FCC week 2016

Beam parameters evolution and luminosity performance

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Acknowledgements :
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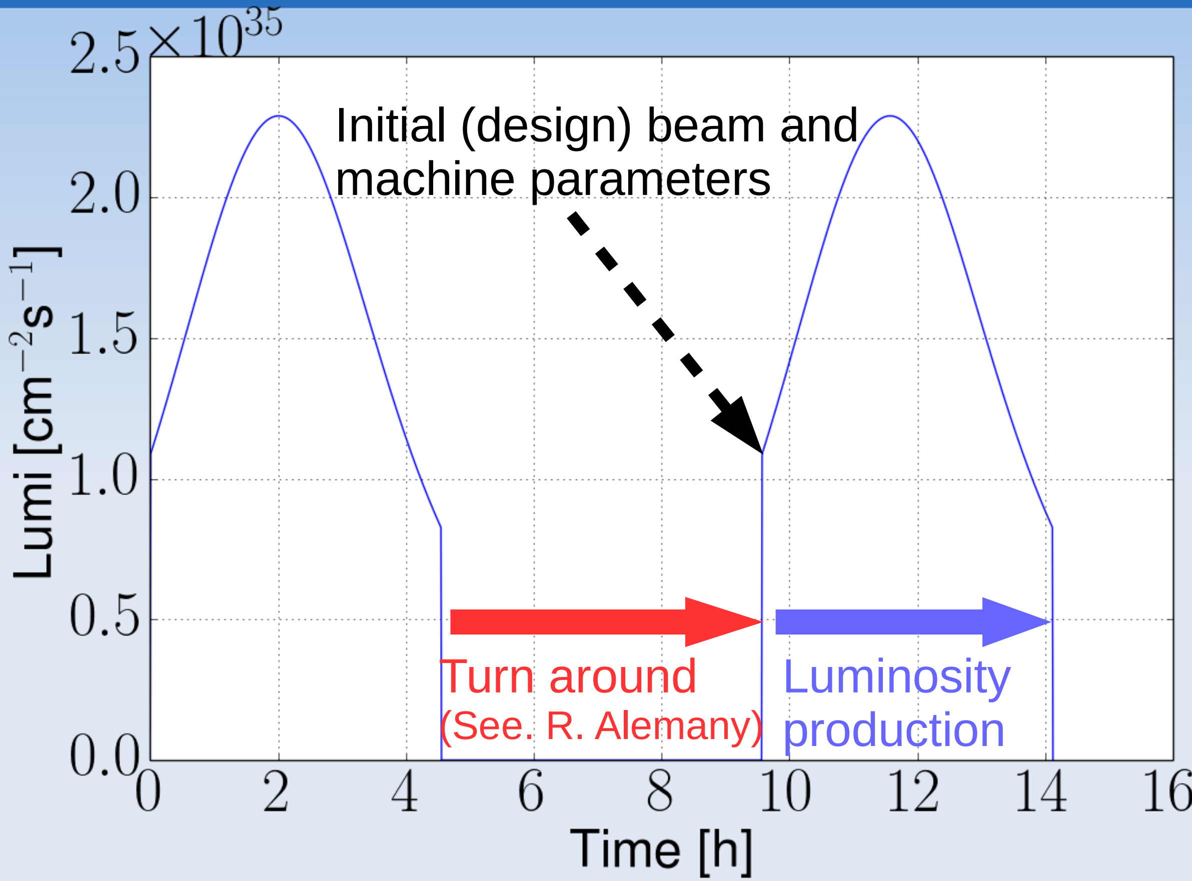
Content

- Beam parameter evolution model
  - Synchrotron radiation
  - Intrabeam scattering
  - Luminosity
  - Bunch length
  - Beam-beam
- Performance estimation
  - Lifetimes
- Conclusion

Introduction

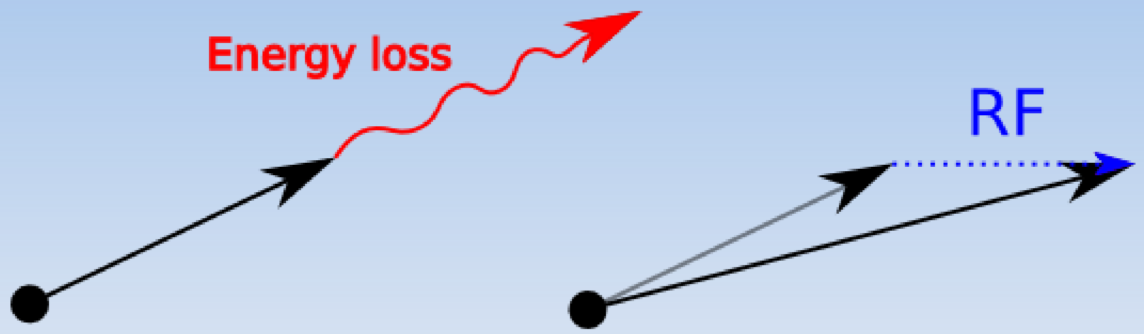


Parameter	Baseline
Energy [TeV]	50
Length [km]	100
Bunch intensity [p]	10^{11}
Normalised emittance [μm]	2.2
Nb. bunches	10'600
Bunch length [cm]	8
Momentum spread	1.1 10^{-4}
Maximum ξ_{tot}	0.01
Turn around [h]	5
Number of IPs	2 (4)
β* [m]	1.1 (0.3)*
Long-range beam-beam separation [σ]	12

- Target performance :
  - Baseline : 2 fb^{-1}/day
  - Ultimate : 8 fb^{-1}/day
- 2 High luminosity experiments are considered → Keep a margin for 2 lower luminosity experiments

- *We consider the current optics design with β* = 0.3 m (See R. Martin)

Synchrotron radiation



- Energy loss per turn : $$\Delta E = \frac{e^5}{3\epsilon_0 (m_p c^2)^4} \frac{E_0^4}{r_b} \approx 4.4 \text{ [MeV]}$$
- Transverse radiation damping rate : $$\tau_{rad} = \frac{\Delta E}{E_0} \approx 1.1 \cdot 10^7 \text{ [turn]} \approx 1 \text{ [h]}$$

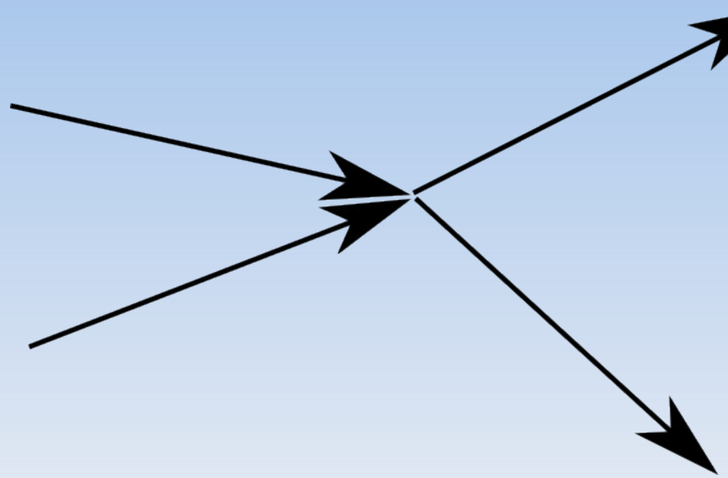
  Twice faster in the longitudinal plane

  $T_{LHC} \approx 10^9$ [turn] ≈ 26 [h] $T_{DA\Phi NE \text{ (w/o wiggler)}} \approx 3.6\ 10^5$ [turn]≈ 0.1 [s]

- Natural lattice emittance :
  (FODO cell with 90º phase advance and θ=360/45º bending angle per cell) $$\epsilon_{x,equ} = 2\sqrt{2}\frac{55\hbar}{32\sqrt{3} m_p c}\gamma^2\theta^3 \approx 0.04 \text{ } [\mu\text{m}]$$
  - Vertical and longitudinal emittances are limited by other effects (see later)

