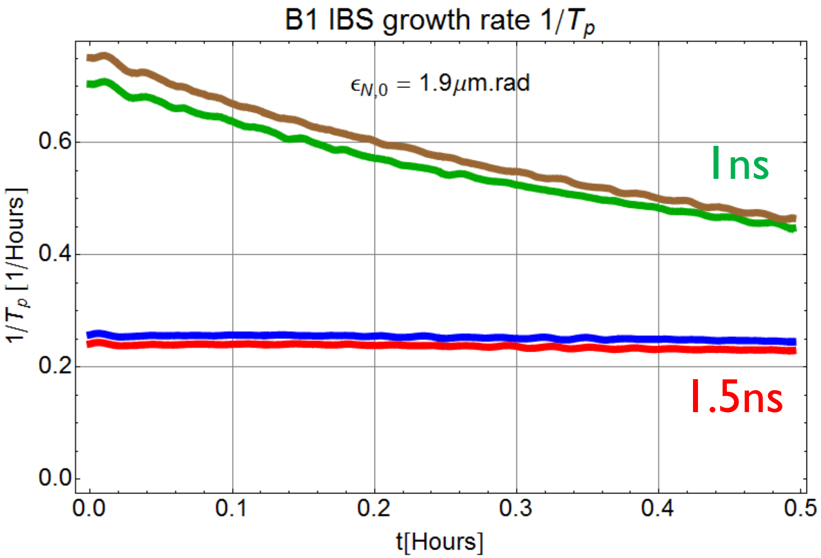


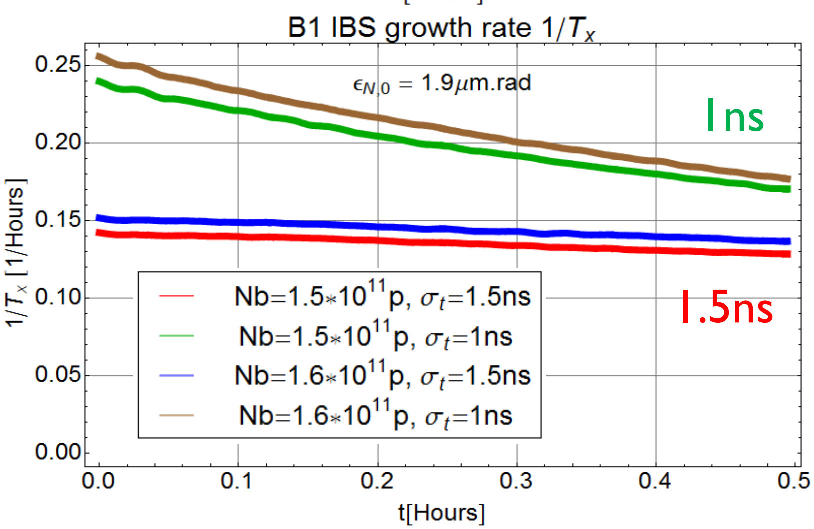
- small initial bunch lengths (1ns) grow much faster
  - particles fill the bucket
- 1.5ns case actually decreases a bit
  - tails of the distribution are cut when particles leave the bucket
  - RMS of the distribution decreases and Gaussian shape is lost



