Beam parameters evolution and luminosity performance

X. Buffat, D. Schulte

Acknowledgements to B. Holzer, R. Martin, R. Thomas and S. White

Content

- Luminosity model
  - Synchrotron radiation
  - Intrabeam scattering
  - Beam-beam effects
  - Luminosity levelling
- Performance
  - Nominal
  - Ultimate 25 ns / 5 ns
- Conclusion

Model

$$
\begin{cases}
\dfrac{\partial I}{\partial t} & = & -\dfrac{I(t)}{\tau_{lifetime}} - \mathcal{L}_{IP}(t) N_{IP} \sigma_{tot} \\
\dfrac{\partial \epsilon_x}{\partial t} & = & -\dfrac{\epsilon_x(t)}{\tau_{rad,x}} + \alpha_{rad,x} + \dfrac{I(t)}{\epsilon_y(t)} \alpha_{IBS,x} \\
\dfrac{\partial \epsilon_y}{\partial t} & = & -\dfrac{\epsilon_y(t)}{\tau_{rad,y}} \\
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\mathcal{L}_{IP} & = & \dfrac{n_b f_{rev} N(t)^2 \gamma_r}{4\pi\beta^* \sqrt{\epsilon_x(t)\epsilon_y(t)}} \dfrac{cos(\phi(t))^2}{\sqrt{1+\frac{\sigma_s^2}{\sigma^2} tan(\phi(t))^2}}
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Lifetime

· Rest gas scattering
· Touschek
· Diffusion mechanisms
· ...

Model

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Lifetime

Luminosity burn off

In the following :

σ = 153•10^{-27} [cm^{-1}]

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Lifetime

Luminosity burn off

Synchrotron damping

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Longitudinal heating

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Quantum excitation

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Geometric reduction

Hourglass is neglected

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Lifetime

Luminosity burn off

Synchrotron damping

Longitudinal heating

Quantum excitation

IBS

Geometric reduction
Hourglass is neglected

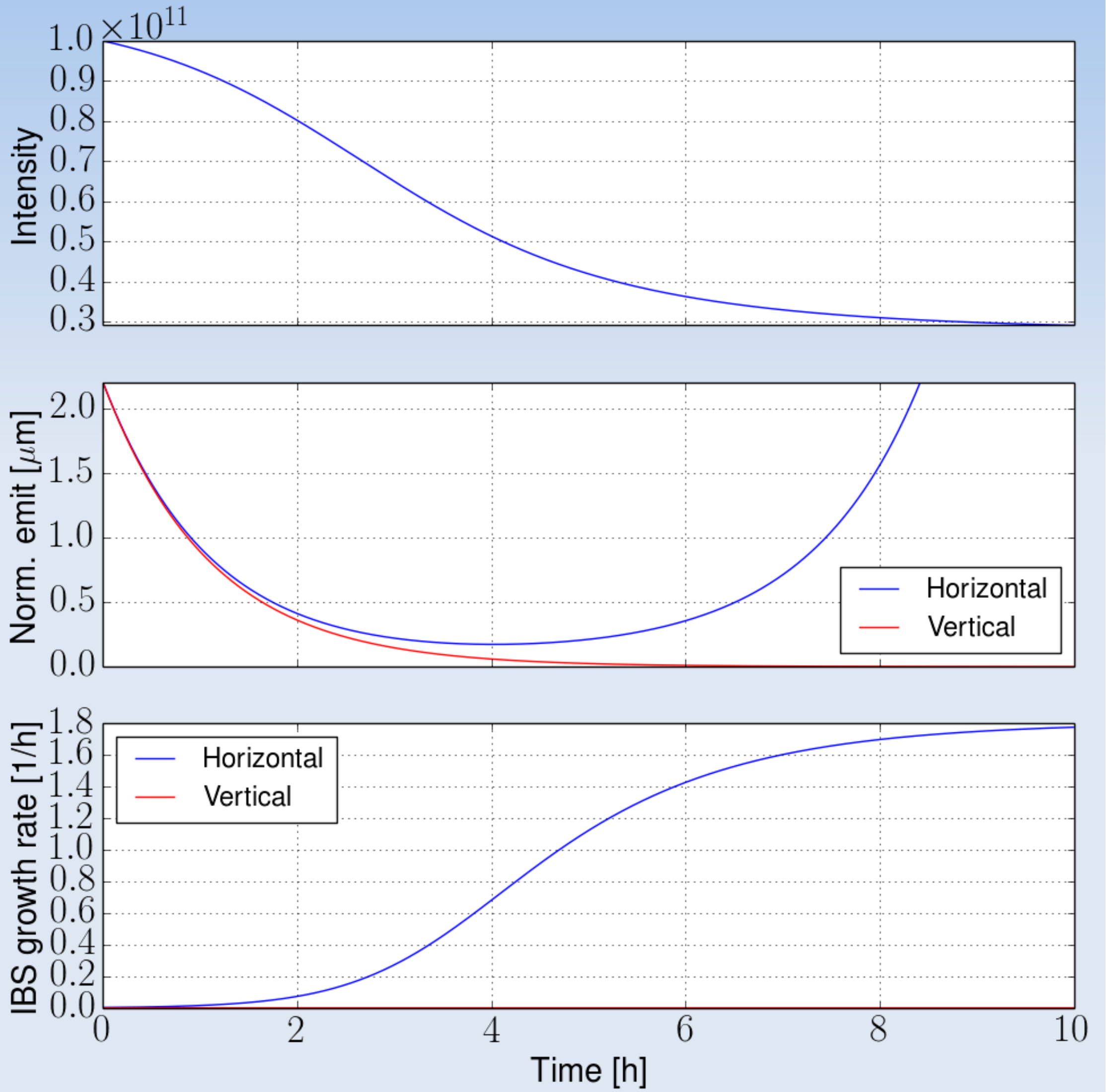
- The reduction of the transverse emittance will be limited by beam-beam effects
  - Assume transverse heating from BB such that $\xi_{tot} < 0.01$