$= \varepsilon_{x,0} / 55$

Intrabeam scattering



- IBS growth rates are a complex function of the lattice parameters
  - Bjorken-Mtingwa algorithm (MAD-X) with Lattice V5 and baseline beam parameters :

$T_{IBS,x,0} = 361$ [h]
$T_{IBS,y,0} \approx 0$ [h]
$T_{IBS,l,0} = 1504$ [h]

- Scale with initial parameters :

$$\frac{\partial \epsilon_x}{\partial t}(t) = \frac{1}{\tau_{IBS}} \frac{I(t)}{I_0} \frac{\epsilon_{x,0}\epsilon_{y,0}\epsilon_{s,0}}{\epsilon_x(t)\epsilon_y(t)\epsilon_s(t)}$$

Luminosity

$$\mathcal{L}_{IP}(t) = \frac{n_b f_{rev} N(t)^2 \gamma_r}{4\pi\beta^*(t)\sqrt{\epsilon_x(t)\epsilon_y(t)}} \frac{cos(\phi(t))^2}{\sqrt{1+\frac{\sigma_s^2}{\sigma_t(t)^2} tan\left(\frac{\phi(t)}{2}\right)^2}}$$

- Hour glass is neglected since $\beta^* >> \sigma_s$
- Luminosity burn off : $\frac{\partial I}{\partial t}(t) = -\sum_{IP} \mathcal{L}_{IP}(t) \frac{1}{n_b} \sigma_{tot}$

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= 0 with crab cavities

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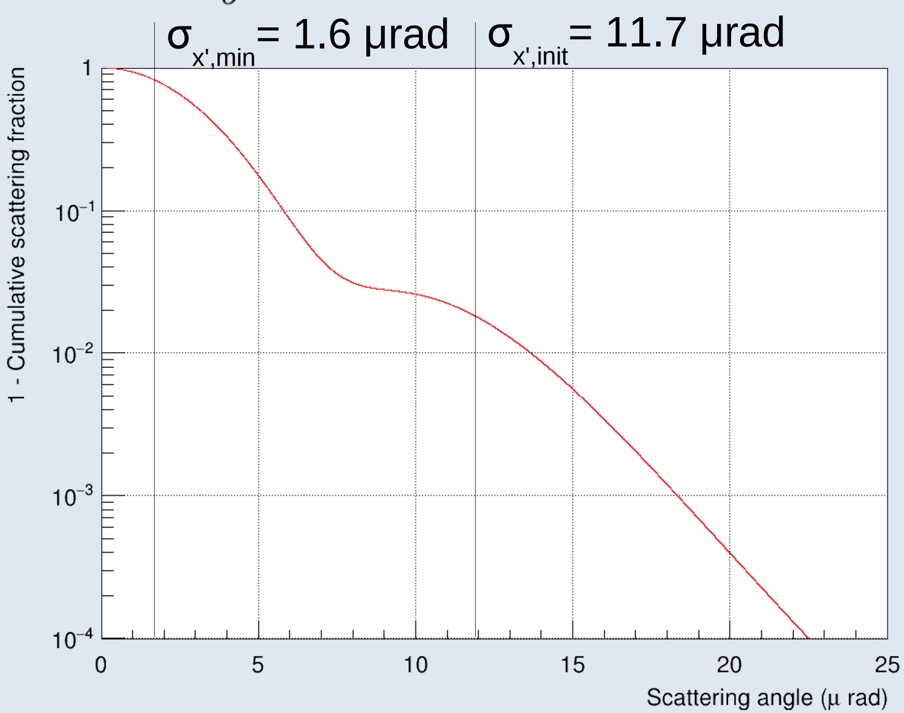

J. Molson, Proton scattering and collimation for the LHC and LHC luminosity upgrade, PhD Thesis, University of Manchester

Luminosity

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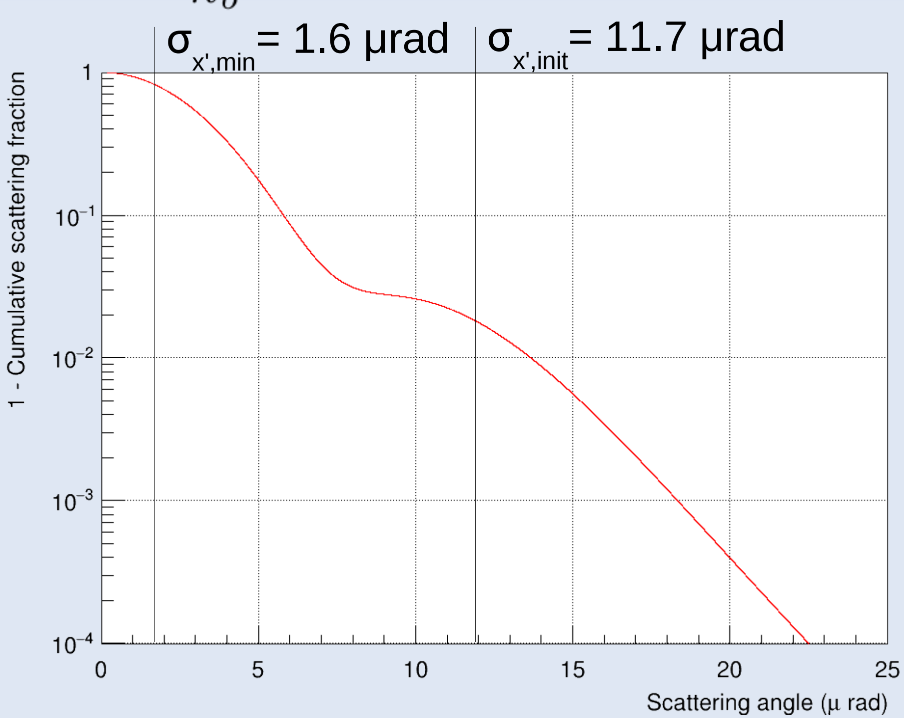
- Hour glass is neglected since $\beta^* >> \sigma_s$
- Luminosity burn off : $\frac{\partial I}{\partial t}(t) = -\sum_{IP} \mathcal{L}_{IP}(t) \frac{1}{n_b} \sigma_{tot}$
- σ_{el} = 45 mb
- The scattering angles are smaller than the initial beam divergence at the interaction point

  → No losses and negligible emittance growth

$$\frac{\partial \epsilon}{\partial t} = \sum_{IP} \frac{1}{2} \frac{L \sigma_{el}}{N_b n_b} \theta_{rms}^2 \beta^* \approx 0$$

- For smaller transverse emittances (end of the fill), only a fraction of the beam is lost
- Conservatively assume $\sigma_{tot} = \sigma_{in} + \sigma_{el}$ =153 mb



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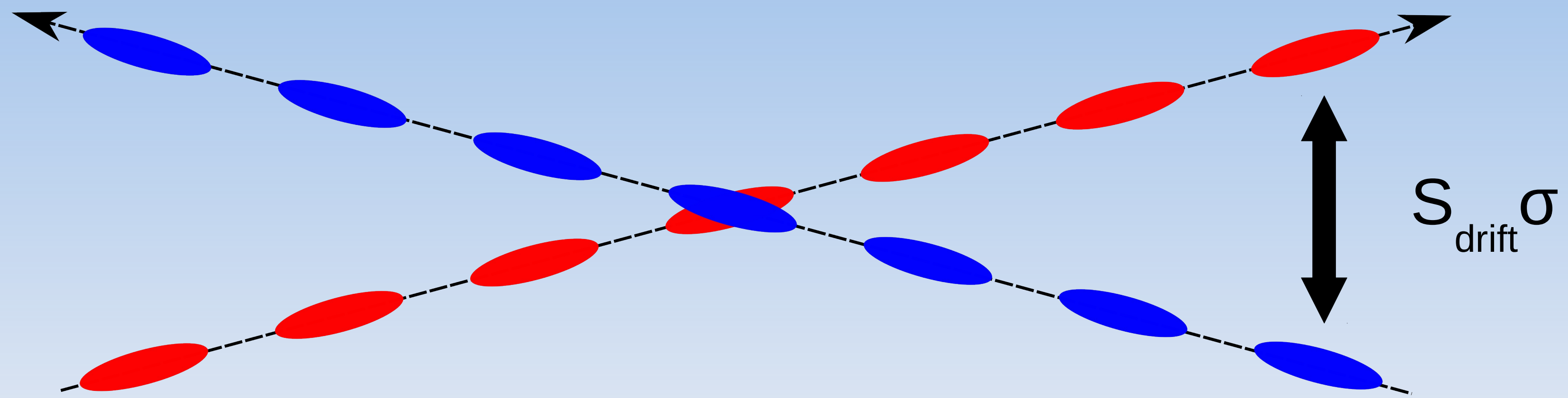
Bunch length

