Simulations of IBS for HL-LHC Protons

Michaela Schaumann

Thanks to John Jowett, Roderik Bruce

Outline

- Collider Time Evolution (CTE) program – IBS simulations
- Current LHC simulations done with CTE
  - published in CERN-ATS-Note-2012-044 PERF
- HL-LHC calculations with MADX based on ATS optics

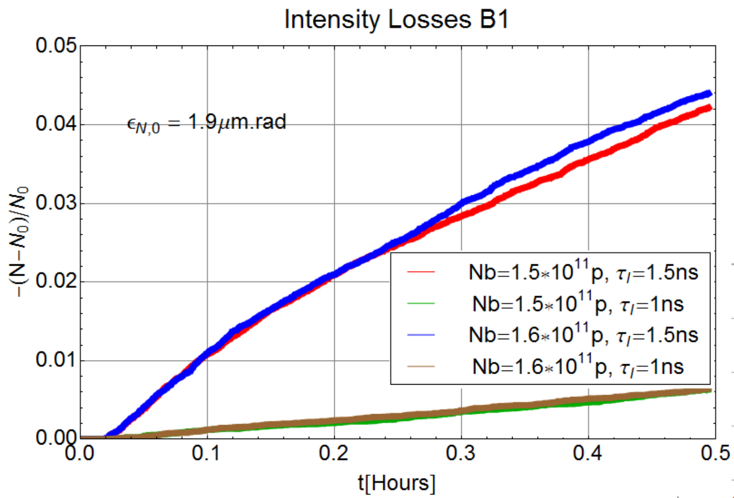
- Benchmark Case Proposal
- Future Plans

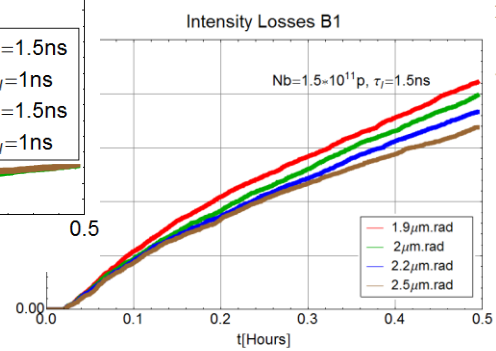
Collider Time Evolution (CTE) Program

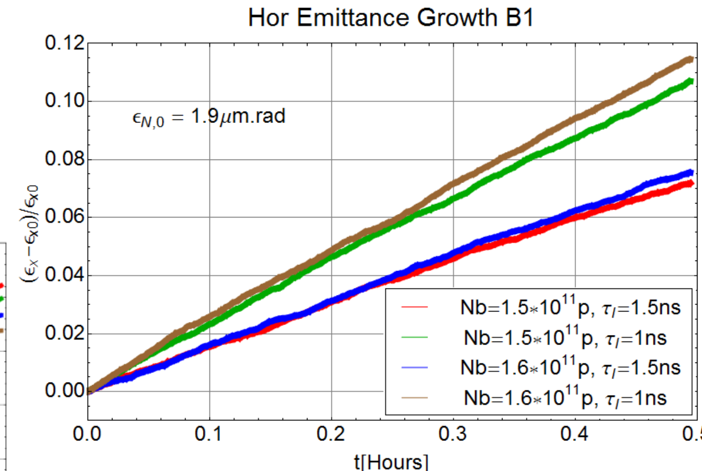
- Authors: Mike Blaskiewicz, Roderik Bruce and Tom Mertens
- Program to track 2 bunches of **macro-particles** in time in a collider
  - Subroutines act on the bunches on a **turn-by-turn basis**: one simulation turn can correspond to any chosen number of machine turns.
  - Several other input parameter 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

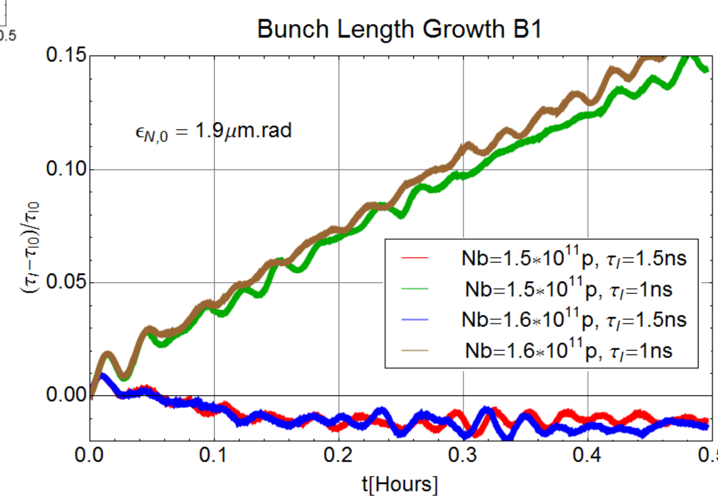
LHC in 2012

LHC Protons in 2012 - Injection









- loss mechanisms
  - particles leave bucket (debunching losses)
  - hit physical aperture (due to dispersion or betatron action)
- highest losses but smaller transverse and longitudinal emittance blow up for bunches with great initial bunch length (1.5ns)
- blow up and losses increase with smaller initial emittances
- no big difference for different initial intensities