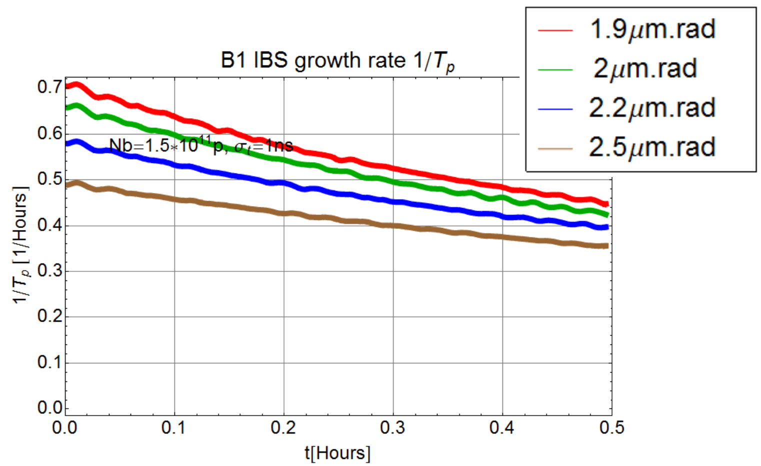


IBS Growth Rates

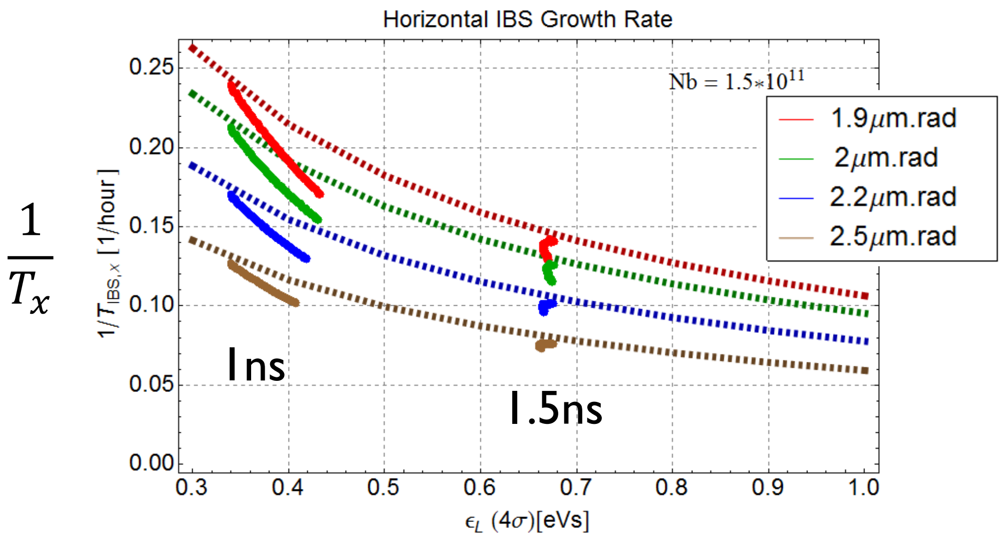


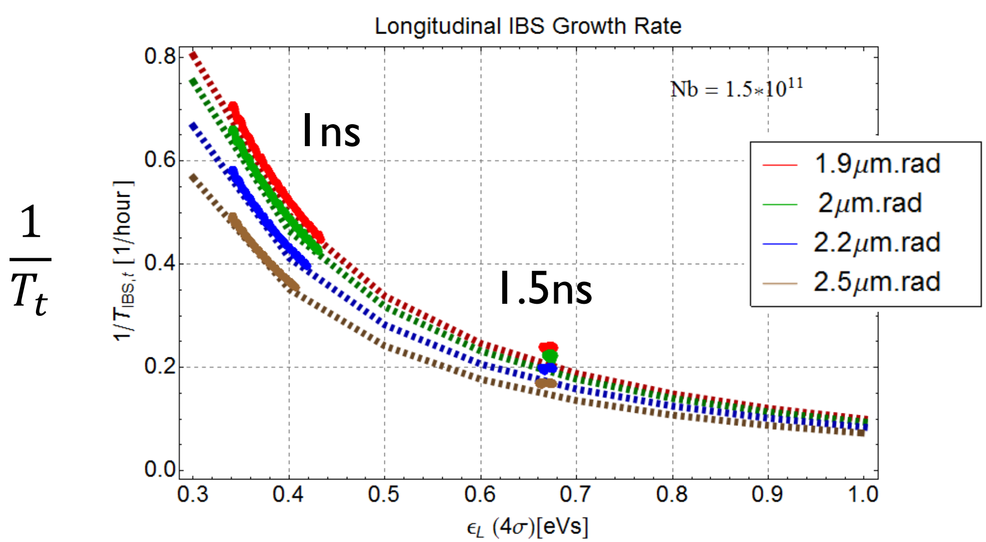


- 1ns growth rates start higher and decreases faster
  - emittances increase faster for small bunch lengths
- 1.5ns growth rates quite stable and much smaller as for 1ns initial bunch length
- initial growth rates increase with smaller initial emittances



Comparison with MADX Calculations Growth Rate vs. Longitudinal Emittance

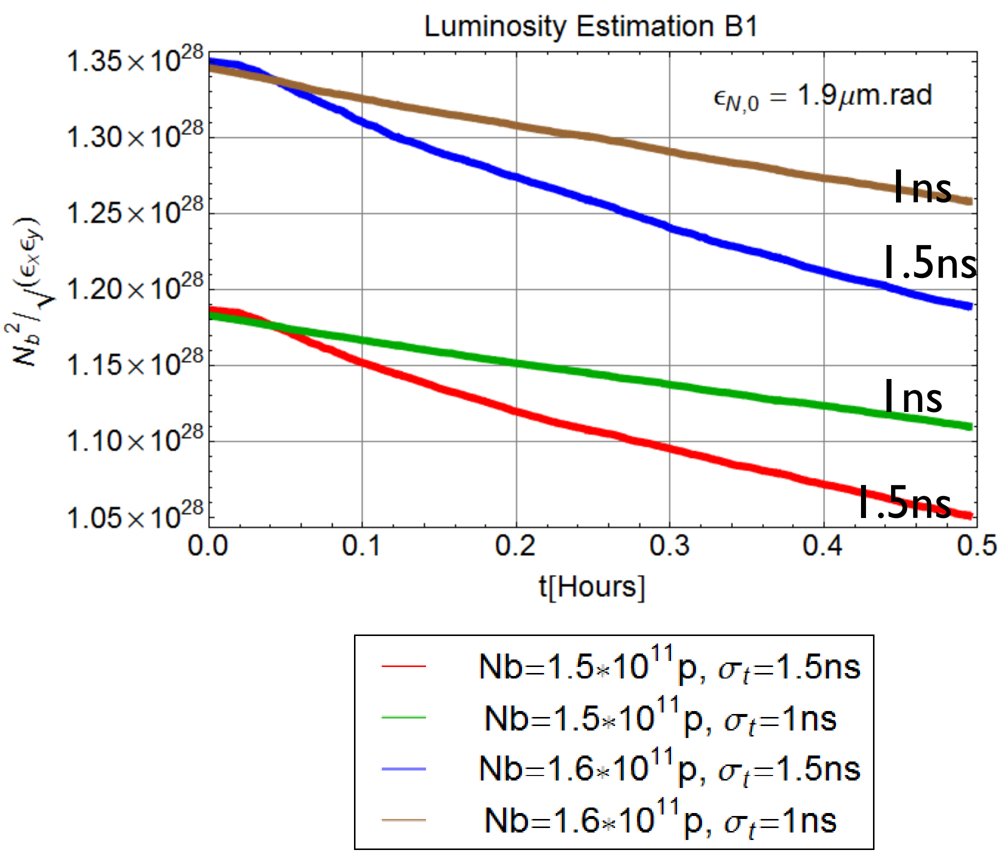




- MADX calculations are shown as the dashed lines
- Growth rate vs. longitudinal emittance ε_l
  - initial points in good agreement
  - lines separate for higher longitudinal emittances
  - MADX calcucation only varies ε_l
  - in the simulation all parameters evolve with time
  - only for initial points, both are expected to agree

Effect of injection conditions on Luminosity

Figure of merit for initial luminosity vs. time spent at injection



- calculate $N^2/\sqrt{\varepsilon_x \varepsilon_y}$ to get an estimate of what the luminosity would be if collisions were 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 initial luminosity (and luminosity lifetime later)

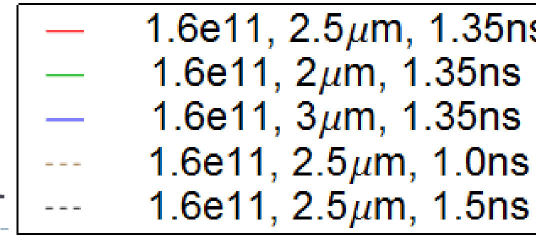
Physics at 4TeV

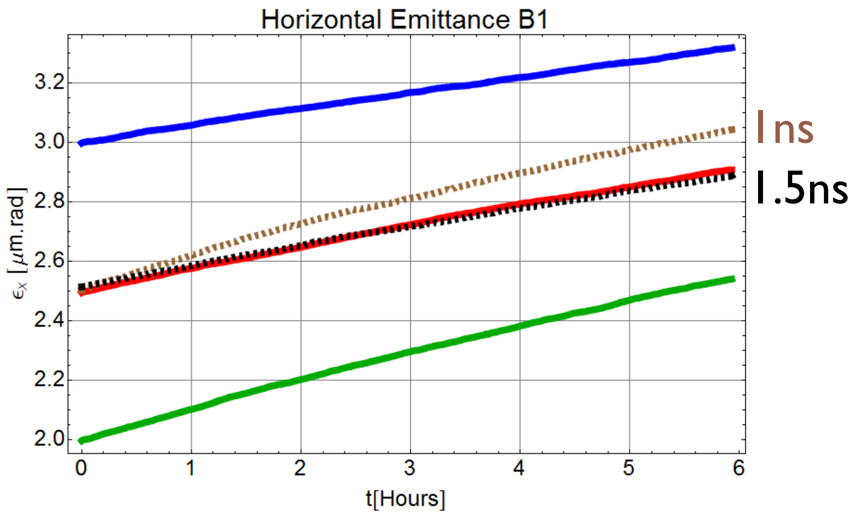
$\varepsilon_N = 2.5\mu m$
$N_b = 1.6 * 10^{11}$ ppb
$\sigma_t = 1.35ns = 10.1cm$
$\beta^* = 0.6m$
$\frac{\theta_c}{2} = 145\ \mu rad$