Synchrotron radiation

- Radiation integrals computed with MAD-X (TOY lattice, 100km)
  - Energy loss per turn 4.2 [MeV/turn]
  - Emittance damping time : 1.1 [h]
  - Natural (normalized) emittance : 0.04 μm
    → 55 times smaller than the initial emittance
- Control of the longitudinal emittance is required to ensure the coherent stability
  - In the transverse plane, the coherent stability will be ensured by the amplitude detuning due to head-on beam-beam interactions
- All systems (instrumentation, cleaning, machine protection, ...) must be designed to cope with the large range of transverse emittances

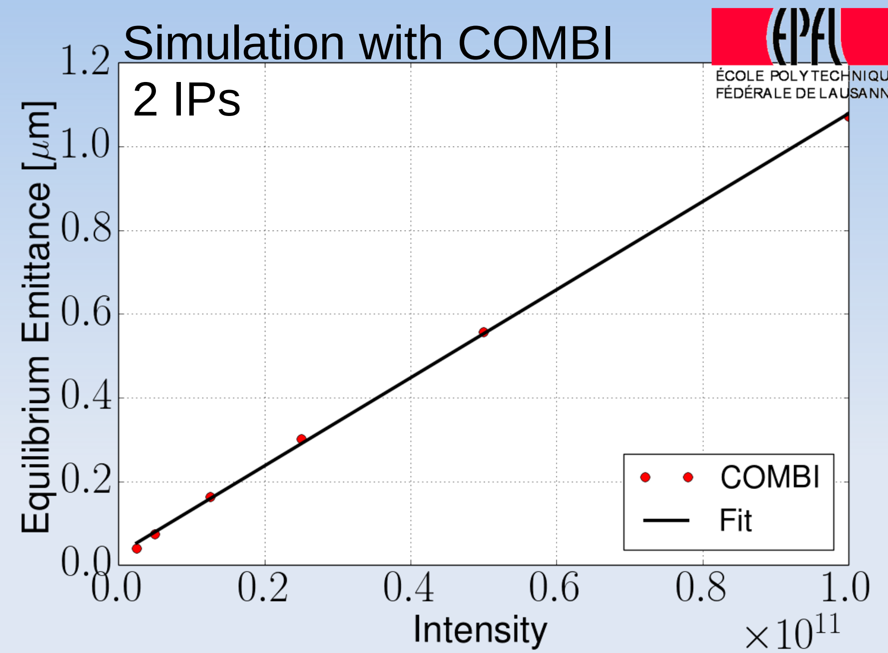
Intrabeam scattering

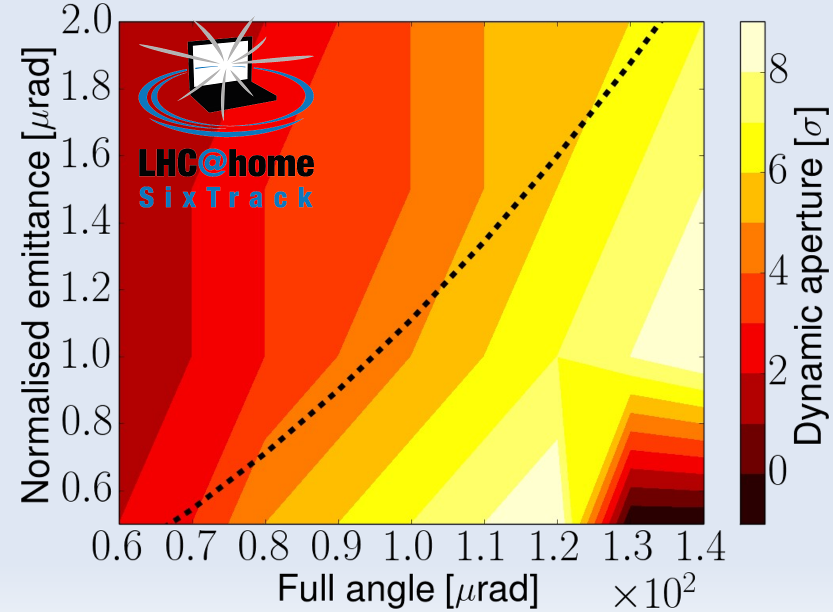
- Growth rate estimated with MAD-X (TOY lattice, 100 km)
- Negligible with initial beam parameters
- Overcomes synchrotron damping in the horizontal plane after few hours if the vertical emittance is uncontrolled
- The optimal scenario might rely on controlled, yet unequal emittances in the two planes
- Let us assume the vertical emittance is artificially blown up to keep round beams (External noise, coupling, …)



Beam-beam interactions

- The equilibrium emittance will be limited by beam-beam effects
- Preliminary estimates yield ξ_{lim}~0.02
  - Baseline assumes ξ_{lim}~0.01
  - Ultimate assumes ξ_{lim}~0.03
- Non-linearities of beam-beam interactions will limit the dynamic aperture
  - The crossing angle and β* could be adjusted during the fill according to the increased normalised physical aperture and increased dynamic aperture





Luminosity levelling

- The nominal scenario foresee a limitation of the luminosity at $5 \cdot 10^{34}$ (Ultimate : $2 \cdot 10^{35}$)

β*	Transverse offset at the IP	Transverse emittance
+ Small β* reached with large aperture margin + Reduced long-range beam-beam effect + Flexible - Operationally difficult (Optics + collimation control)	+ Easy to implement + Flexible (Reduction of the beam-beam tune shift)* **- Does not ensure coherent stability through head-on collision**	+ Easy to implement + Reduction of the beam-beam tune shift + Reduced IBS - Non local