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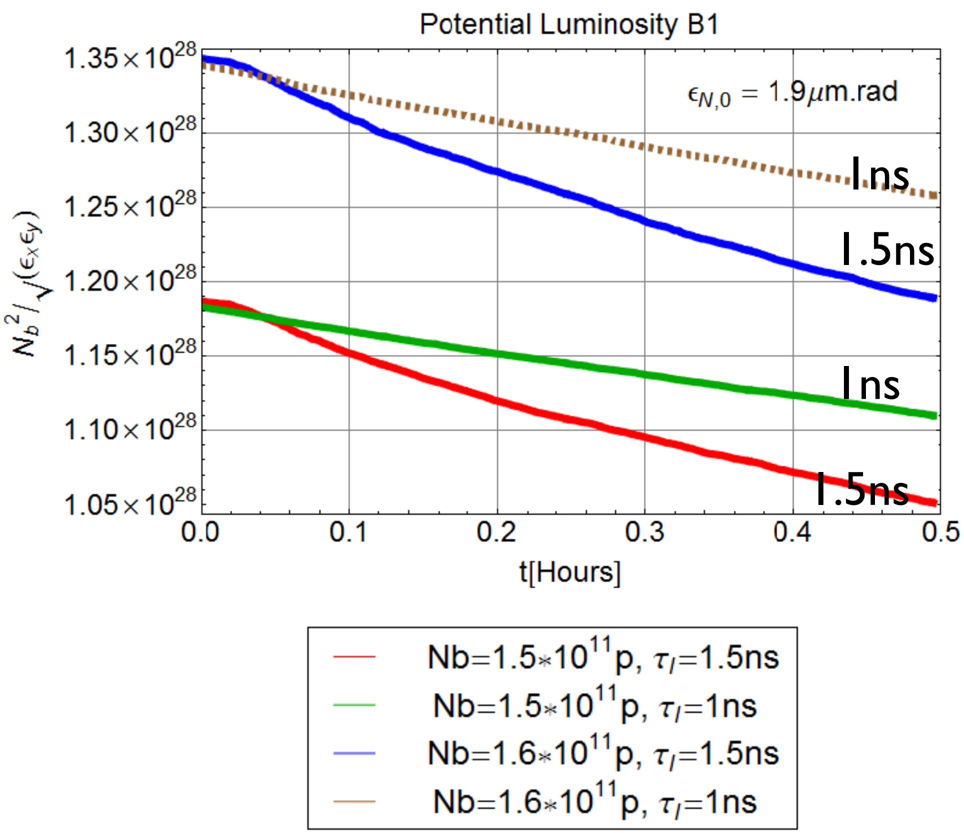
LHC Protons in 2012 – Effect of injection conditions on Luminosity

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)

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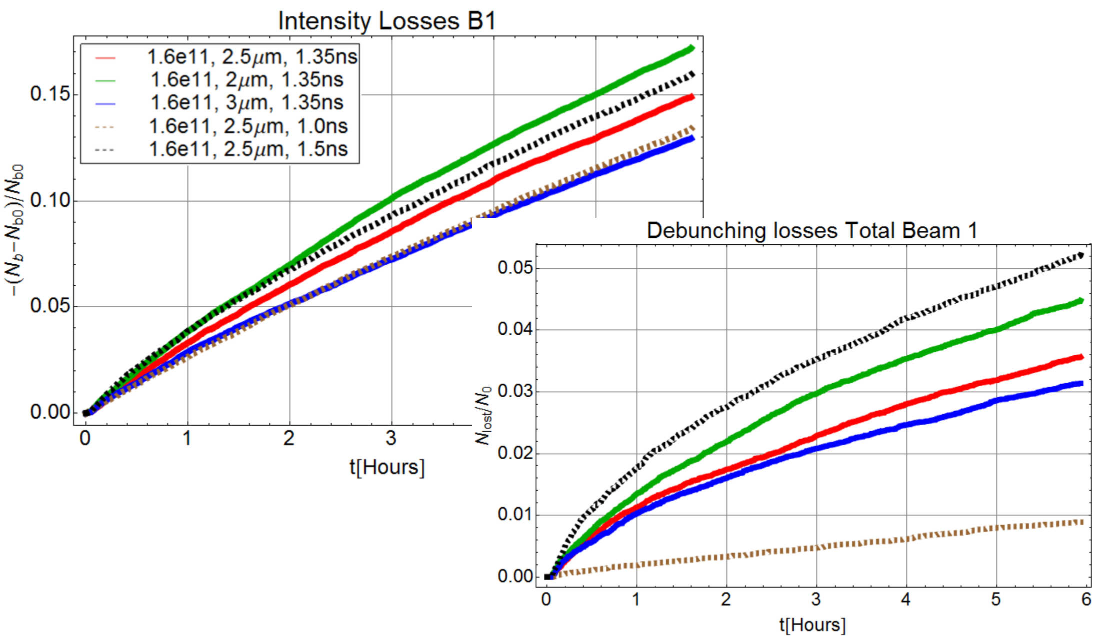
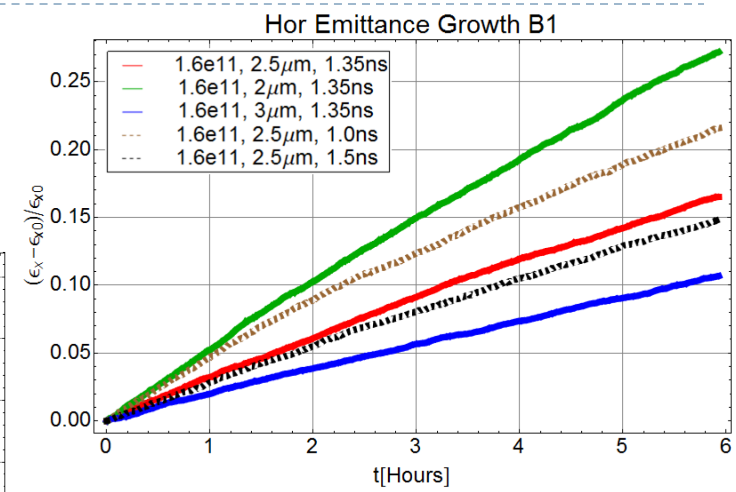
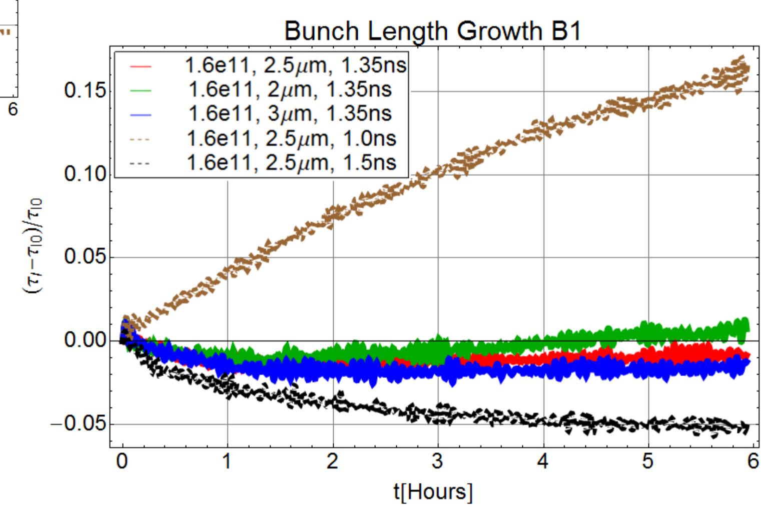
LHC Protons in 2012 – Physics @ 4TeV