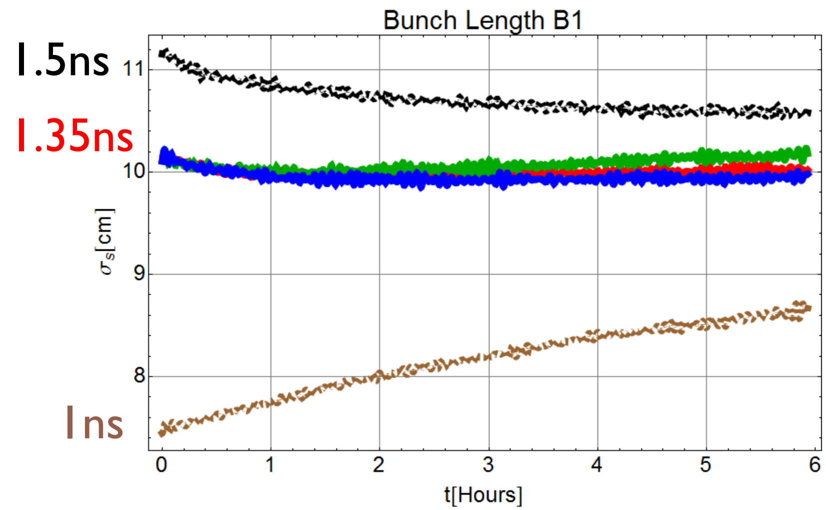
Suggested Performance Reach for 50ns by G.Arduini in Charmonix 2012

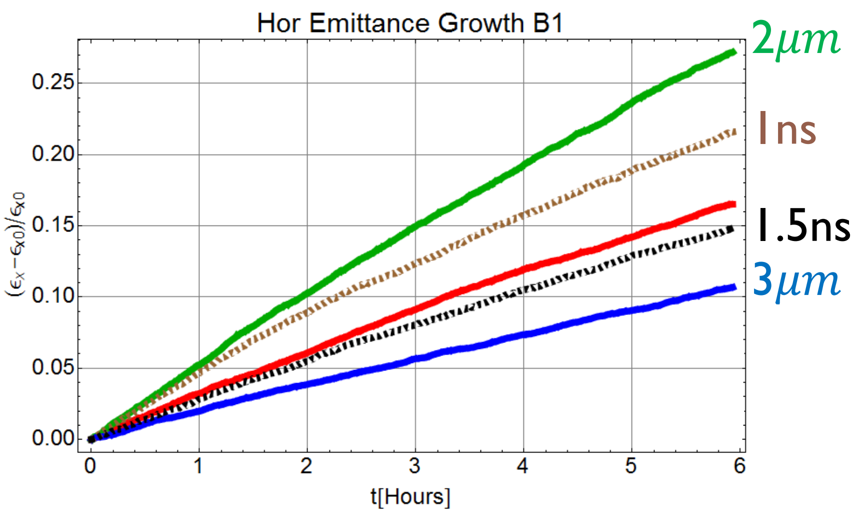
		Unit	@ 450 GeV	@ 4TeV
Emittance	$\varepsilon_{x,y}$	[um rad]	1.9 / 2.0 / 2.2 / 2.5	**2.0 / 2.5 / 3.0**
Intensity per Bunch	Nb	[10^11 charges]	1.5 / 1.6	**1.6**
Bunch Length	σ_t (4σ) $= 4\ \sigma_s/c$	[ns]	1.0 / 1.5	**1.0 / 1.35 / 1.5**