- A combination of the techniques should not be excluded, e.g. one could level the luminosity with the transverse emittance and reduce the β* once the equilibrium emittance is reached

→ The choice will depend on the limiting factors

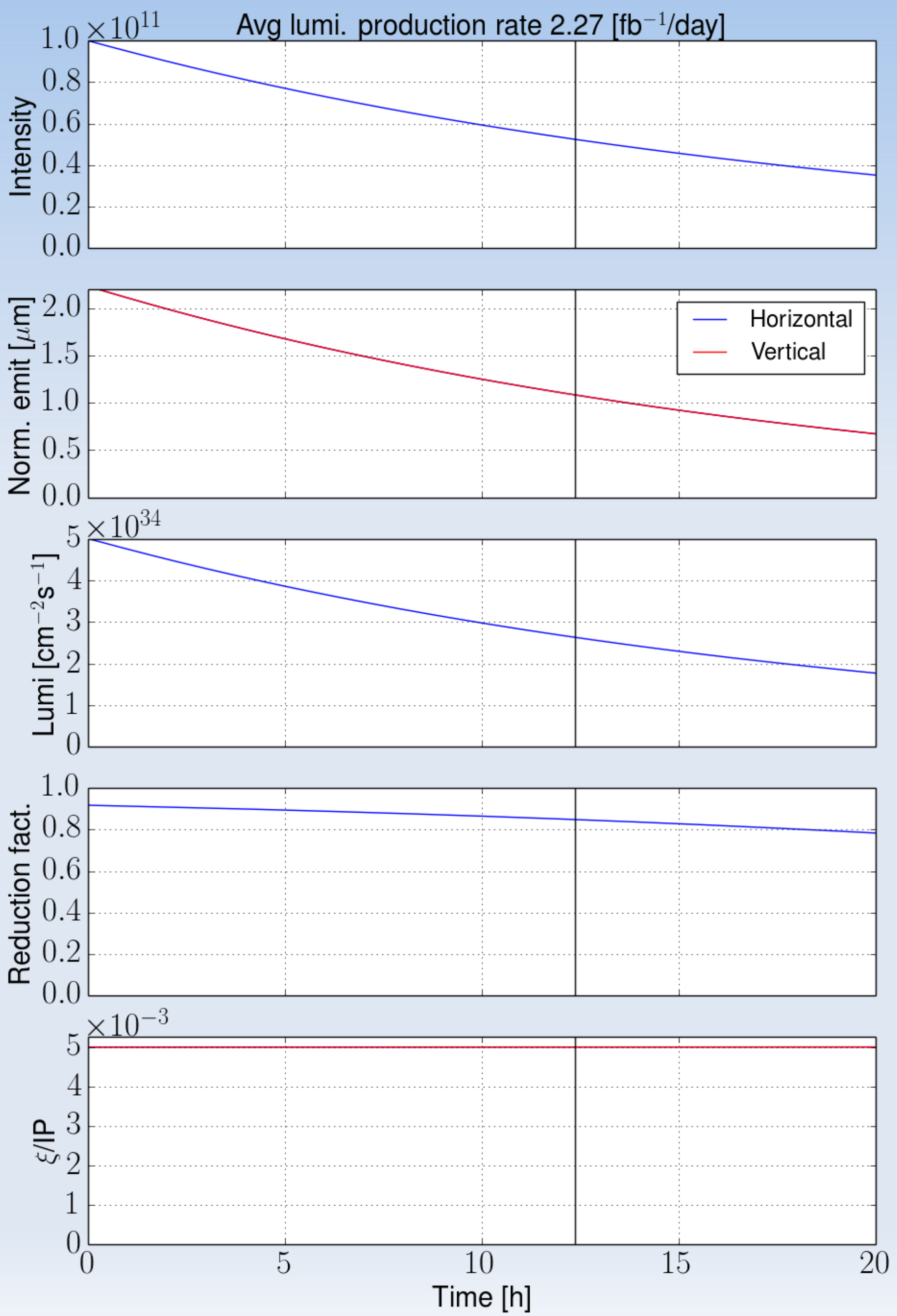
* Does not reduce beam-beam non-linearities → could lead to similar equilibrium emittance as with head-on collision

Nominal parameters

Parameter	Nominal
Energy [TeV]	50
Length [km]	100
Bunch intensity [p]	10^{11}
Normalised emittance [μm]	2.2
Nb. bunches	10'600
Target luminosity [$cm^{-2}s^{-1}$]	$5 \cdot 10^{34}$
Bunch length [cm]	8
ξ_{tot}	0.01
Turn around [h]	5
Number of IPs	2
β* [m]	1.1
Long-range beam-beam separation [σ]	12