- The longitudinal emittance damping time due to synchrotron radiation is much faster (0.5 h) than the growth mechanisms (Quantum excitation, IBS, RF noise)
  - Longitudinal stability → $\varepsilon_s \propto$ (bunch intensity)$^{2/5}$
  - Other stabilizing mechanisms in the longitudinal plane, e.g. Landau cavities?

  → Bunch length would be limited by
    - Intrabeam scattering
    - Beam induced heating ($\sigma_s \propto$ bunch intensity)
    - Transverse stability (stabilised by head-on beam-beam tune spread ?)
    - Luminous region width

$$\sigma_{\mathcal{L}} = \frac{\sigma_s}{\sqrt{2\left(1+\phi_p^2\right)}}$$

Beam-beam



- Beam-beam limitations are a complex function of the beam parameters and interaction region design → Two simplified design constrains
  - $\xi_{tot} < 0.01$ (ultimate : $\xi_{tot} < 0.03$)

    Assume alternating crossing angle / round beams

$$\xi_{tot} = \sum_{IP} \frac{N r_0}{4\pi\epsilon} \frac{1}{\sqrt{1 + \frac{\sigma_s^2}{\sigma_t^2} tan\left(\frac{\phi}{2}\right)^2}}$$

  - $S_{drift} = 12$

    See J. Barranco, T. Pieloni

$$\phi(t) = \sqrt{\frac{\epsilon_x(t)}{\beta^*(t)\gamma_r}} S_{drift}$$

Model

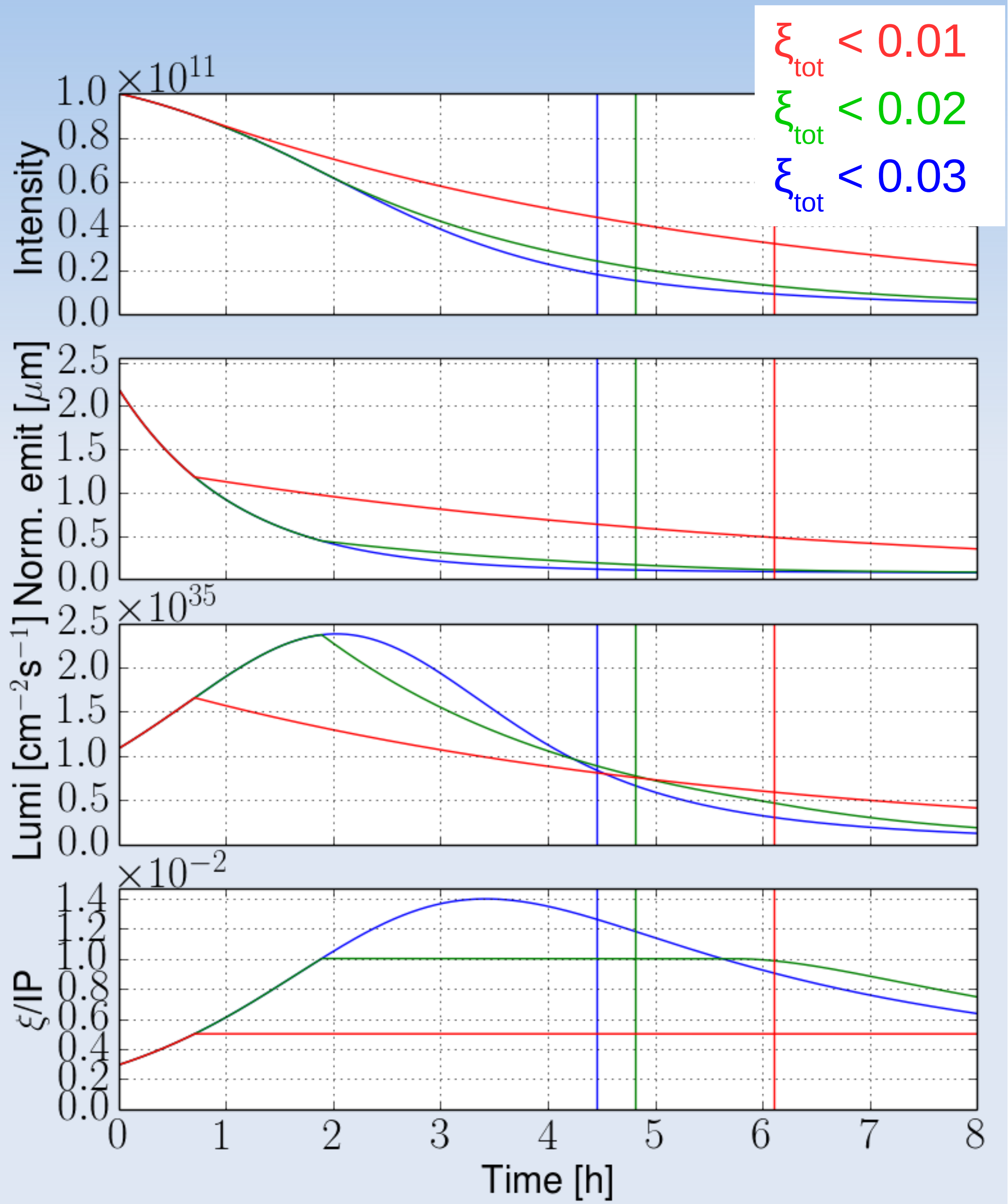
$$
\begin{cases}
\frac{\partial I}{\partial t}(t) & = -\frac{I(t)}{\tau_l} - \sum_{IP} \mathcal{L}_{IP}(t)\frac{1}{n_b}\sigma_{tot} \\
\frac{\partial \epsilon_x}{\partial t}(t) & = \frac{\epsilon_x(t)}{\tau_{\epsilon_x}} - \frac{\epsilon_x(t)}{\tau_{rad}} + \sqrt{\frac{2\epsilon_{x,equ}}{\tau_{rad}}} \\
 & + \frac{1}{\tau_{IBS}}\frac{I(t)}{I_0}\frac{\epsilon_{x,0}\epsilon_{y,0}\epsilon_{s,0}}{\epsilon_x(t)\epsilon_y(t)\epsilon_s(t)} \\
\frac{\partial \epsilon_y}{\partial t}(t) & = \frac{\epsilon_y(t)}{\tau_{\epsilon_y}} - \frac{\epsilon_y(t)}{\tau_{rad}} \\
\epsilon_s(t) & = \left(\frac{I(t)}{I_0}\right)^{\frac{2}{5}}\epsilon_{s,0} \\
\mathcal{L}_{IP}(t) & = \frac{n_b f_{rev} N(t)^2 \gamma_r}{4\pi\beta^*(t)\sqrt{\epsilon_x(t)\epsilon_y(t)}} \frac{cos(\phi(t))^2}{\sqrt{1+\frac{\sigma_s^2}{\sigma_t(t)^2}tan\left(\frac{\phi(t)}{2}\right)^2}} \\
\phi(t) & = \sqrt{\frac{\epsilon_x(t)}{\beta^*(t)\gamma_r}}S_{drift}
\end{cases}
$$