Emittance and Bunch Length



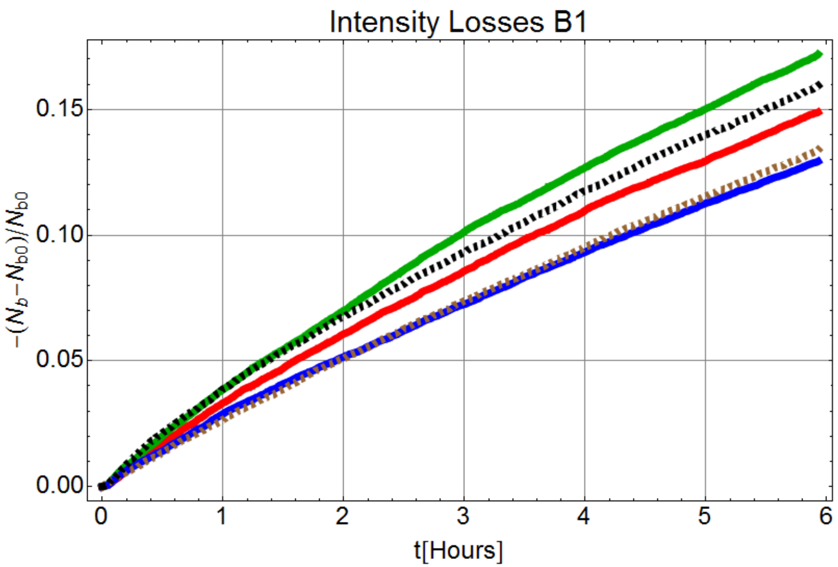




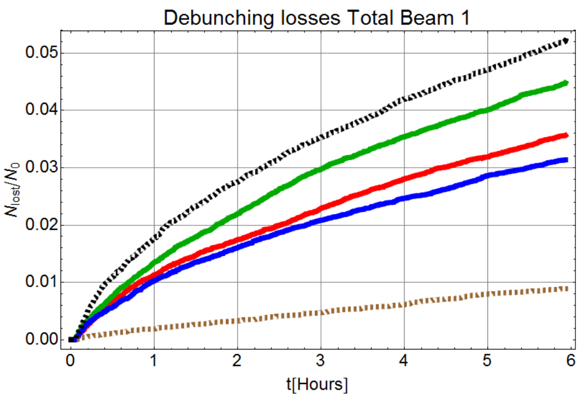


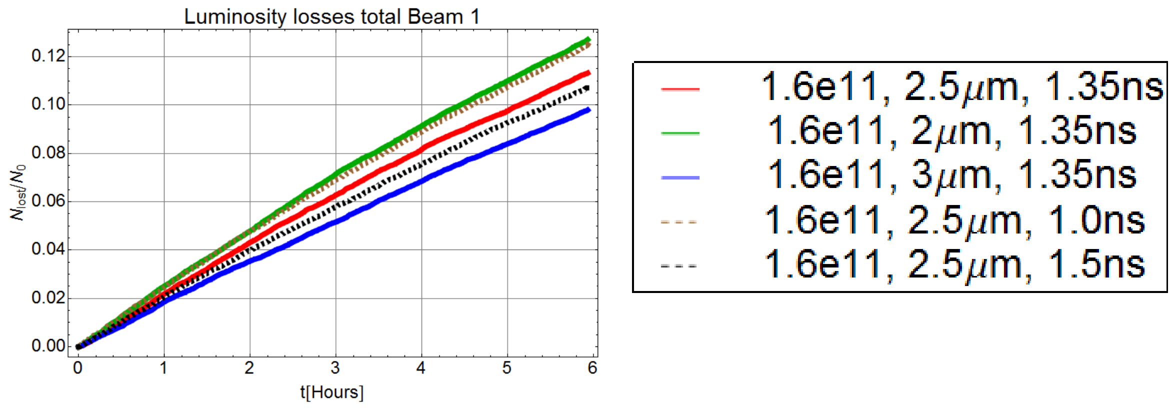
- small initial bunch length grow faster in transverse and longitudinal plane
  - effect begins to saturate at 1.35ns
- smaller initial transverse emittances grow faster

Intensity

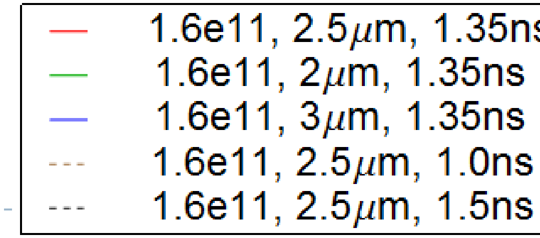


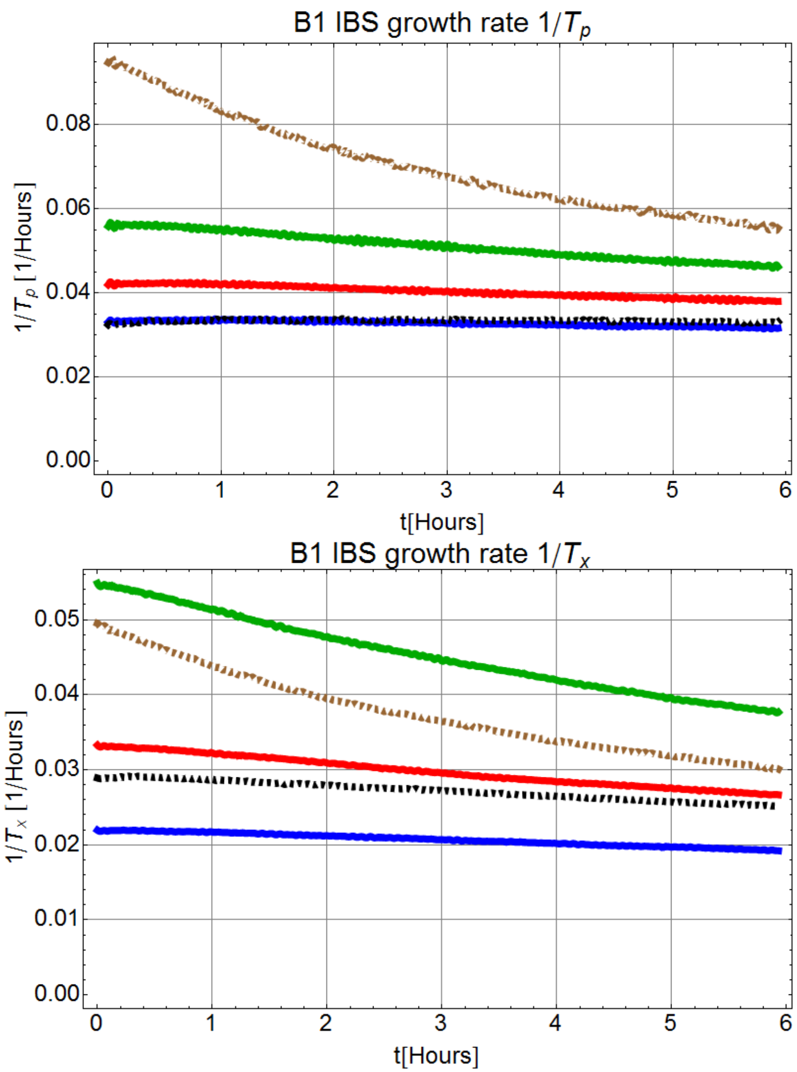
- ~ 15% lost after 6h
  - debunching losses differ significantly for different initial bunch lengths
  - for greater bunch lengths the debunching losses become more important
  - total losses dominated by luminosity burn off
- smaller transverse emittances lose more