- total intensity losses are the sum of debunching and luminosity losses
  - significant differences in debunching losses: they become more important for greater bunch lengths
  - total losses dominated by luminosity burn-off
- smaller initial transverse emittances lose more and grow faster
- small initial bunch length grow faster

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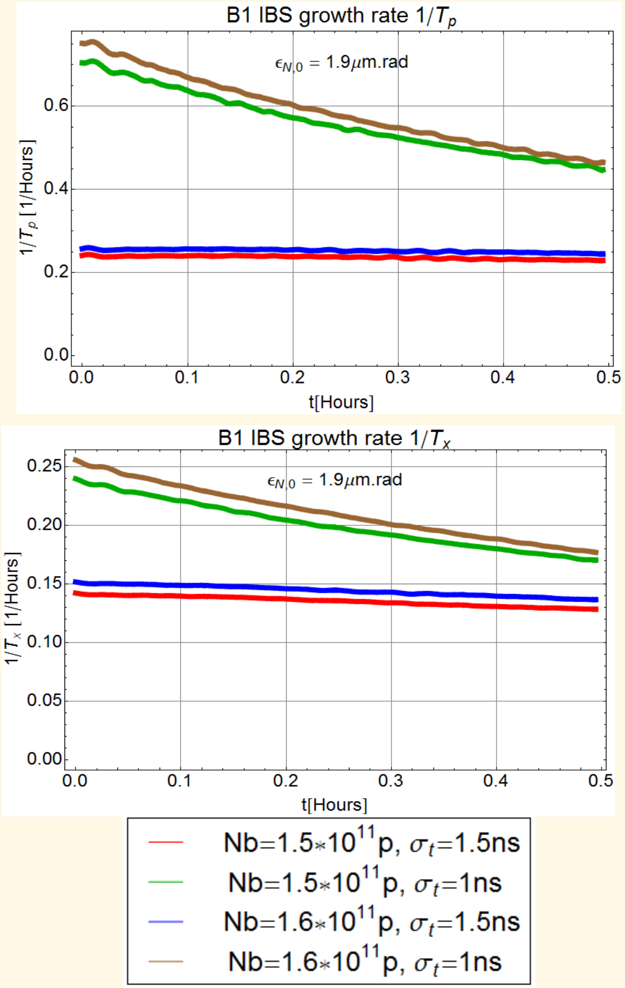
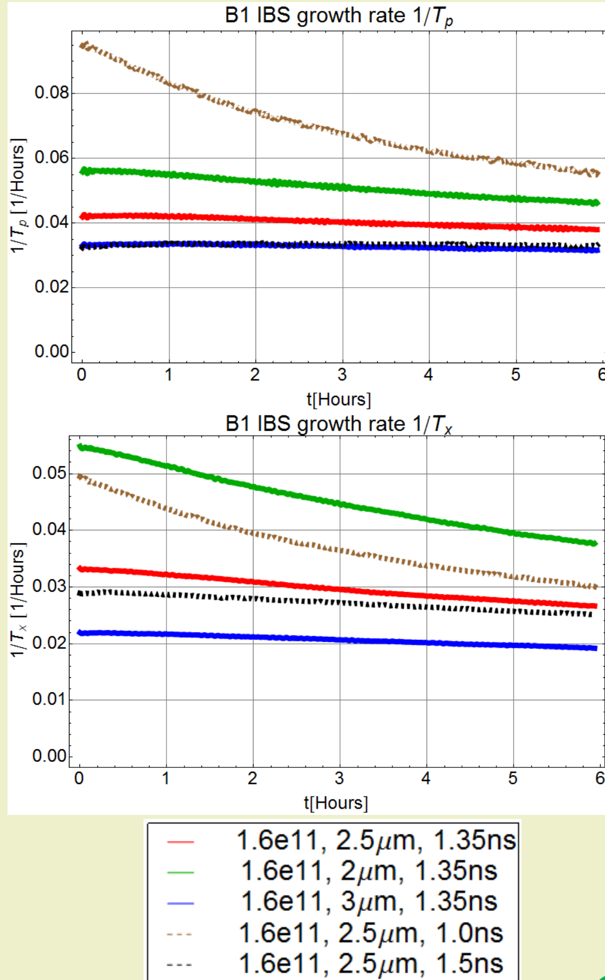
LHC Protons in 2012 – IBS Growth Rates

Injection



Collisions@4TeV



- small initial bunch length leads to higher IBS growth rates which decrease fast
- growth rates for higher initial length are quite stable and much smaller
- initial growth rate increases with smaller initial emittance