- $\xi_{tot} < 0.01$

Performance

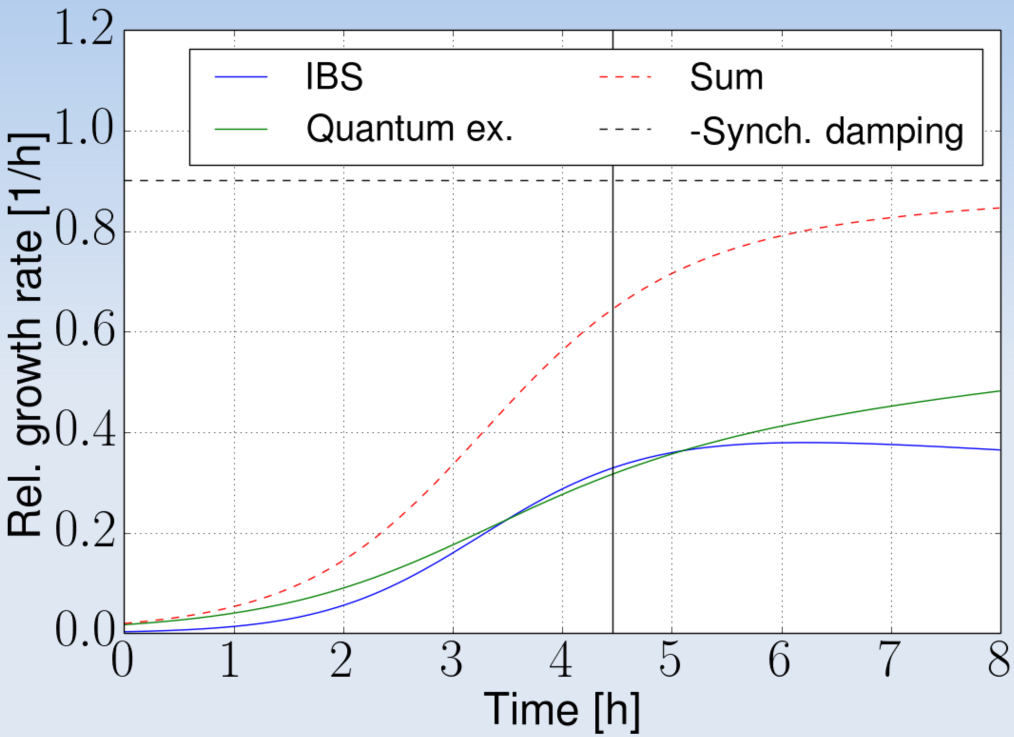
25 ns

- The optimal time in luminosity production is comparable to the turn around time
- Baseline performance : 2.3 fb^{-1}/day
  - With β* =0.3 [m]: 5.1 fb^{-1}/day
  - With $\xi_{tot} < 0.03$: 7.2 fb^{-1}/day
- The bunch length varies from 8 to 5 cm
- The crossing angle is adjusted from 140 to 30 μrad



Intrinsic sources of noise

- We assume that the beams from the injectors are round ($\varepsilon_x = \varepsilon_y$)
  - First, we assume that the beams are kept round during luminosity production (Coupling, controlled noise,...)
- The effect of IBS and quantum excitation are negligible with initial beam parameters

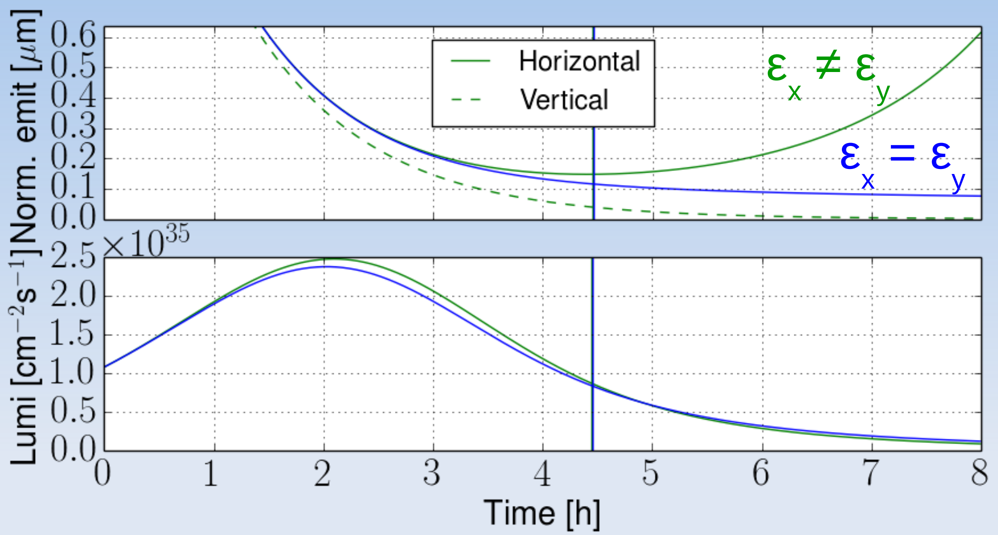


→ They become comparable to the synchrotron damping rate only after few hours

→ Difficult to design an optics that is optimal for both round and flat beams

Intrinsic sources of noise

- Letting the vertical emittance shrink leads to unequal beams after few hours
  - The shrinkage of the vertical leads to a blow-up of the horizontal emittance (IBS)



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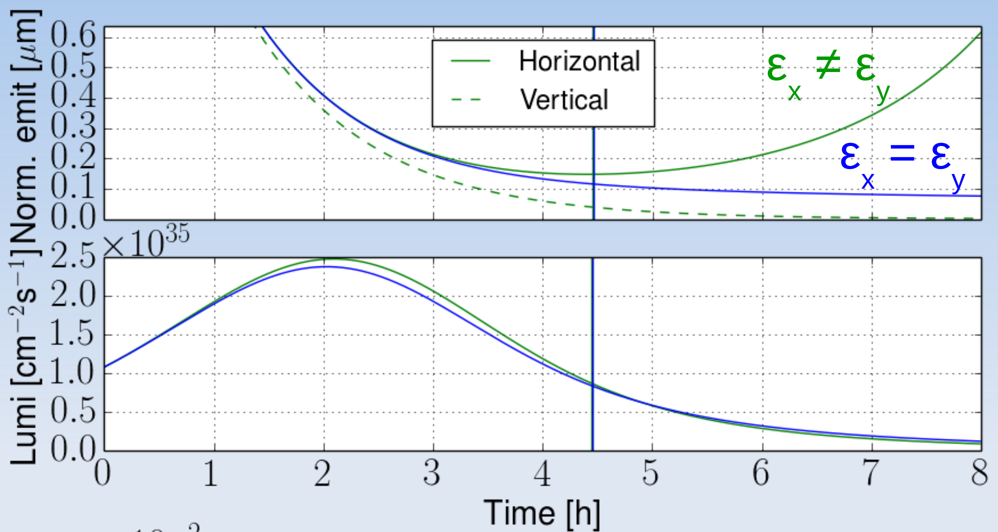
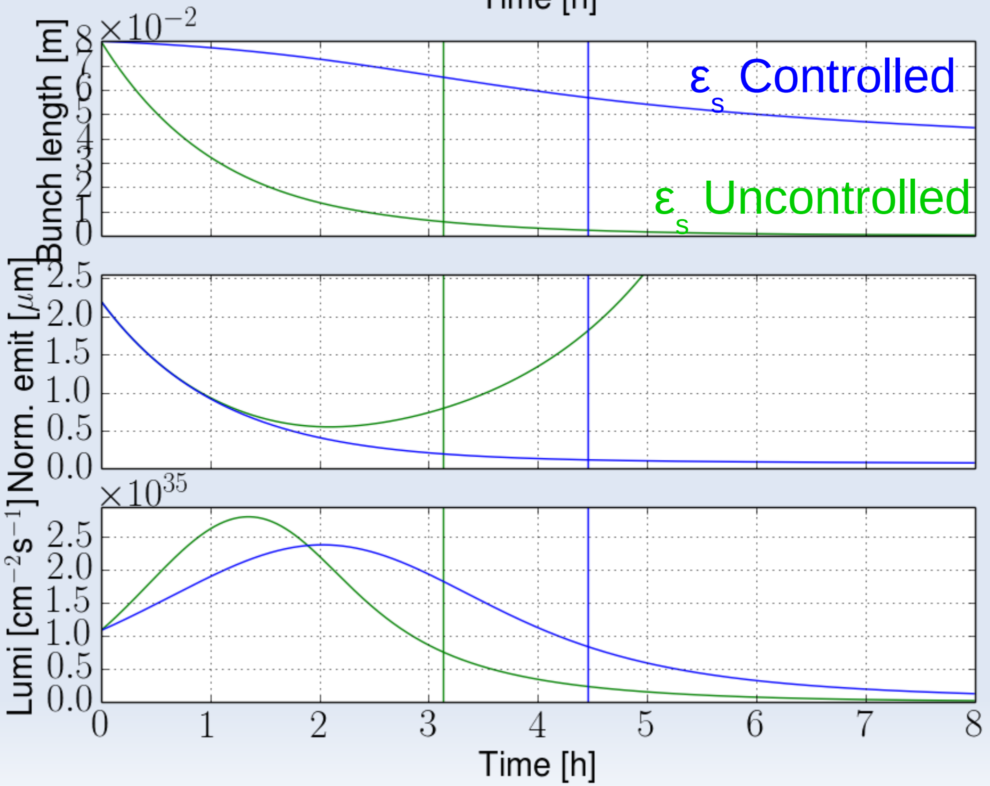