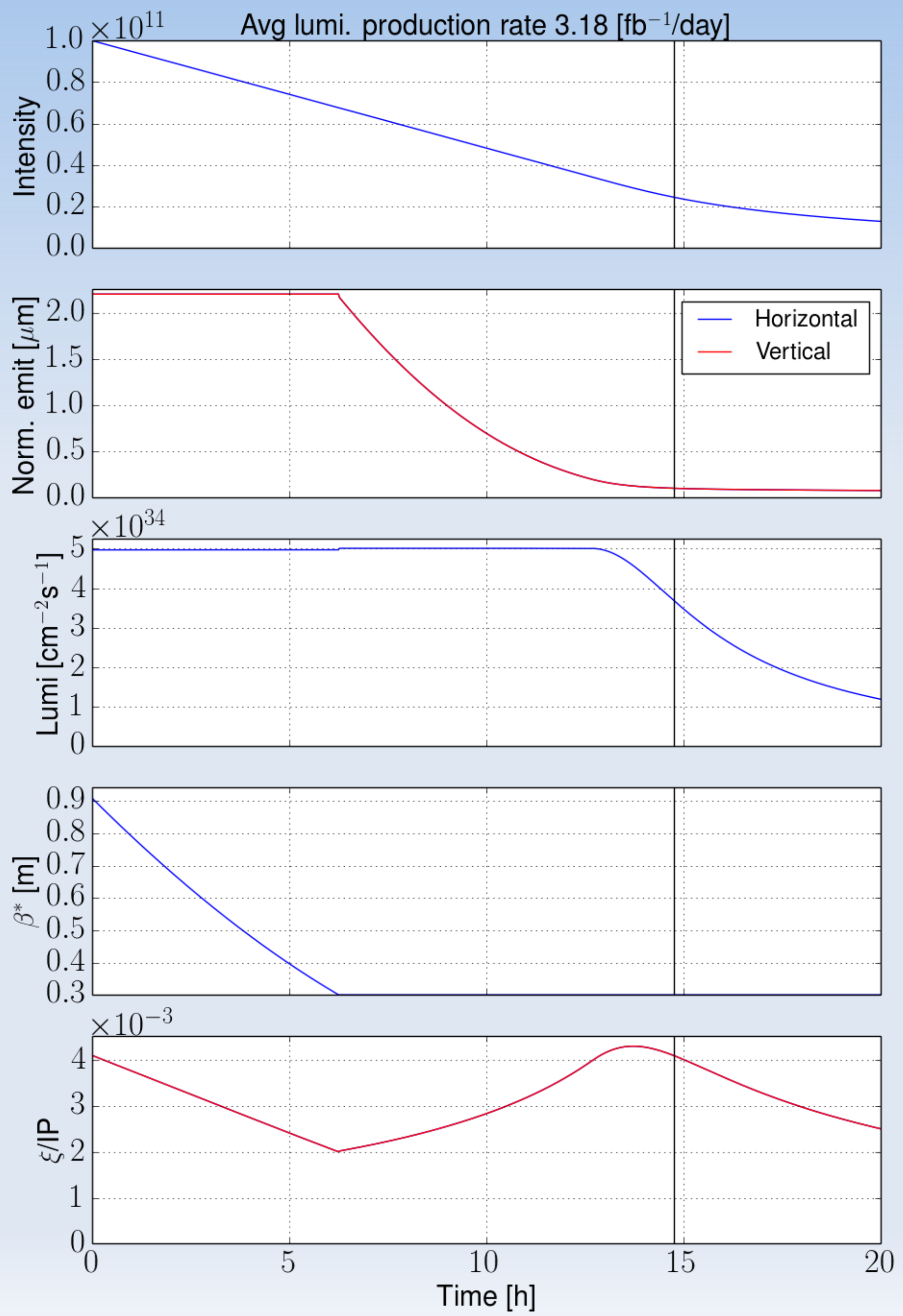
Nominal configuration

- Luminosity leveling is not required with nominal parameters
- Long fills needed (~12h)
  - → High reliability
- Limited by the maximum beam-beam tune shift