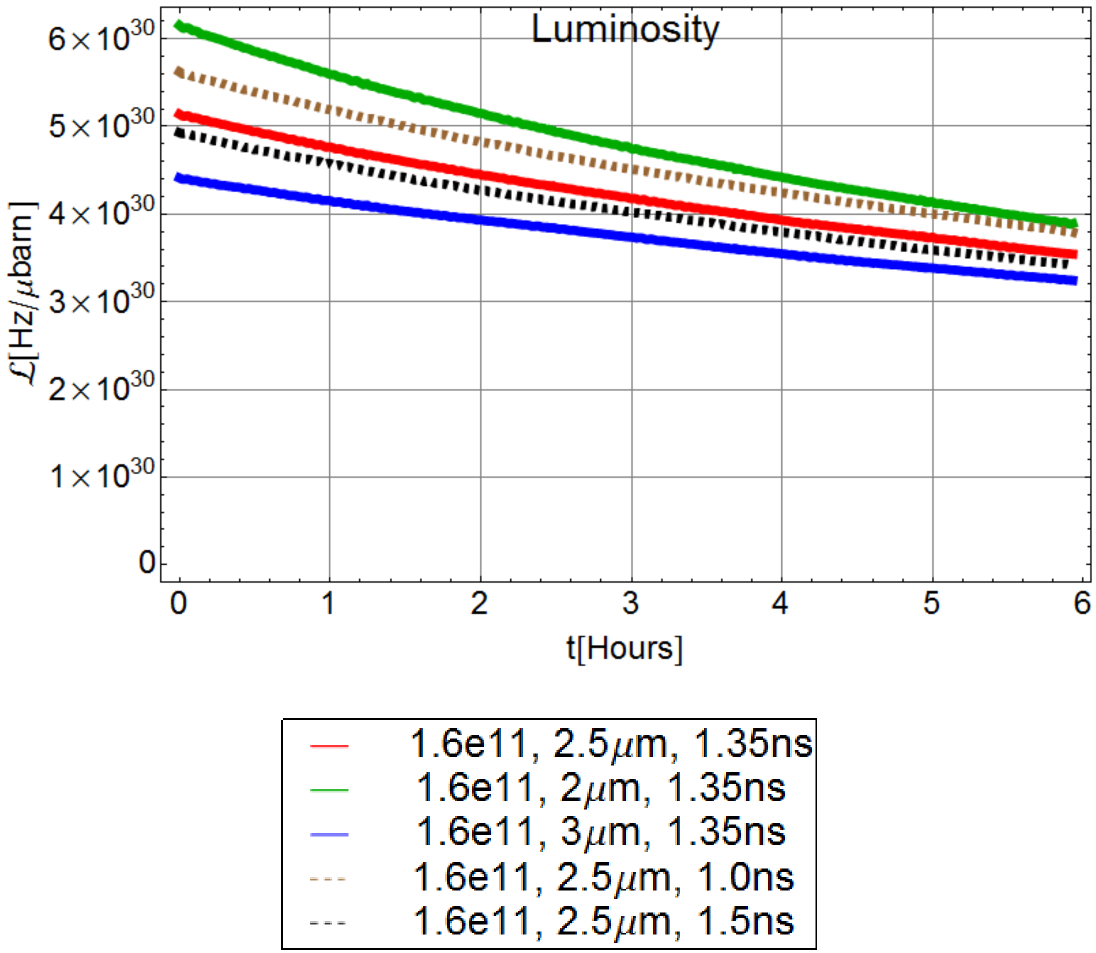
IBS Growth Rates





- same behaviour as at injection
- transverse and longitudinal beam size both have influence on each IBS growth rate
  - growth rates are higher for smaller beams
- for $\geq$1.35ns initial bunch length the longitudinal growth becomes quite stable in time
- horizontal growth as well for $\geq 2.5\mu m$

Luminosity



- bunch with smallest emittance has highest luminosity
- bunches with different initial bunch lengths show different initial luminosities
  - effect in agreement with the geometric luminosity reduction due to the crossing angle

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma_{xy}}\right)^2}$$

  - 1.5ns case smallest luminosity – has highest debunching losses

Conclusion

- Simulations were done for single bunch at injection and in physics.
- The beam conditions are shown as a function of time: this gives an estimate 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 at injection.
- The estimate of the potential luminosity at injection shows a great dependence 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.
  - Simulations in collisions show a tendency of the increased emittance blow-up to saturate around 1.3ns bunch length
  - Debunching losses become less important at higher energies – luminosity burn off dominates

- 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.

BACK- UP

Collider Time Evolution (CTE) Program

Processes taken into account:

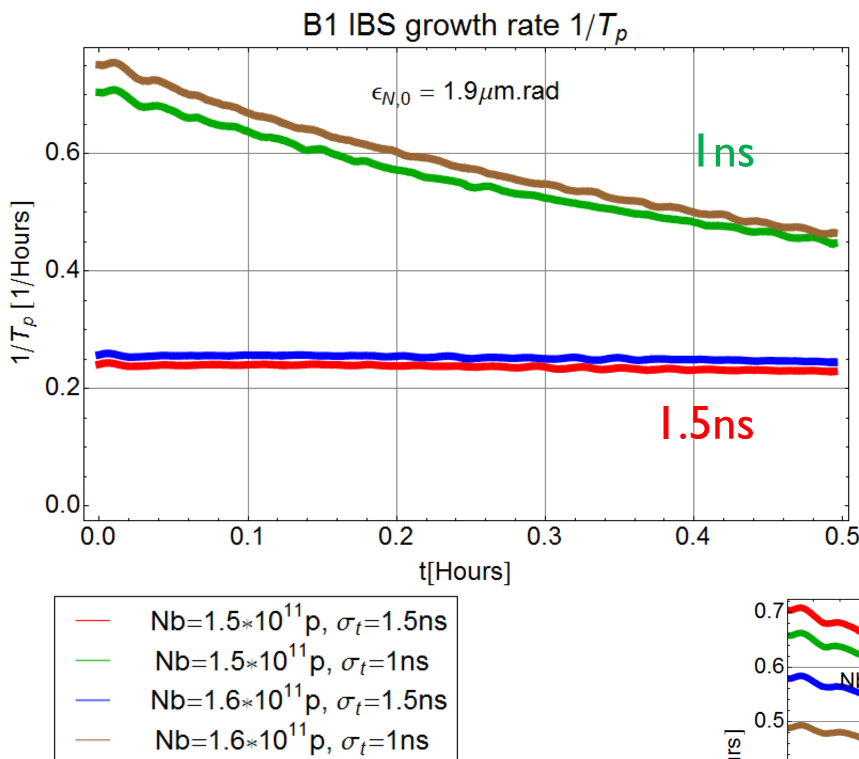
- COLLISIONS
  - user can choose between 2 collision routines:
    - very slow, integrates interaction probability for every particle by sorting particles in opposing beam in discrete bins. **No assumptions on the shape of the beam distribution**.
    - fast routine, **assumes Gaussian transverse distribution** 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