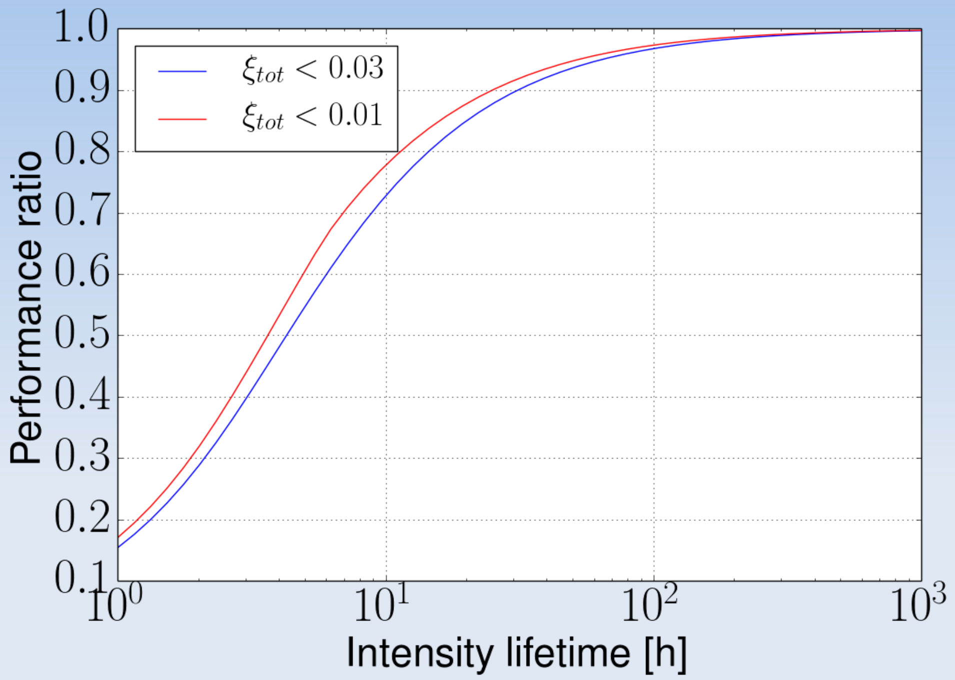
- Similarly, letting the longitudinal emittance shrink leads to a blow-up of the horizontal emittance (IBS)
  - The performance is reduced by 10%

→ Control of the longitudinal and vertical emittances is required



Lifetimes

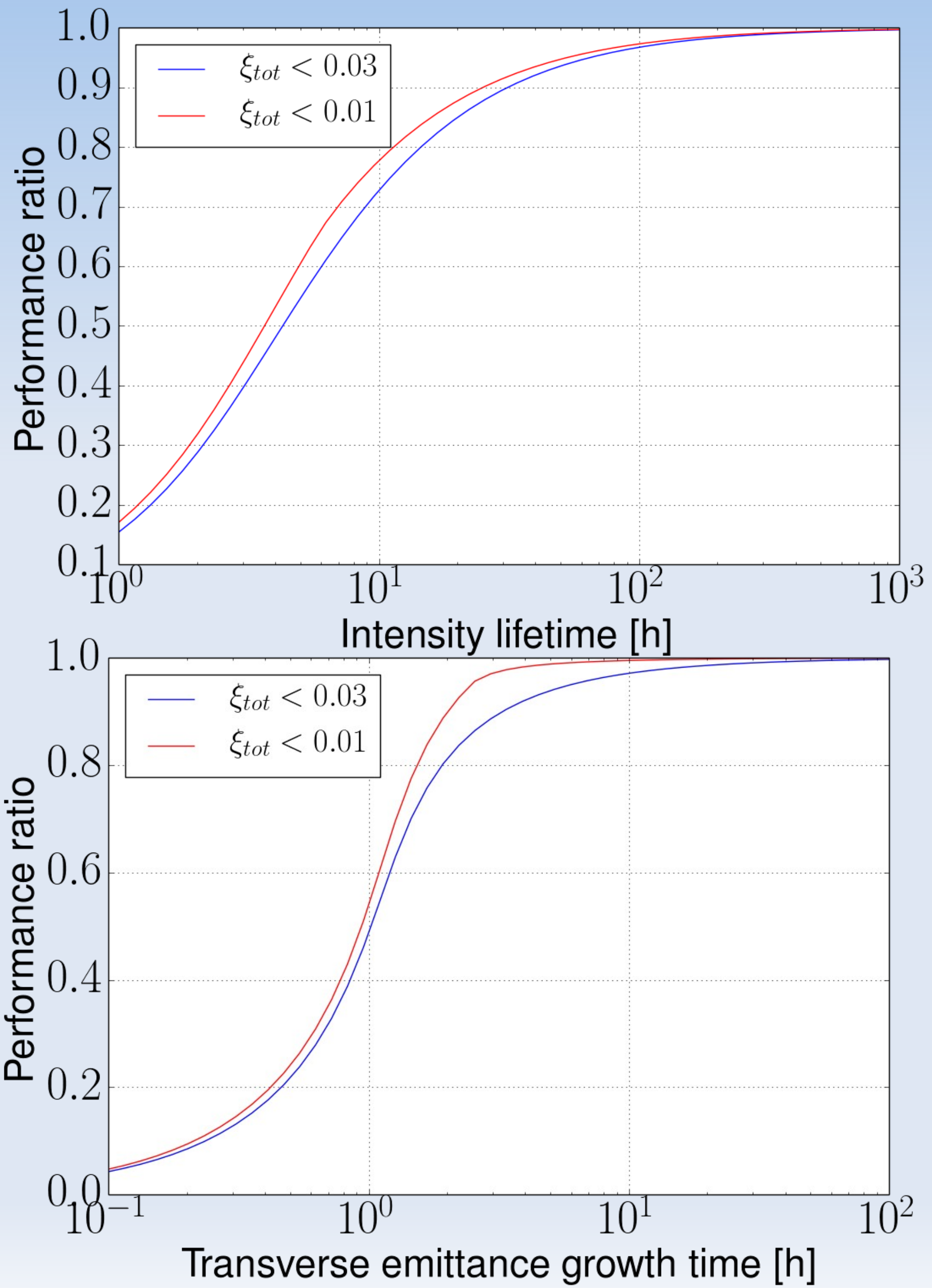
- Lifetime due to other loss mechanisms (Rest gas scattering, Touschek, non-linear diffusion, …) should be kept above ~20-30 hours