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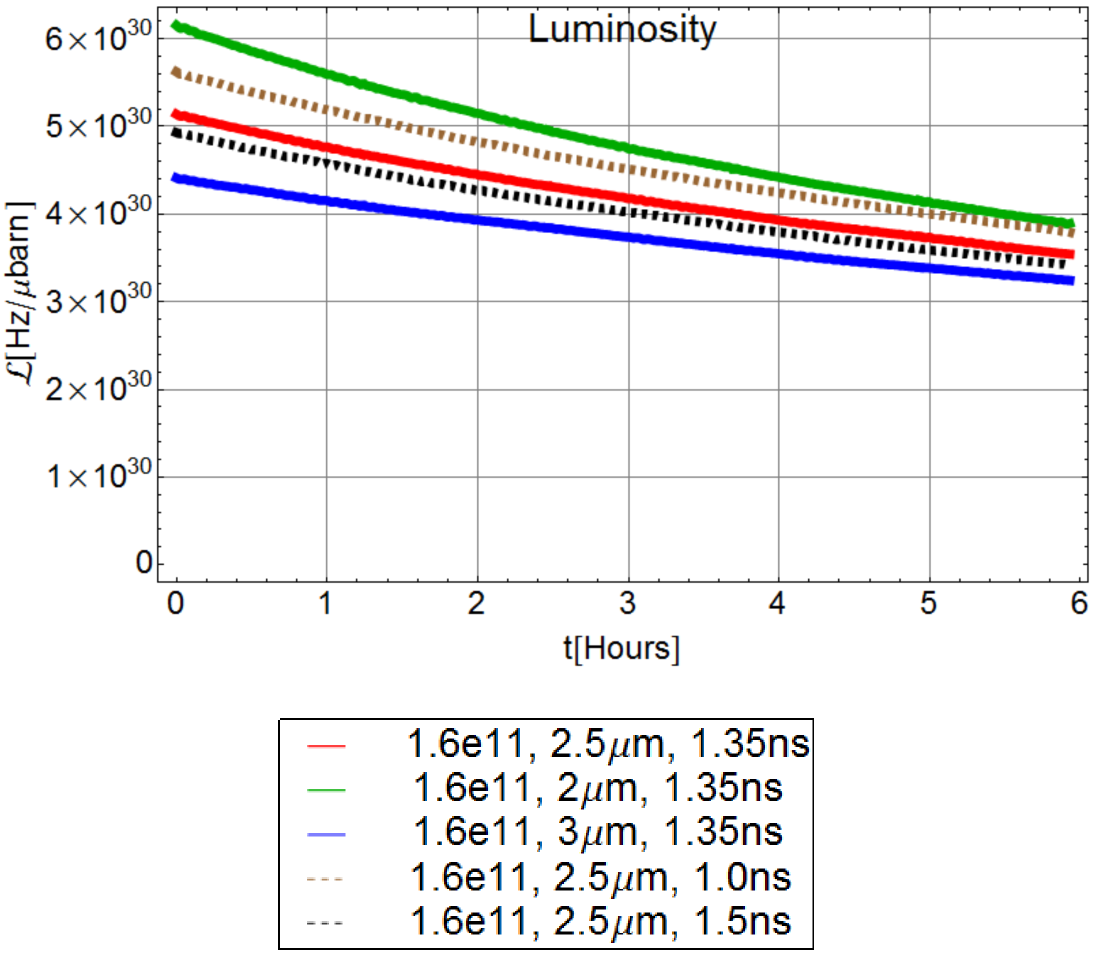
LHC Protons in 2012 - Luminosity



- 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

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HL-LHC

HL-LHC Beam Parameters

Beam parameters from HL-LHC Kick off:	25 ns	25ns (short)	50 ns
# protons / bunch [1E11]	2.2	2.2	3.5
Longitunal emittance [eV.s]	2.5	~1.4	2.5
Rms bunch length [cm]	7.5	4	7.5
Rms momentum spread [1E-4]	1	~1	1
Normalized rms transverse emittance [microm]	2.5	3.0	3.0

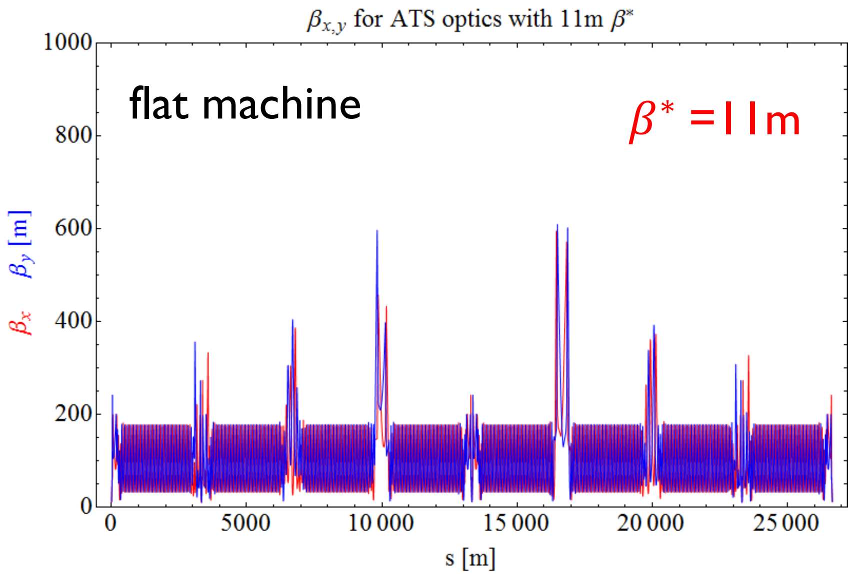
Collisions with round beams @ 7TeV

- Beta Star = 0.1m
- ½ x-angle = 290 microrad (IP1 & 5)
- RF voltage = 16MV @ 400MHz
- for the reduced bunch length case with 25ns spacing an additional RF System with 24MV @ 800MHz is necessary