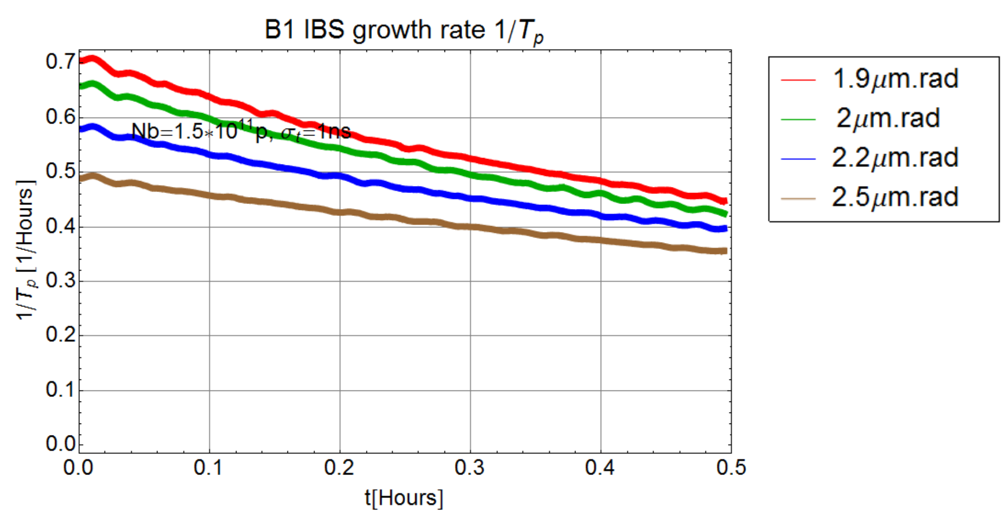
- Output on a turn-by-turn basis
  - IBS rise times
  - Intensity
  - Transversal and longitudinal emittances
  - Luminosity

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

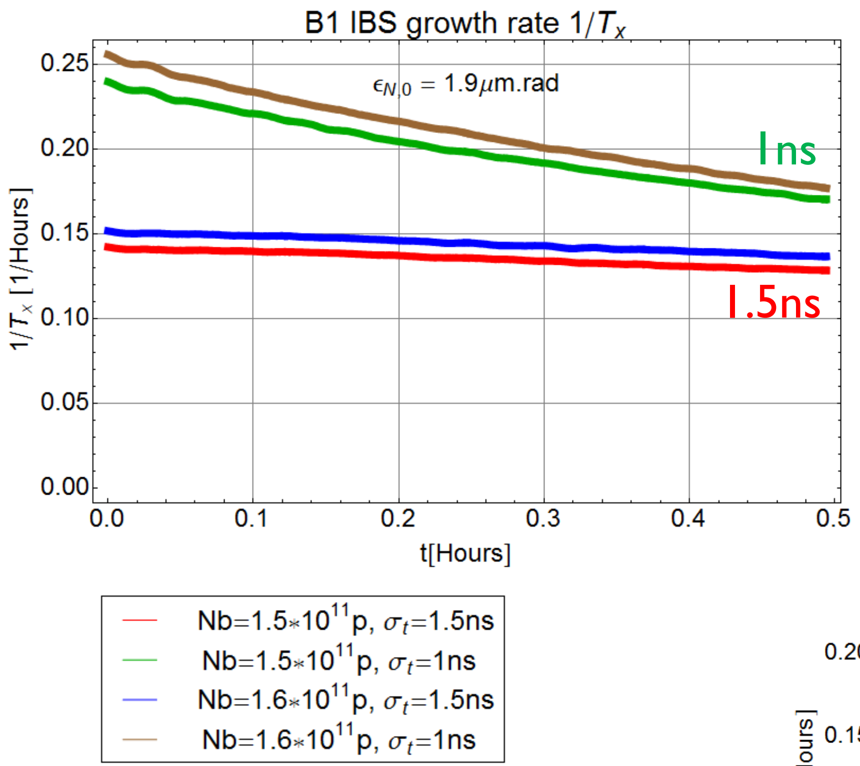
Longitudinal IBS Growth Rates



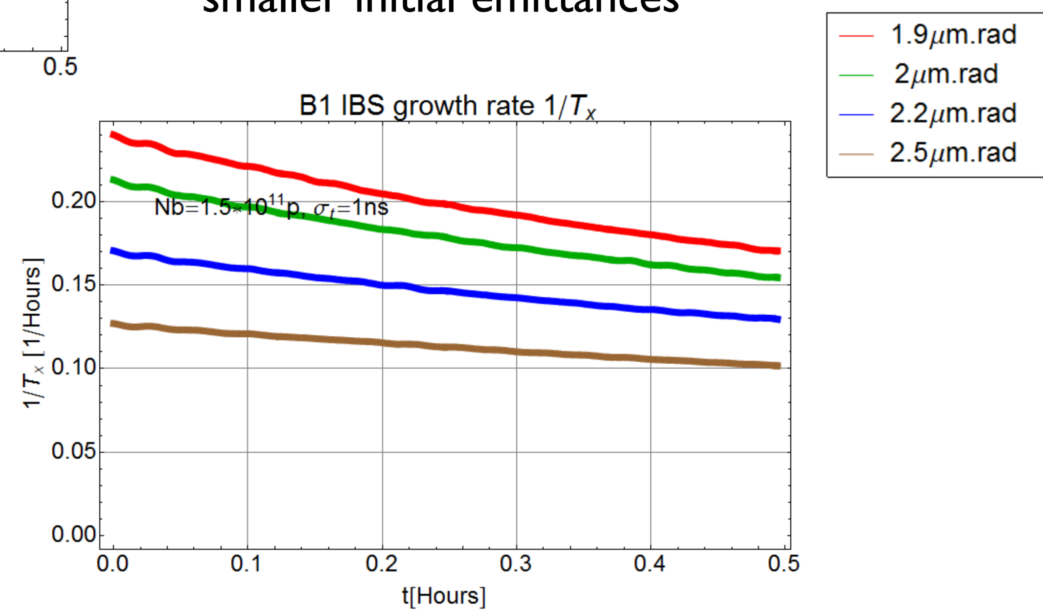
- 1ns growth rate starts higher and decreases faster
  - bunch length grows faster
- 1.5ns growth rate quite stable and much smaller as for 1ns initial bunch length
- initial growth rate increases with smaller initial emittances