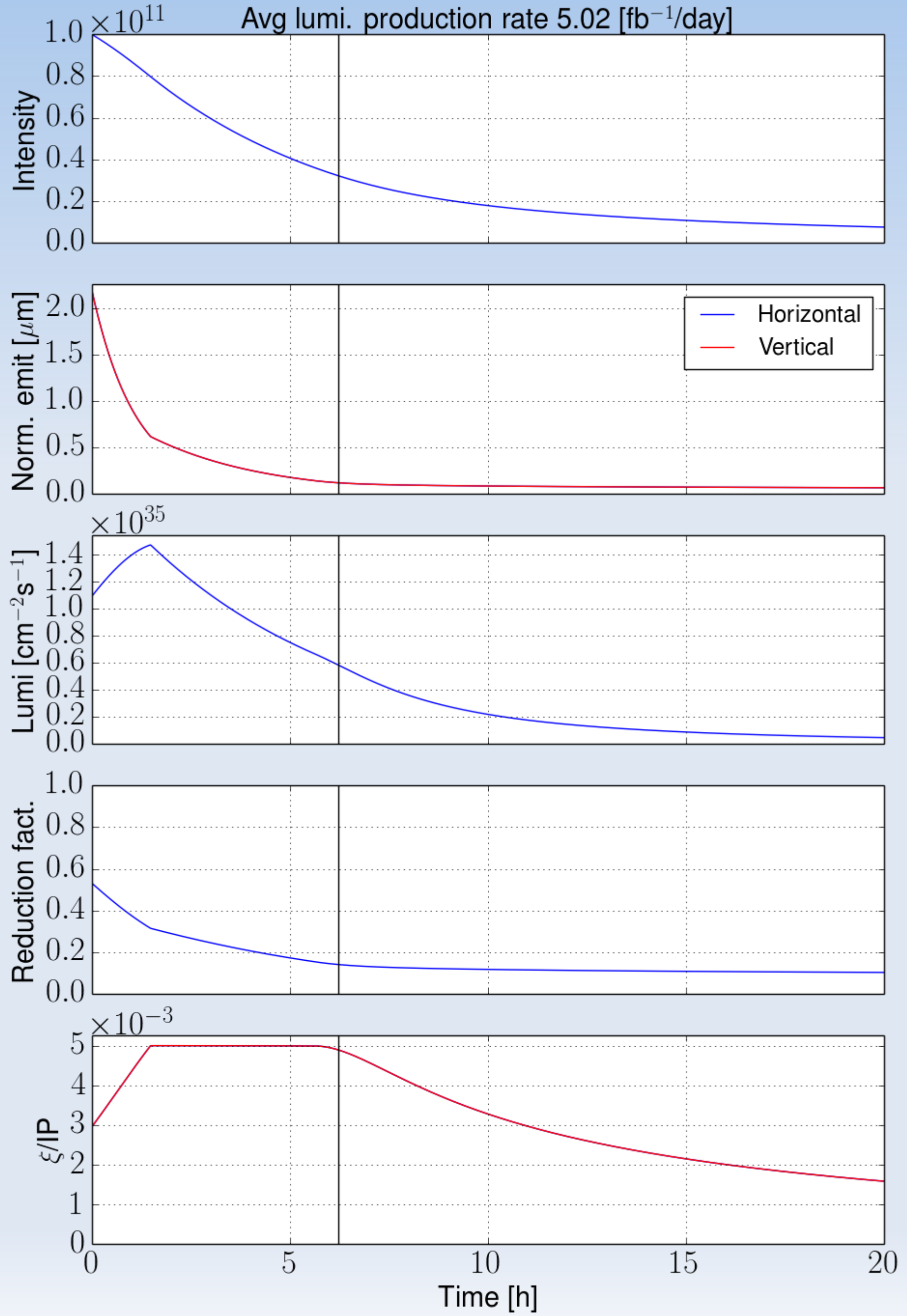
Nominal configuration

- Luminosity leveling is not required with nominal parameters
- Long fills needed (~12h)
    - → High reliability
- Limited by the maximum beam-beam tune shift
    - → reduce β*
- Limited by the levelled luminosity



Nominal configuration
with higher instantaneous luminosity

- Shorter fills thanks to the faster luminosity burn off
- Large reduction factor
  - → Large Piwinski angle
- Limited by the beam-beam tune shift



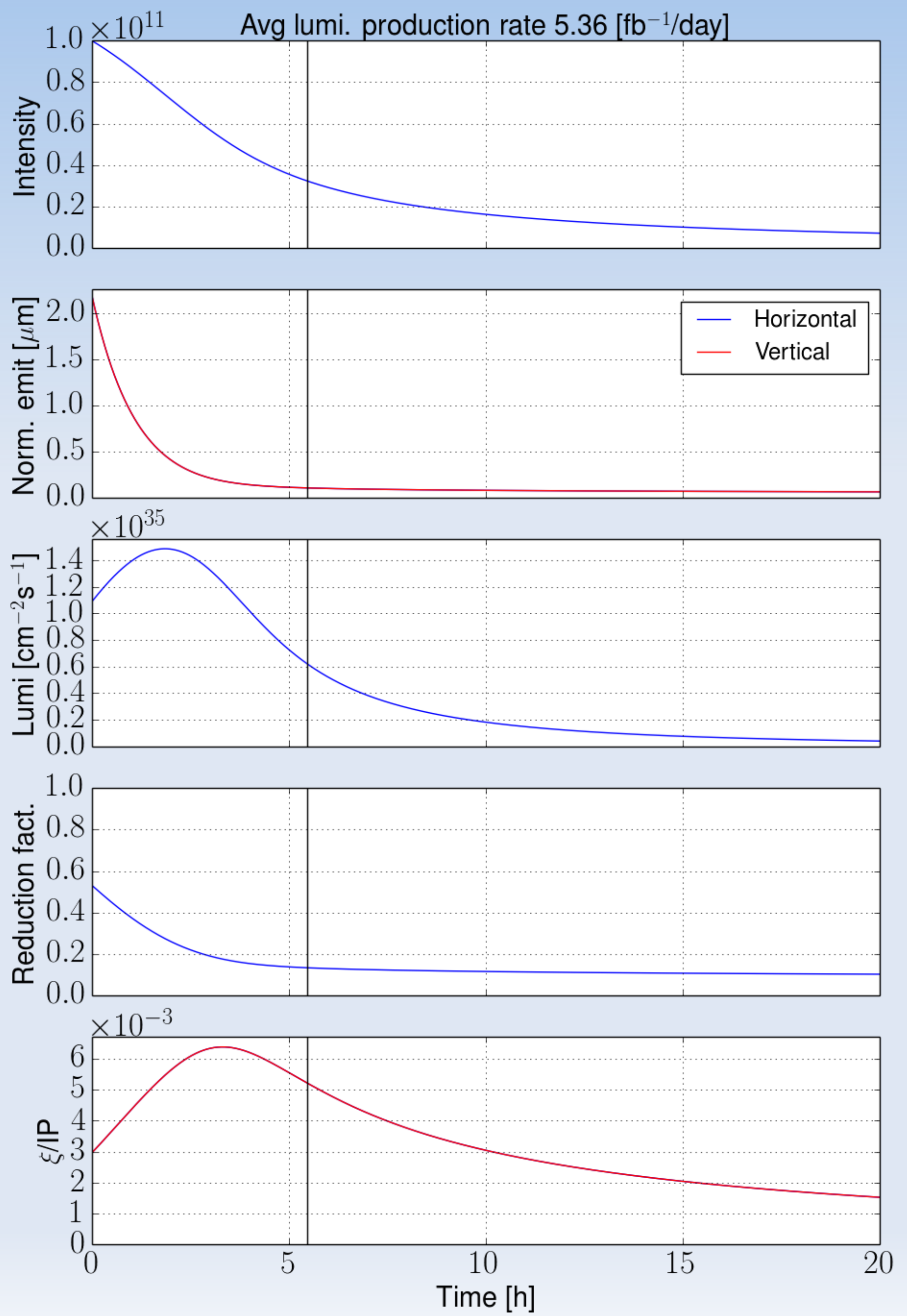
Nominal configuration
with higher instantaneous luminosity

- Shorter fills thanks to the faster luminosity burn off
- Large reduction factor