Lifetimes

- Lifetime due to other loss mechanisms (Rest gas scattering, Touschek, non-linear diffusion, …) should be kept above ~20-30 hours
- Emittance growth due to other mechanisms (Field ripple, ground motion, non-linear diffusion,...) should be kept above ~3-4 hours

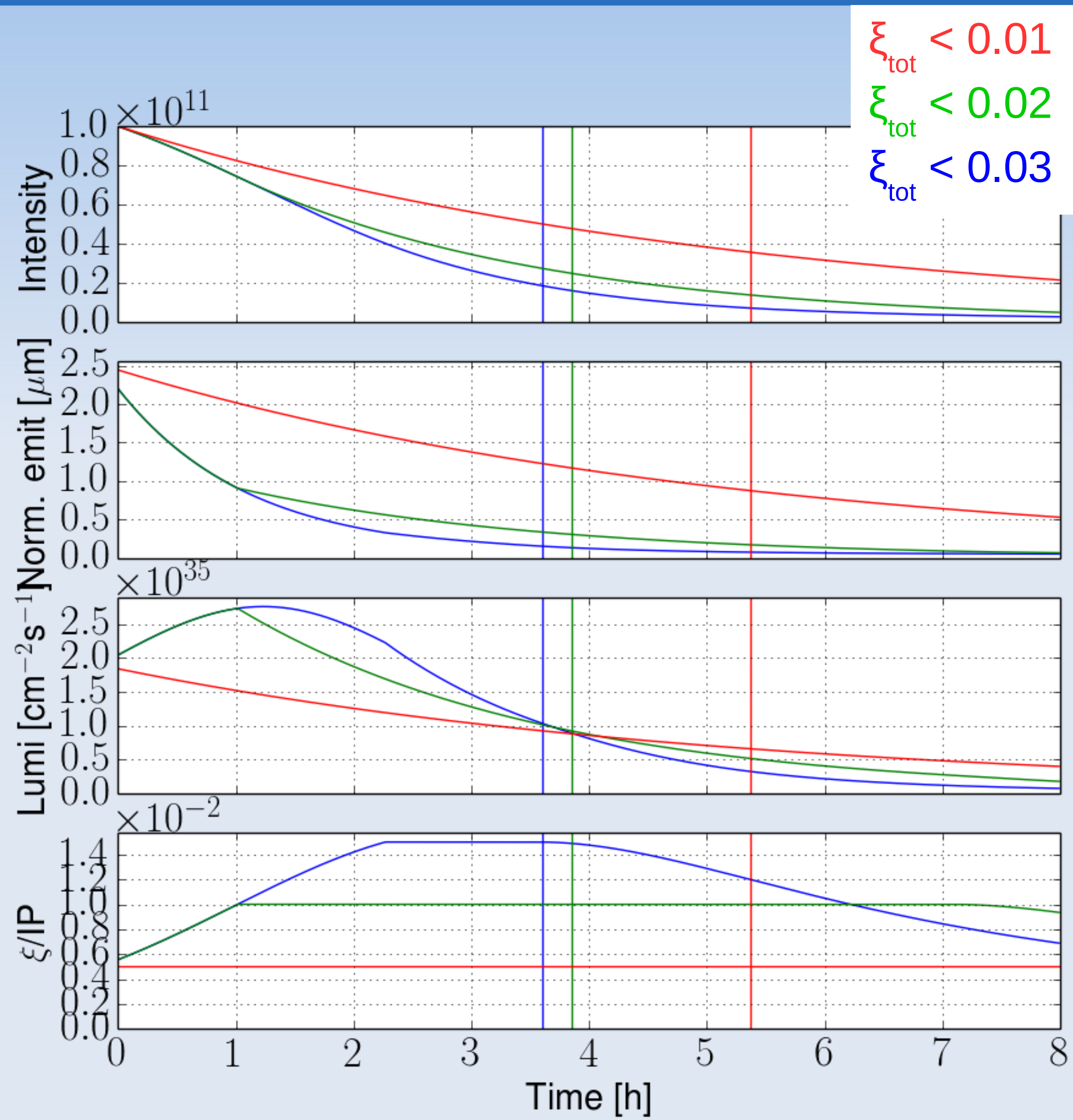
  → Tight constraints on external noise sources



Performance
Ultimate 25 ns

Configuration	Performance [fb^{-1}/day]
Baseline	2.3
+ β^*=0.3 m	5.2
+ xi < 0.03	7.2
+ Crab cavity	7.9
- 1h turn around time (→ Ultimate)	8.9

- Achieving large beam-beam parameter and fast turn around are a key for the ultimate scenario



Performance
Small β*

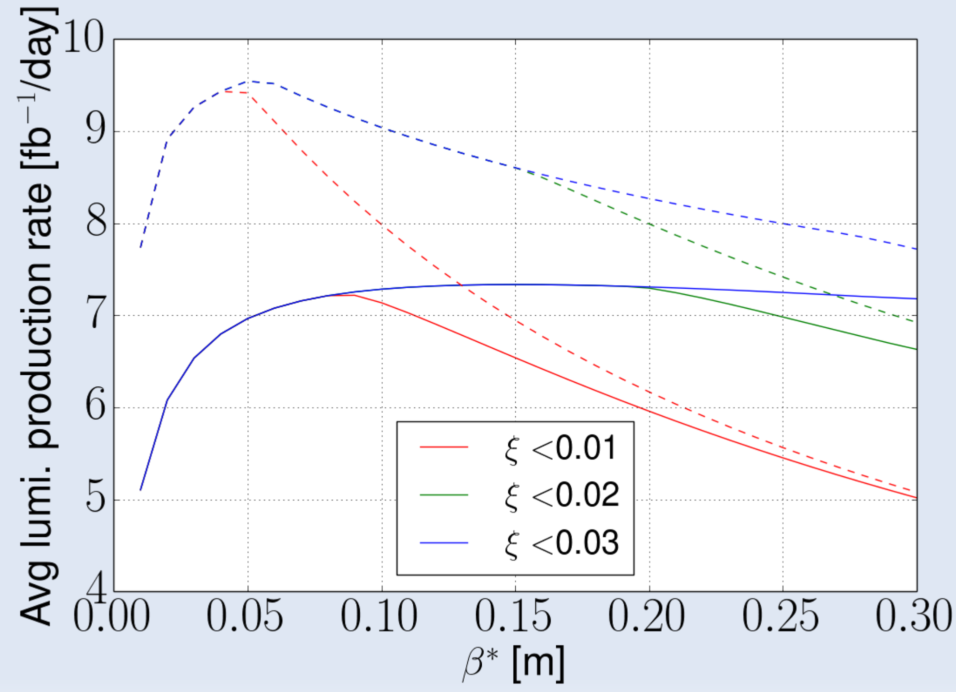
- Small β* are profitable in configurations limited by the beam-beam parameters
- Assuming large beam-beam parameters, the scenario w/o crab cavities is already saturated due to the geometric loss factor
  - Configurations with $\beta^*_x \neq \beta^*_y$ should be considered
- The β* could be adapted during the fill profiting from the larger aperture (smaller transverse emittance)