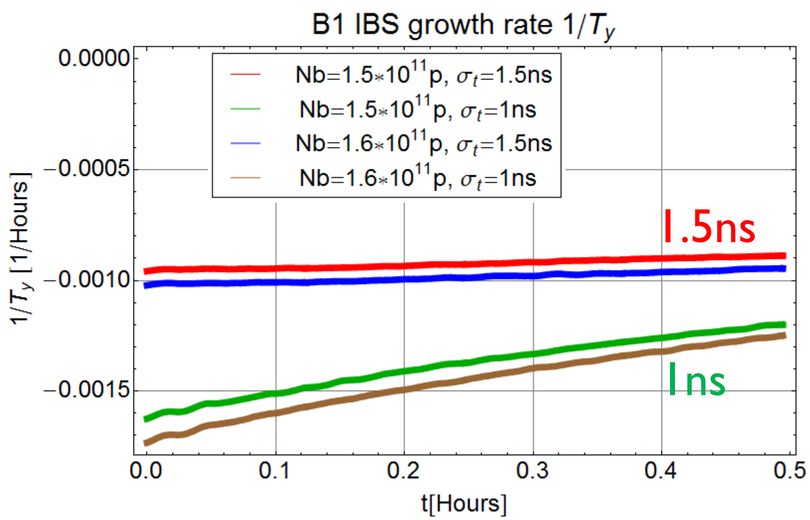
Horizontal IBS Growth Rate



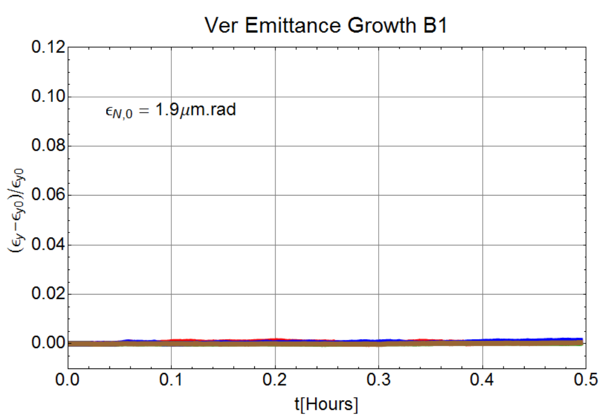
- same picture as for the longitudinal growth rate, but lower amount
- 1ns growth rate starts higher and decreases faster
  - horizontal emittance growth faster
- 1.5ns growth rate quite stable and much smaller as for1ns initial bunch length
- initial growth rate increases with smaller initial emittances

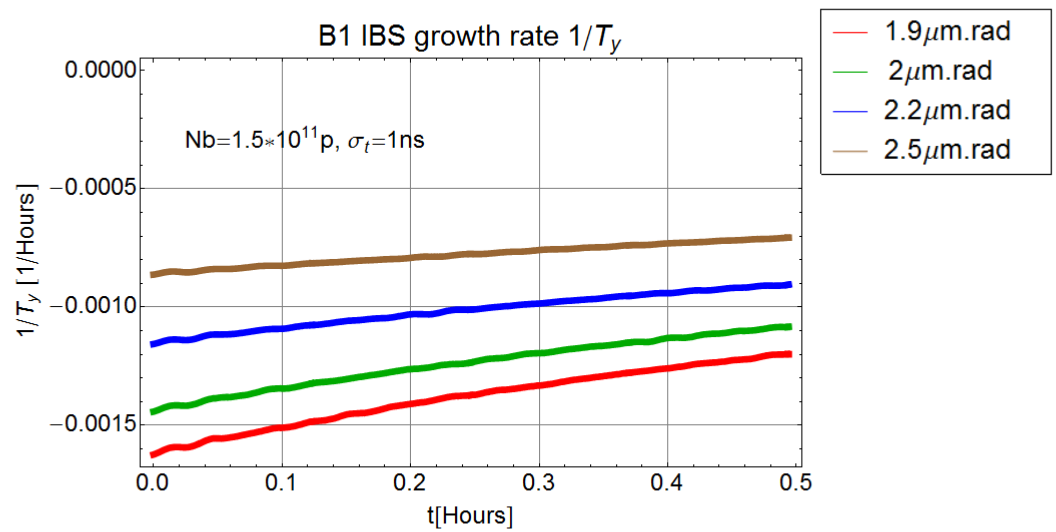


Vertical IBS Growth Rate

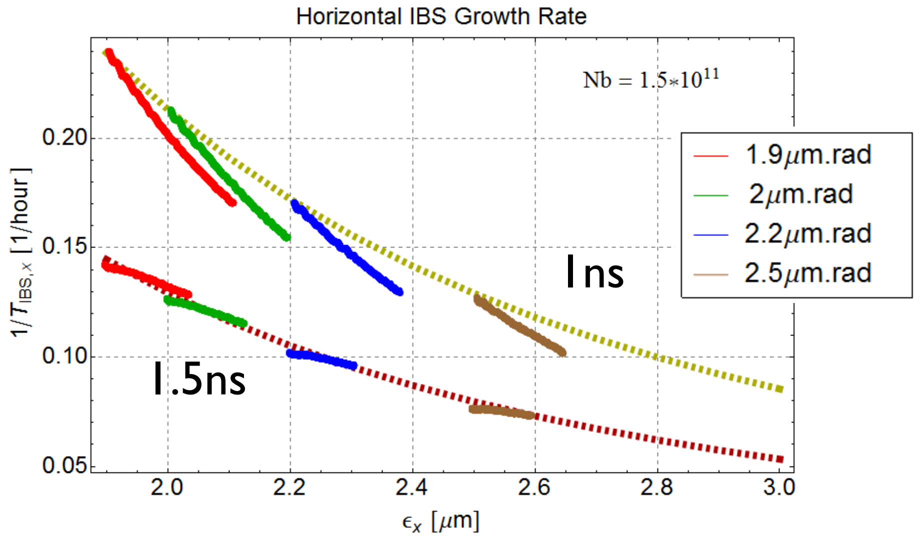


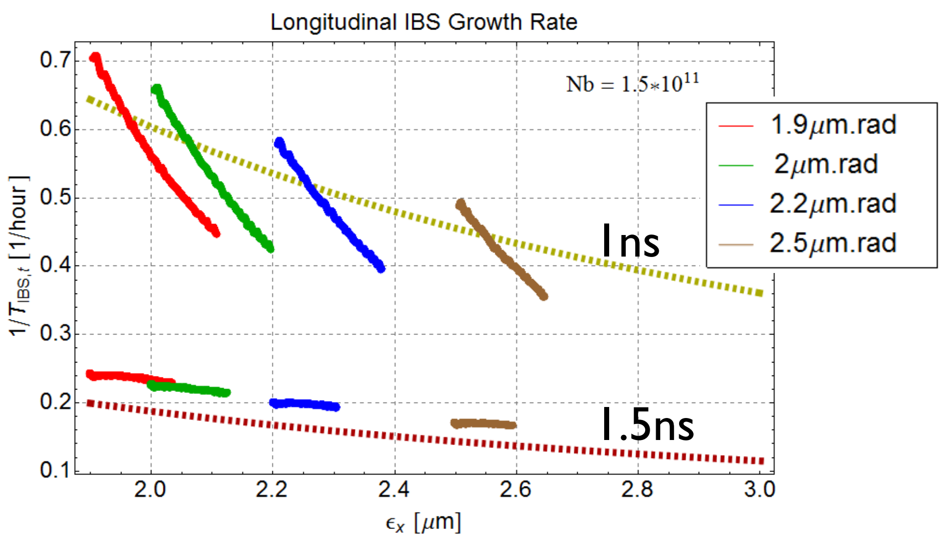
- Simulation was done for uncoupled transverse planes
- vertical growth rate very small and negative
  - vertical emittance shrinks very slowly due to IBS