  → Large Piwinski angle

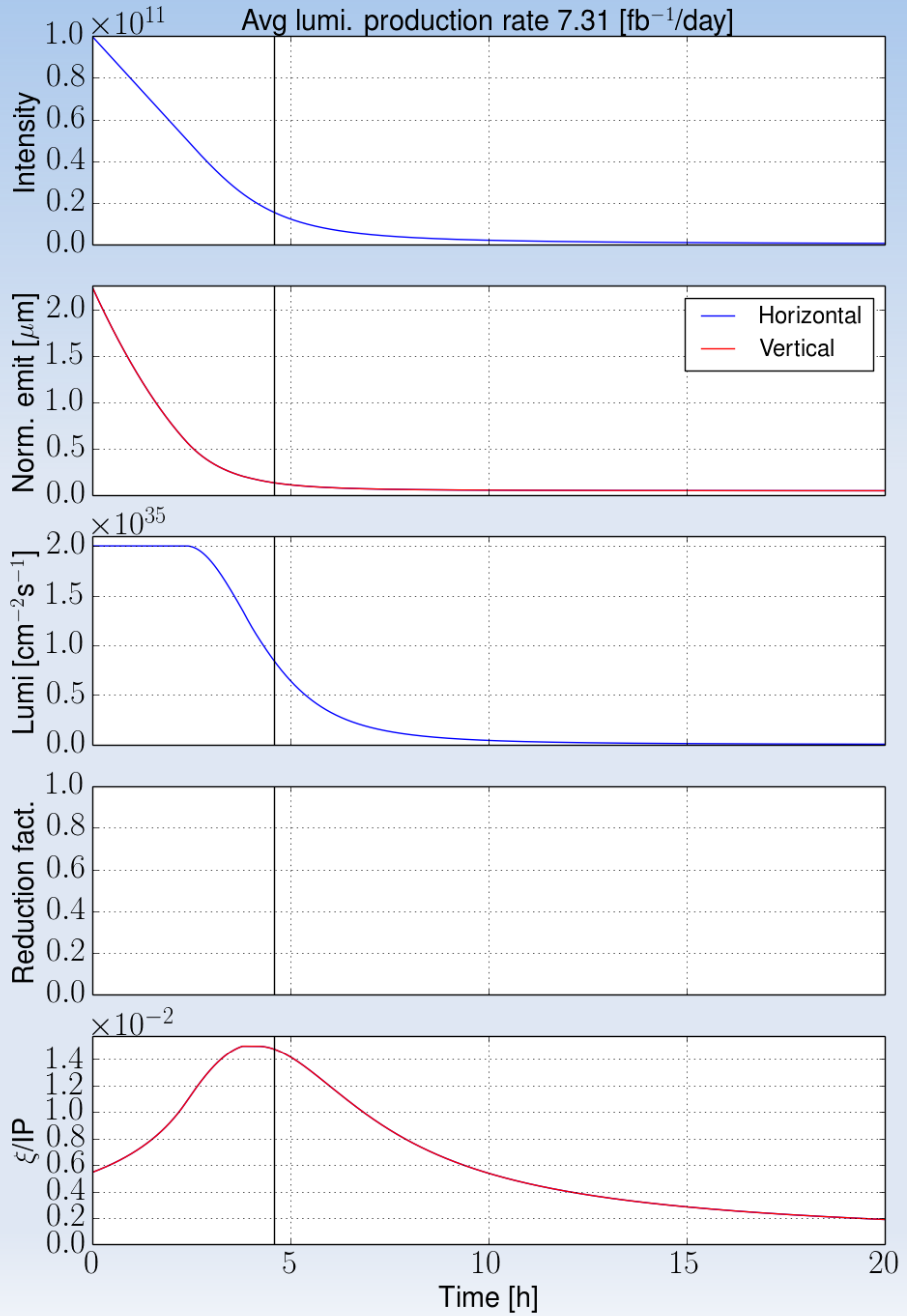
- Limited by the beam-beam tune shift

  → Increase the limit (compensation?)



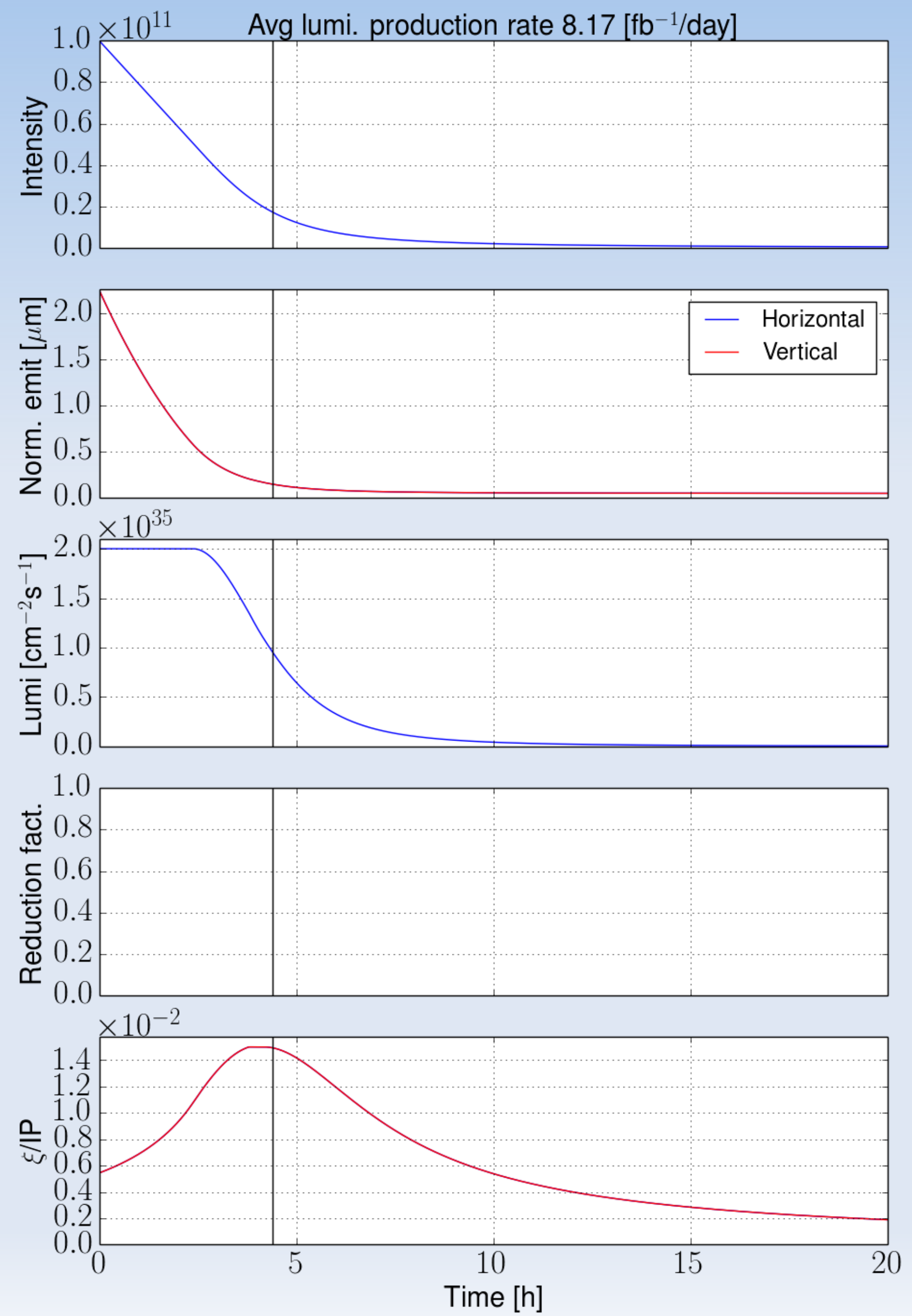
Nominal configuration
with higher instantaneous luminosity