- Approximated estimation of the hourglass effect :

$$\mathcal{L} = \mathcal{L}_0 R_{HG}$$

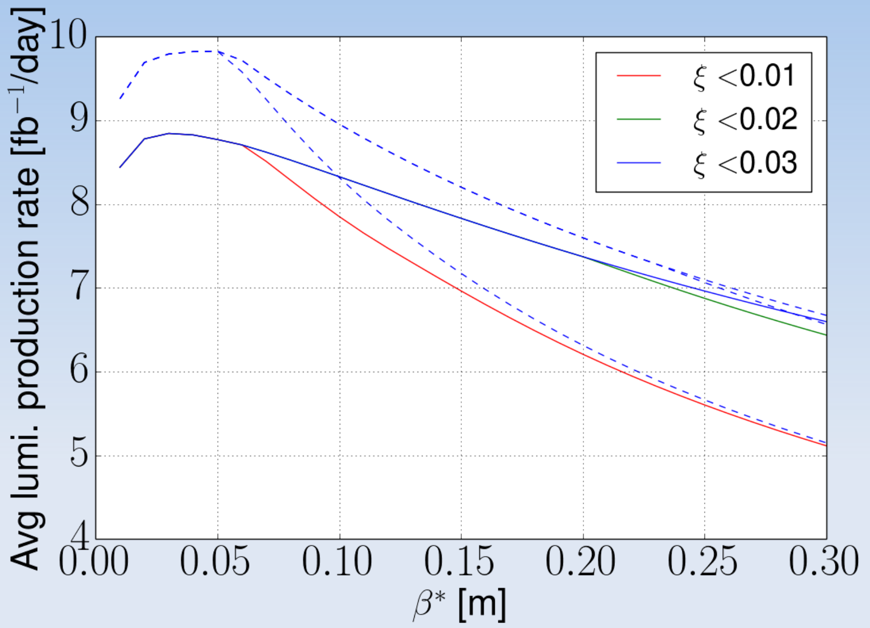
$$R_{\mathrm{HG}}(t) = \sqrt{\pi} r e^{r} \left(1 - \frac{2}{\sqrt{\pi}} \int_0^r e^{-x^2} dx\right)$$

$$r = \frac{\beta^*}{\sigma_s(t)}$$



Performance
Short bunches

- Assuming that the bunch length can shrink down to 1 cm, the configurations w/o crab cavities are no longer limited by the geometric factor



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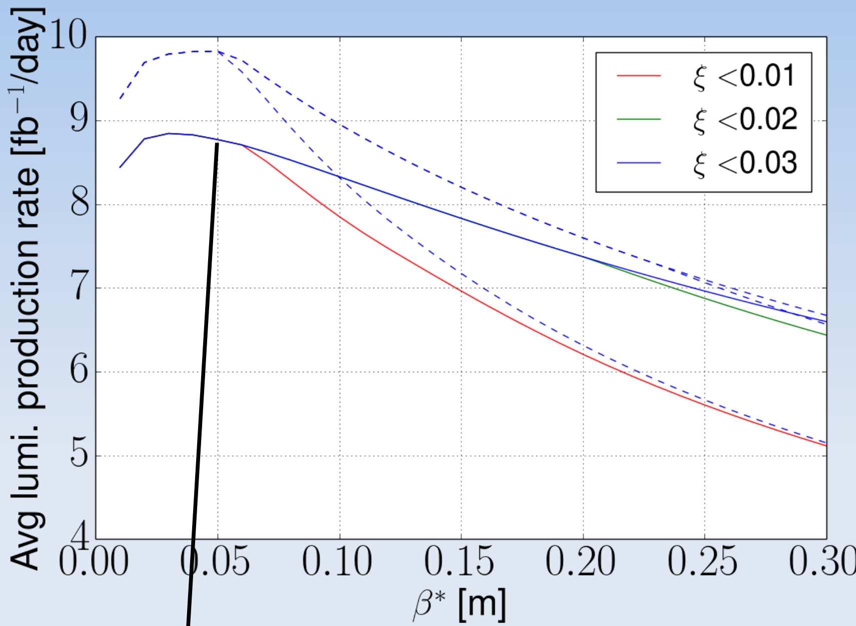
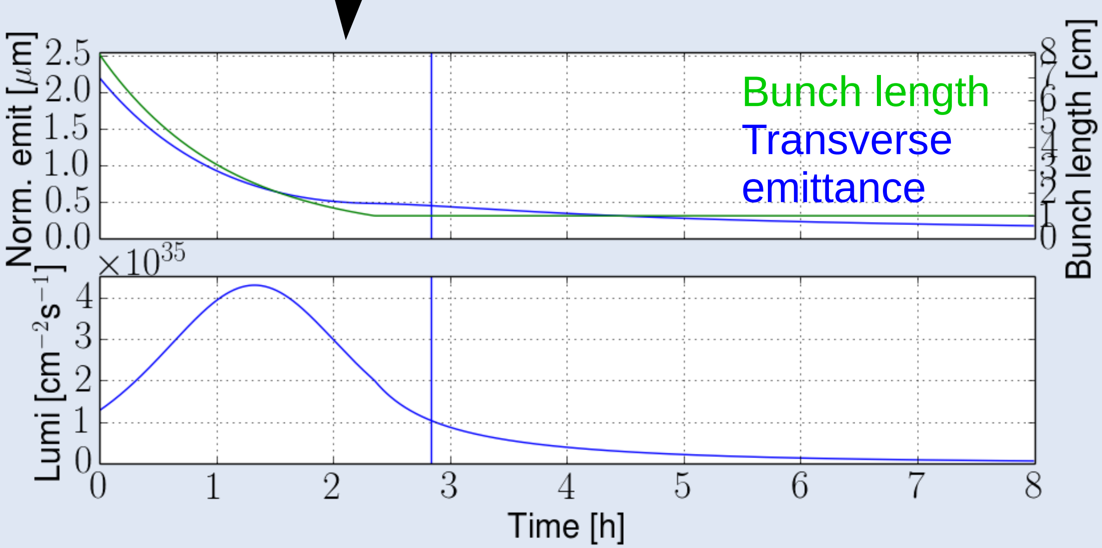
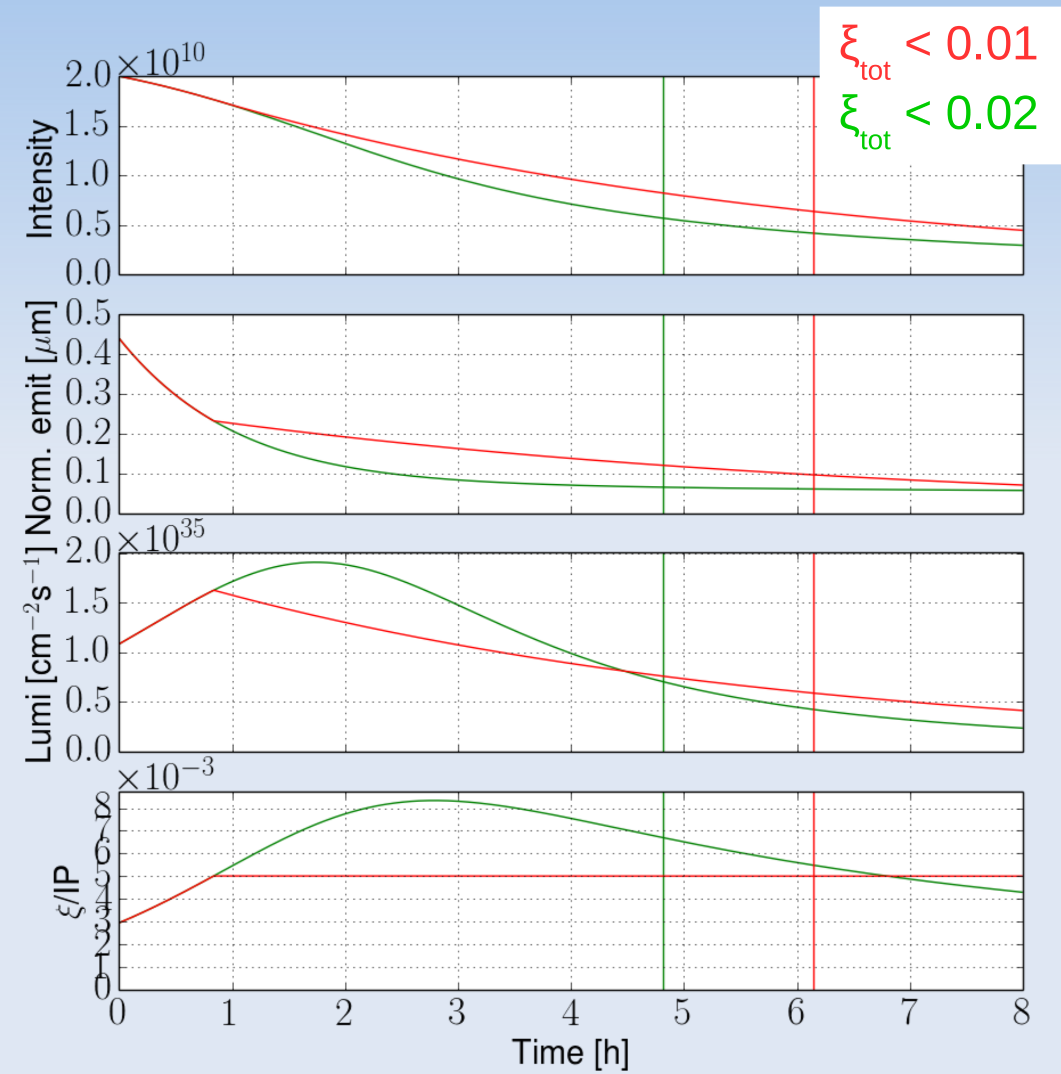