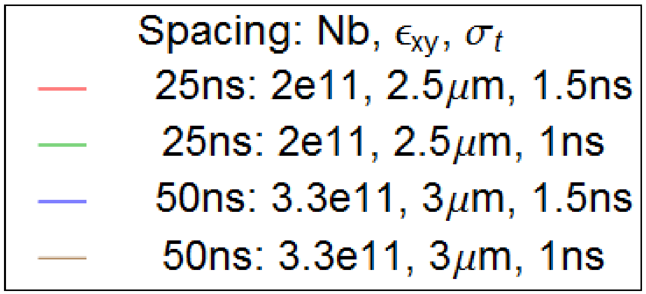


Comparison with MADX Calculations Growth Rate vs. Transverse Emittance

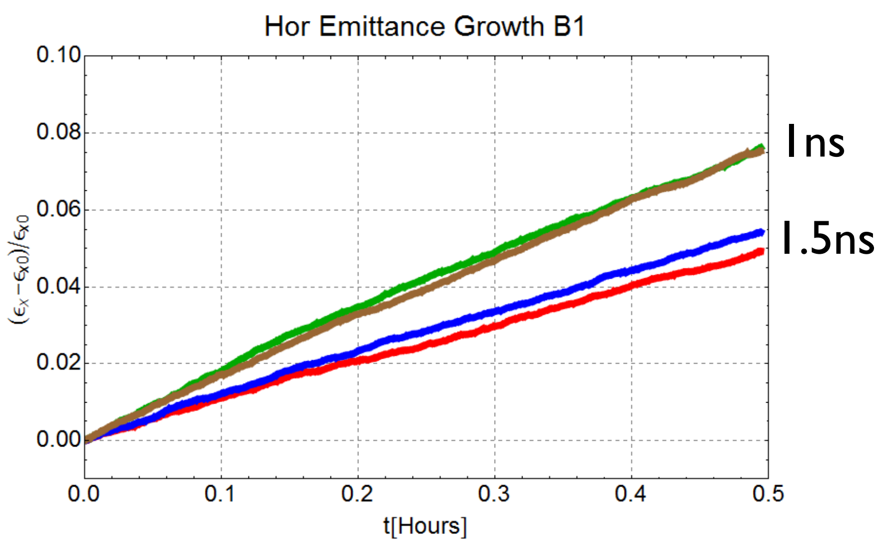


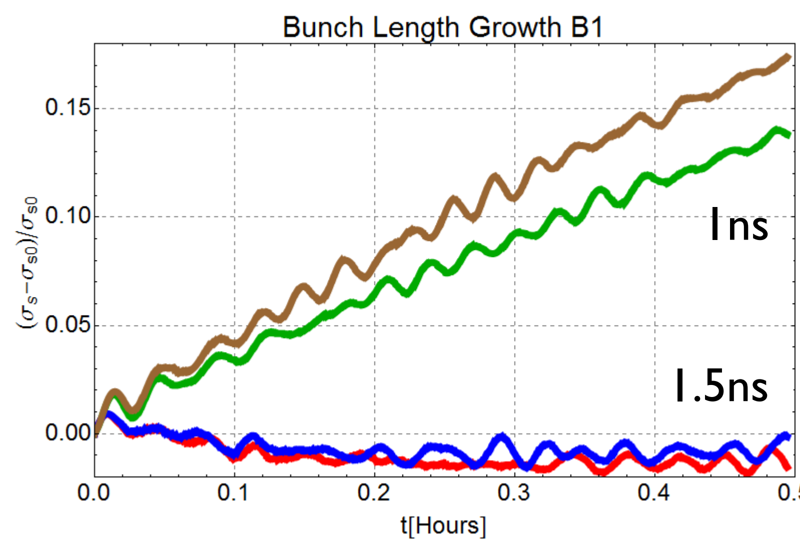


Simulation with HL-LHC Parameters

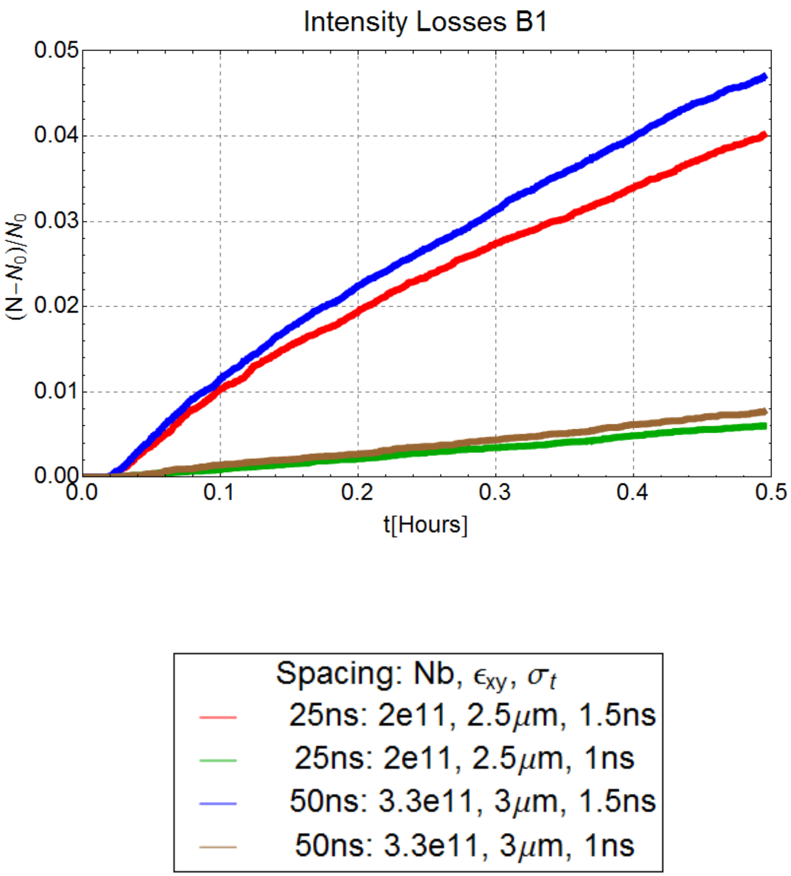


- same picture as for 2012 parameters
- different bunch lengths have big effect on the evolution
- small initial bunch lengths lead to faster growth in transverse and longitudinal plane
- combination 3.3e11ppb/3μm (50ns) and 2e11/2.5μm (25ns) only show small differences for equal initial bunch length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