- Shorter fills thanks to the faster luminosity burn off
- Large reduction factor
  - → Large Piwinski angle
  - → Crab crossing
- Limited by the beam-beam tune shift
  - → Increase the limit (compensation?)
- Limited by the turn around time (5h)



Ultimate configuration

Parameter	Nominal	Ultimate
Energy [TeV]	50	
Length [km]	100	
Bunch intensity [p]	10^{11}	
Normalised emittance [μm]	2.2	
Nb. bunches	10'600	
Target luminosity [$cm^{-2}s^{-1}$]	$5 \cdot 10^{34}$	$2 \cdot 10^{35}$
Bunch length [cm]	8	
ξ_{tot}	0.01	0.03
Turn around [h]	5	4
Number of IPs	2	
β* [m]	1.1	0.3
Long-range beam-beam separation [σ]	12	Crab Cavity



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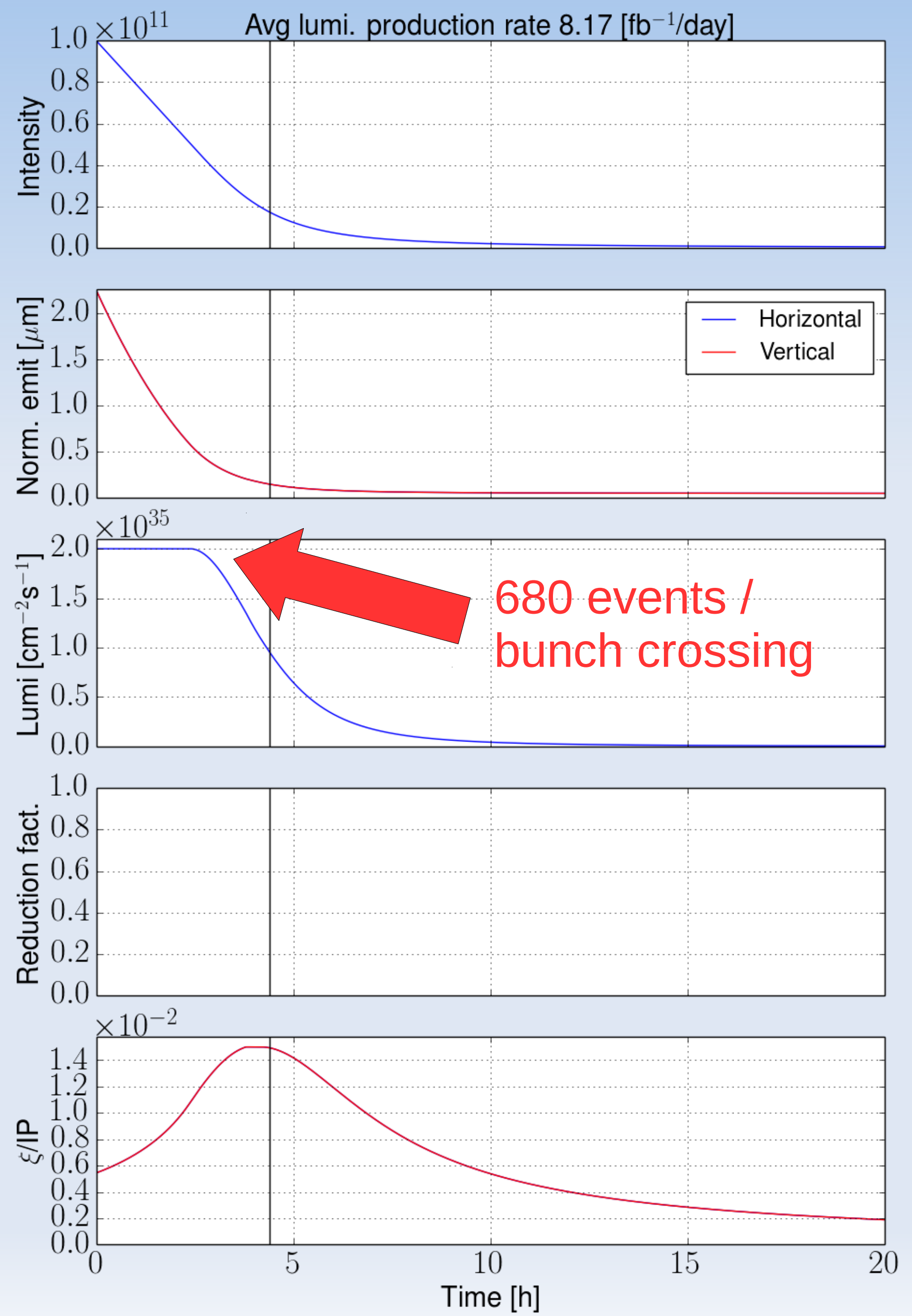