- ATS version of nominal LHC is used for the analysis

Taken from: https://espace.cern.ch/HiLumi/WP2/task4/SitePages/Home.aspx

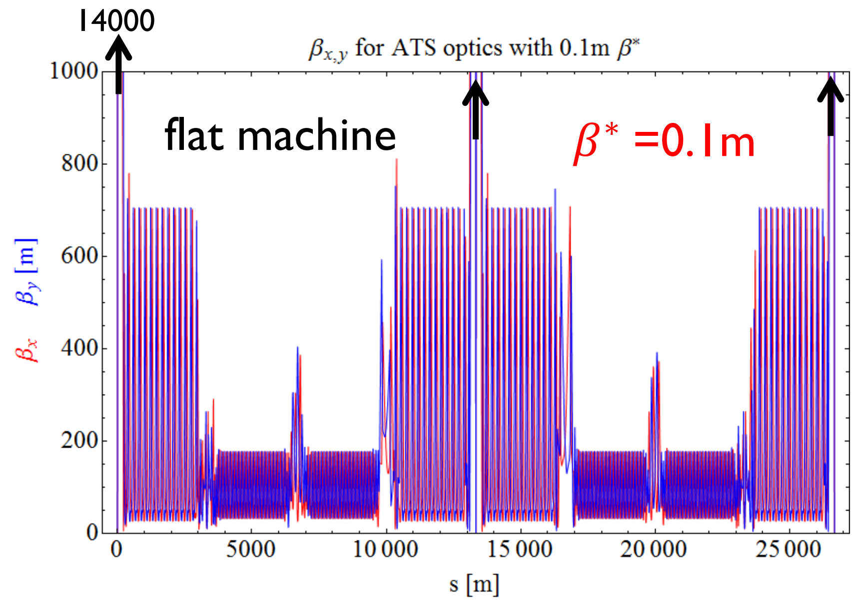
ATS Optics



- 31 Optics files with β^* values from 11m to 0.1m
- the squeeze to smaller β^* creates high β-values in the arcs around IP1&5
- increasing the β-function in arcs starts for $\beta^* \leq 0.4$m

The effects of the different optics on IBS are studied

1. as a function of β^*
2. for different beam parameters



Injection @ 450GeV

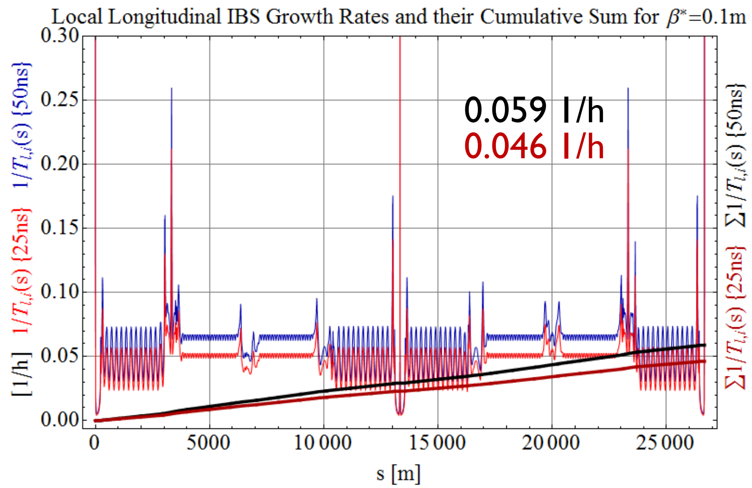
- IBS growth rates/times at injection energy calculated with MADX
- at $\beta^* = 11m$ - ATS optics file 1, flat machine
- all cases are calculated with a longitudinal emittance of 1eVs and with only the main RF system (8MV@400MHz)
- growth rates increase with increasing intensity and decreasing emittance

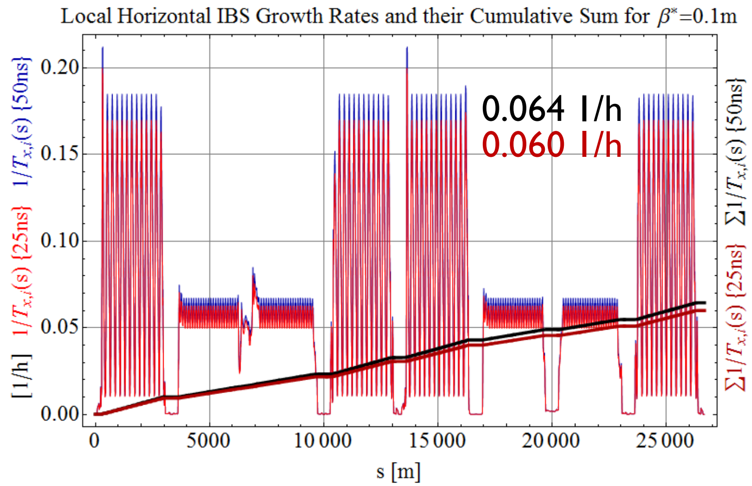
	25ns		50ns
Cases	2.2e11, 2.5μm, 1eVs	2.2e11, 3μm, 1eVs	3.5e11, 3μm, 1eVs
$1/T_{IBS,l}$ [1/hour]	0.0964	0.0780	0.124
$1/T_{IBS,x}$ [1/hour]	0.0957	0.0648	0.103
$1/T_{IBS,y}$ [1/hour]	-0.00063839	-0.00043271	-0.00068840

	25ns		50ns
Cases	2.2e11, 2.5μm, 1eVs	2.2e11, 3μm, 1eVs	3.5e11, 3μm, 1eVs
$T_{IBS,l}$ [hour]	10.4	12.8	8.06
$T_{IBS,x}$ [hour]	10.4	15.4	9.70
$T_{IBS,y}$ [hour]	-1566.4	-2311.0	-1452.6