- A configuration with β* = 5 cm and σ_s > 1cm can achieve the ultimate performance without crab cavity and large beam-beam parameter



Short bunch spacing 5 ns

Parameter	Baseline 5 ns
Energy [TeV]	50
Length [km]	100
Bunch intensity [p]	$10^{11}/5$
Normalised emittance [μm]	2.2 /5
Nb. bunches	10'600*5
Bunch length [cm]	8
Momentum spread	10^{-4}
ξ_{tot}	0.01
Turn around [h]	5
Number of IPs	2
β* [m]	1.1 (0.3)
Long-range beam-beam separation [σ]	12

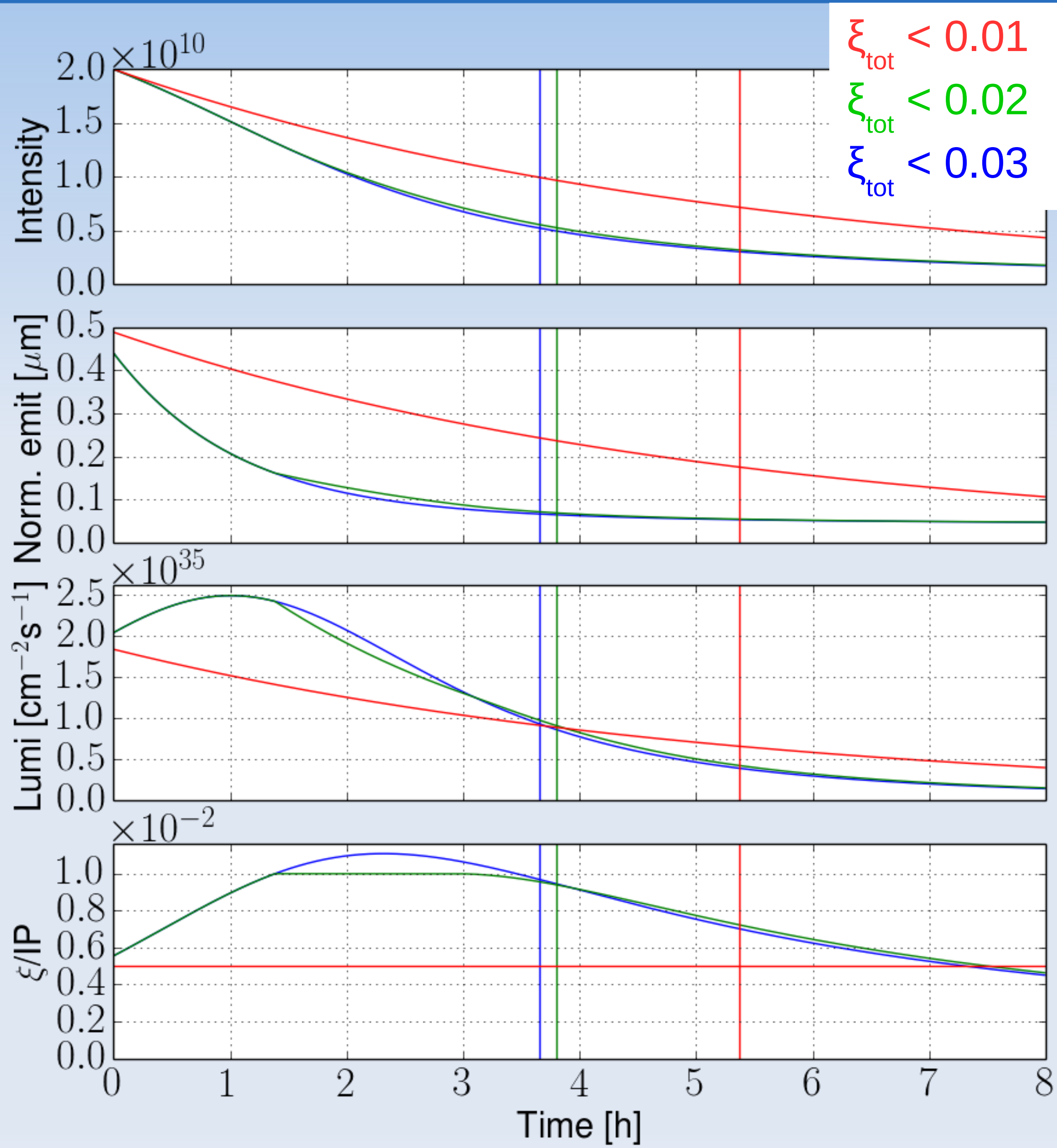


- Similar performance (5.1 fb^{-1}/day) can be achieved with the nominal 5 ns configuration

Short bunch spacing
Ultimate 5 ns

Configuration	Performance [fb^{-1}/day]	
	25 ns	5 ns
Baseline	2.3	2.3
+ β* = 0.3	5.2	5.1
+ xi < 0.03	7.2	6.0
+ Crab cavity	7.9	7.1
- 1h turn around time (→ Ultimate)	8.9	8.0

- Similar performance as for the 25 ns configurations
    - Ultimate configurations seems at the edge of the required performance



Conclusion

- The target performance is comfortably achieved within the baseline scenarios (5 and 25 ns)
  - $\beta^*=0.3$ [m] seems reasonable and offers a factor ~2 margin
  - Lower β^* may increase further the performance when coupled with mitigations of the geometric reduction factor (crab cavities or short bunches)

    → Input from the experiments is critical (e.g luminous region length)
  - Detailed studies of the beam-beam effects are required to define an optimal IR design ($\beta^*_x \neq \beta^*_y$, crossing scheme,...)
- Intrabeam scattering can lead to a strong blowup of the horizontal emittance because of the shrinkage of the vertical (or longitudinal) emittance

    → Dedicated control mechanisms are required
- In all scenarios, the performance could be jeopardized by an external source of emittance growth → Need to evaluate constraints on the noise sources
- The maximum performance saturates at around 10 fb^{-1}/day as the time spent colliding is smaller that the turn around time

Performance

Bunch intensity/Turn around

- The luminosity performance is close to linear with the bunch intensity
- The turn around time is a critical parameter, especially for high luminosity options