Local contributions of the IBS Growth

Compare $\beta^* = 0.1\text{m}$ (optics file 31) for 25ns and 50ns nominal cases

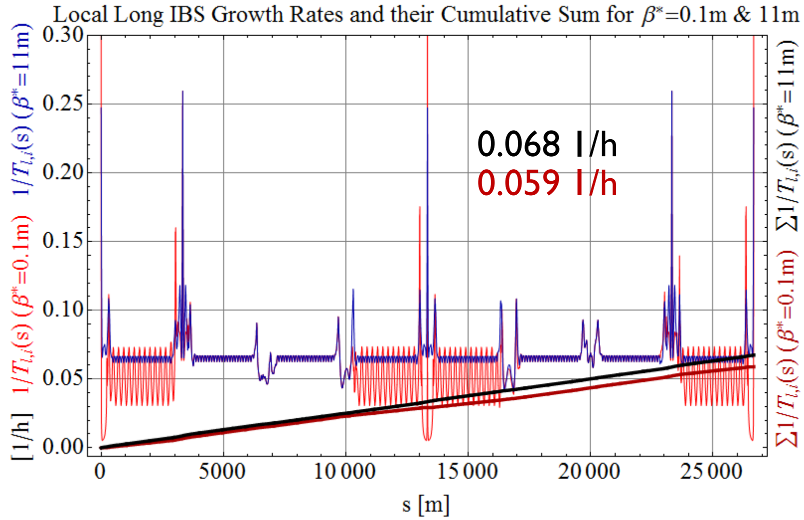


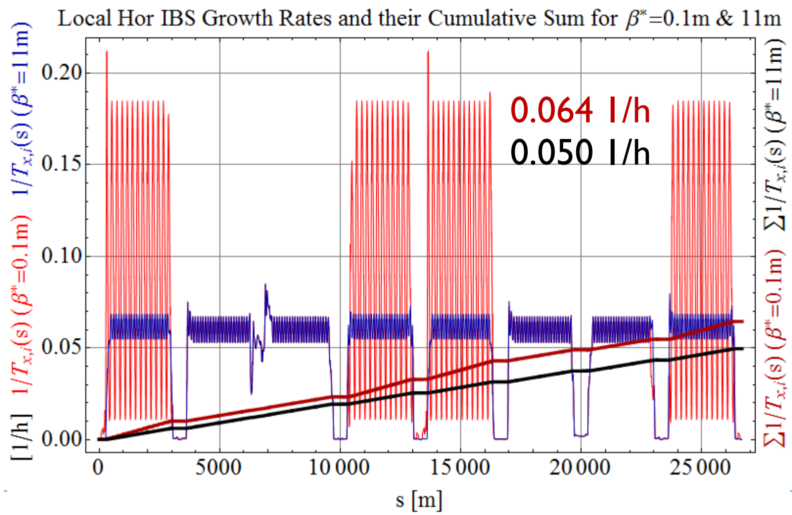


- in the 25ns case (red) the IBS is weaker, due to the relaxed beam parameters
- longitudinal the cumulative sum increases approx. linear
  - spikes are quite narrow
  - the contribution to the total growth rate is similar for all elements
- the local horizontal growth rates are increased for the high β-regions in the arcs around IP1&5, while the contribution of the straight sections is almost zero, due to the small dispersion
- the vertical growth is very small and negative (damping)

Local contributions of the IBS Growth

Compare $\beta^* = 11\text{m}$ and $\beta^* = 0.1\text{m}$ (optics file 1 and 31) for 50ns case

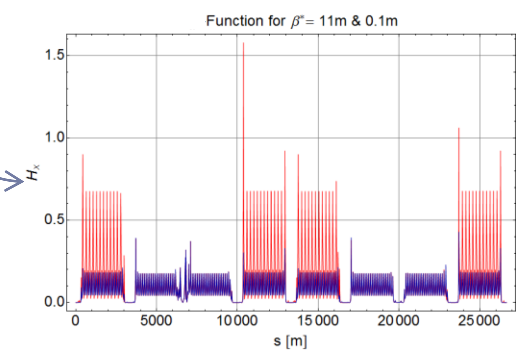




- longitudinal the squeeze slows down the IBS growth
- while the growth rates increase in the transverse planes (see next slide), due to the strong contribution of the arcs around IP1&5

$$\begin{pmatrix} \frac{1}{\tau_x} \\ \frac{1}{\tau_l} \\ \frac{1}{\tau_y} \end{pmatrix} = A \left\{ \begin{matrix} \frac{\gamma^2 H_x}{\epsilon_x} \\ \frac{\gamma^2}{\sigma_\delta^2} \\ \frac{\beta_y}{\epsilon_y} \end{matrix} \right\} \int_0^\infty \left(\frac{\lambda^{1/2}}{(\lambda^3 + a\lambda^2 + b\lambda + c)^{3/2}} \left\{ \begin{matrix} [a_x\lambda + b_x] \\ [a_l\lambda + b_l] \\ [a_y\lambda + b_y] \end{matrix} \right\} d\lambda \right)$$

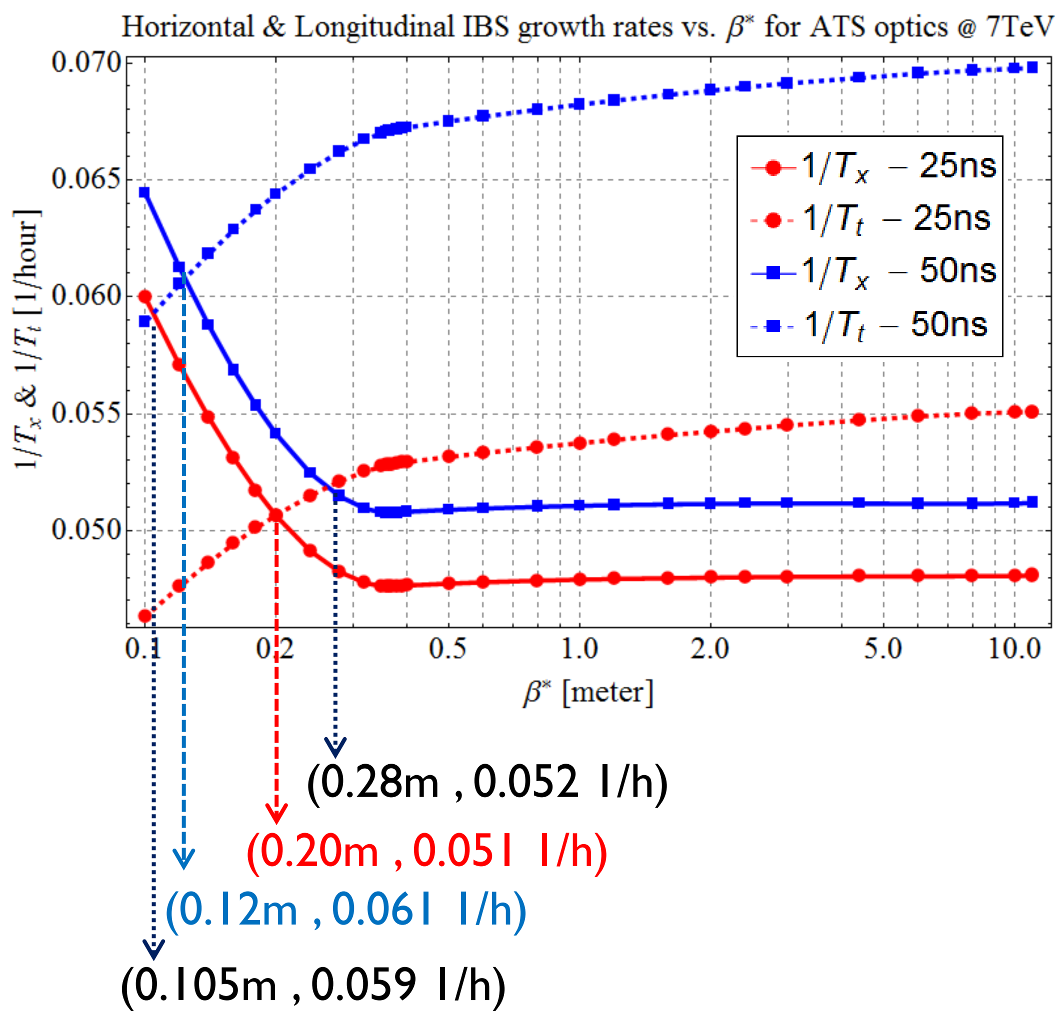
$$H_x = \frac{D_x^2}{\beta_x}(1 + \alpha_x^2) + \beta_x D_x'^2 + 2\alpha_x D_x D_x'$$



$$A = \frac{r_0^2 v_c N(log)}{8\pi\beta^3\gamma^4\epsilon_x\epsilon_y\sigma_\delta\sigma_z}$$

IBS Growth Rates vs. β^*, 7TeV

- longitudinal growth rate (dashed line) improves with smaller β^*
- horizontal growth rate (solid line) increases with β^* smaller ~0.4m
- vertical growth rate shows minimum at around 0.25m (plot in back up slides)



Conclusion

- Growth rates increase with increasing intensity and decreasing emittance.
  - Leading to stronger IBS effects for the beam parameters of the 50ns spacing.
  - IBS growth rates are higher at injection, due to the smaller longitudinal emittance
- Throughout the squeeze to low β with the ATS optics the longitudinal IBS growth rate improves (~20%), whereas the horizontal growth rate increases (~20%).
  - Calculations were done for a flat machine.
  - The increased IBS contribution in the horizontal plane of the high β regions in the arcs around IP1 & 5 lead to an increased accumulated IBS growth rate.
  - In this regions the average longitudinal IBS contribution is reduced

IBS growth times @ 7TeV for β^* = 0.1m in a flat machine

	25ns	50ns
Cases	2.2e11, 2.5μm, 7.5cm	3.5e11, 3μm, 7.5cm
$T_{IBS,l}$ [hour]	21.6	17.0
$T_{IBS,x}$ [hour]	16.7	15.5
$T_{IBS,y}$ [hour]	-6.3624×10^5	-5.9841×10^5

Benchmark Case Proposal

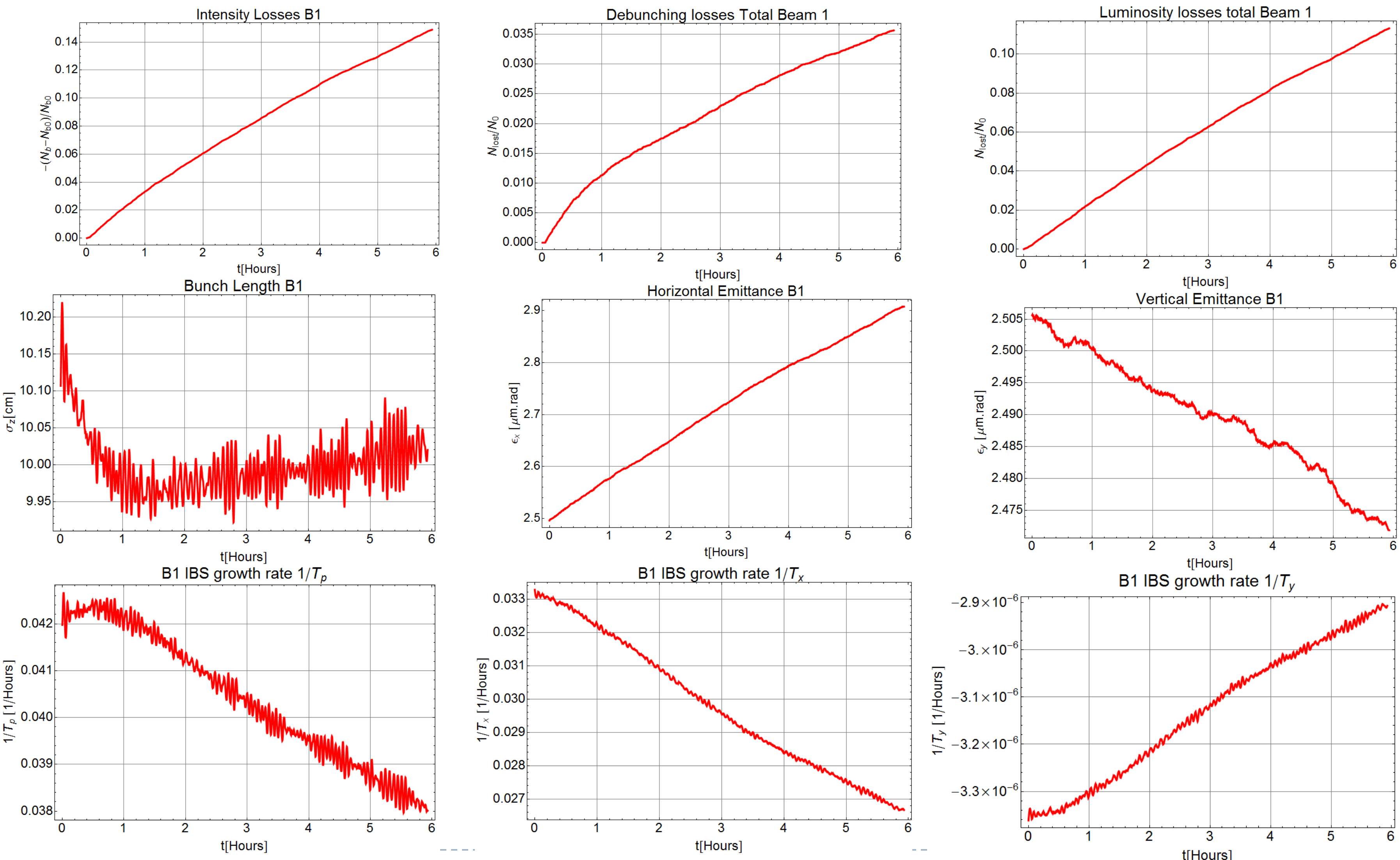
- Beam parameters from 2012 simulations to compare with reality:

$$\varepsilon_N = 2.5\mu m$$
$$N_b = 1.6 * 10^{11} \text{ ppb}$$
$$\sigma_t = 1.35ns = 10.1cm$$
$$\beta^* = (0.6, 3, 0.6, 3)m$$
$$\frac{\theta_c}{2} = 142\ \mu rad$$

nominal optics
V6.503

Beam	1.6e11, 2.5μm, 1.35eVs	
Program	CTE	MADX
$T_{IBS,l}$ [hour]	23.8	27.7
$T_{IBS,x}$ [hour]	30.1	29.3
$T_{IBS,y}$ [hour]	-2.98×10^5	2.43×10^3

Beam Evolution of the Benchmark Case



Plans for the future…

- Simulations with CTE for ATS optics
- Calculations and Simulations based on the SLHC optics (SLHCV3.1b)
  - IBS growth rates at injection and in physics
- Redo the calculations with MADX shown in this presentation with bumps and crossing angles in the machine
  - CTE does not use this information in the IBS calculations

BACK- UP

Collider Time Evolution (CTE) Program

Processes taken into account:

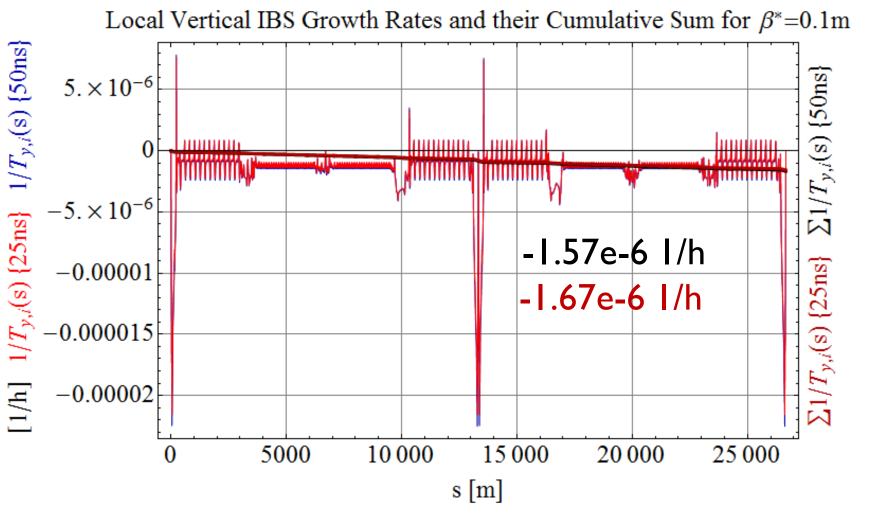
- COLLISIONS
  - user can choose between 2 collision routines:
    - very slow, integrates interaction probability for every particle by sorting particles in opposing beam in discrete bins. **No assumptions on the shape of the beam distribution**.
    - fast routine, **assumes Gaussian transverse distribution**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

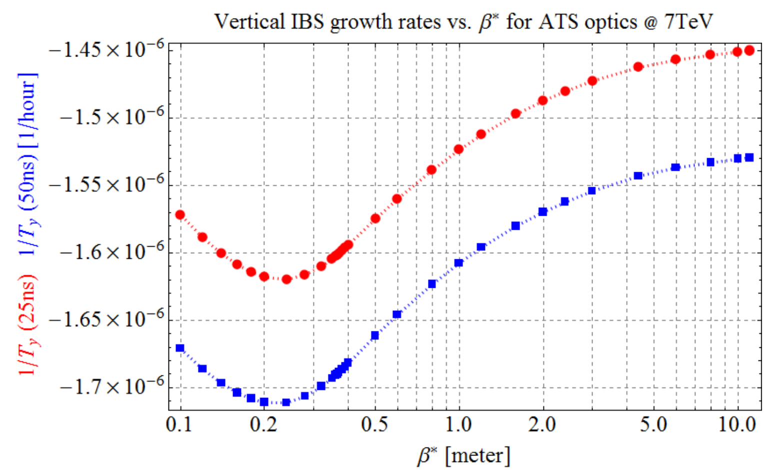
Collider Time Evolution (CTE) Program

- 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

IBS Growth in the Vertical Plane





- vertical IBS growth rate very small and negative (damping)
- calculations done for flat machine
- if x-angle and vertical dispersion is introduced this behaviour may not be realised any more!