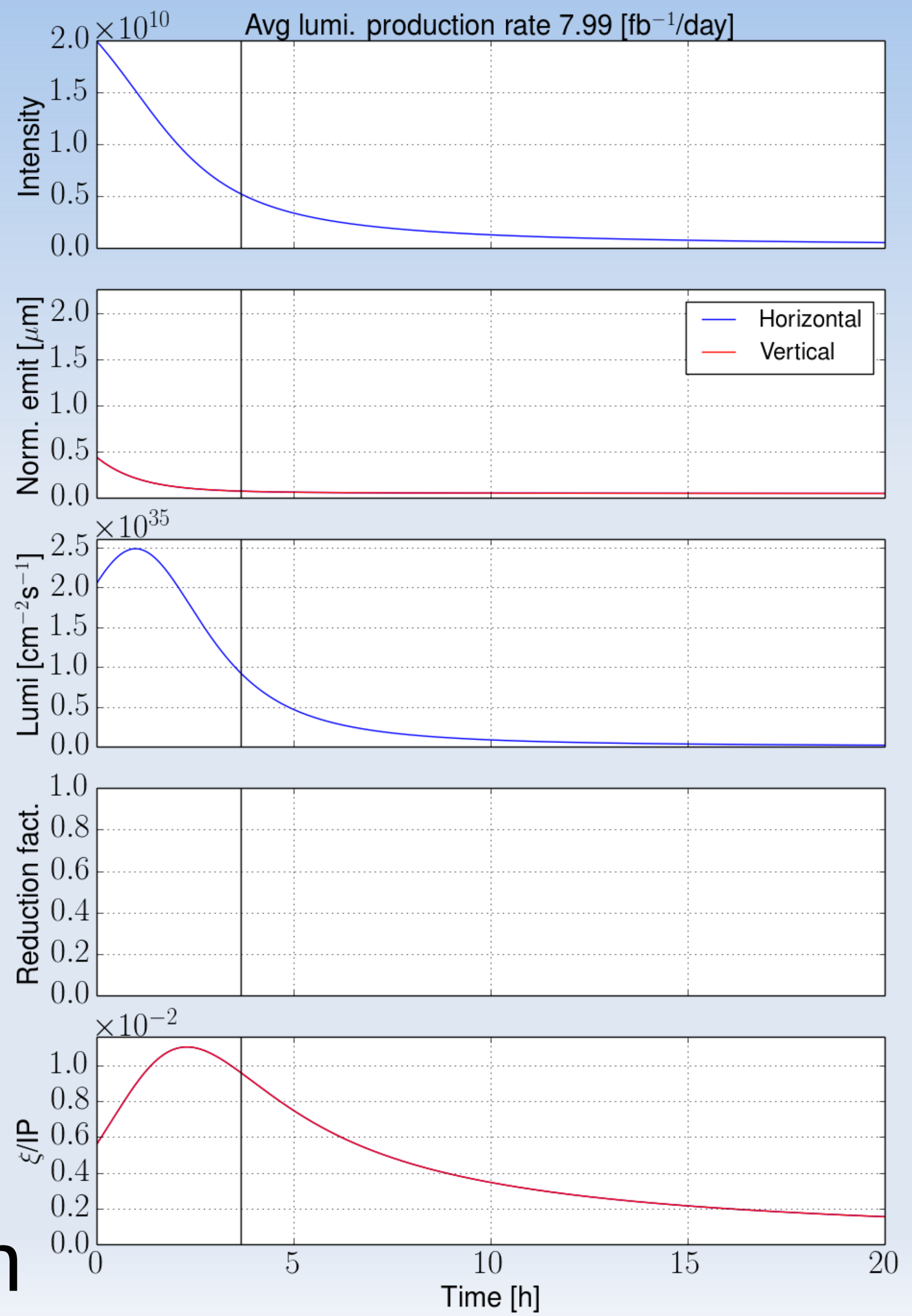
Nb. bunches	10'600	
Target luminosity [$cm^{-2}s^{-1}$]	$5 \cdot 10^{34}$	$2 \cdot 10^{35}$
Bunch length [cm]	8	
ξ_{tot}	0.01	0.03
Turn around [h]	5	4
Number of IPs	2	
β* [m]	1.1	0.3
Long-range beam-beam separation [σ]	12	Crab Cavity



Ultimate 5 ns

Parameter	Ultimate 25 ns	Ultimate 5 ns
Energy [TeV]	50	
Length [km]	100	
Bunch intensity [p]	10^{11}	$2\cdot10^{10}$
Normalised emittance [μm]	2.2	0.44
Nb. bunches	10'600	53'000
Target luminosity [$cm^{-2}s^{-1}$]	$2\cdot10^{35}$	$> 2\cdot10^{35}$
Bunch length [cm]	8	
ξ_{tot}	0.03	
Turn around [h]	4	
Number of IPs	2	
β* [m]	0.3	
Long-range beam-beam separation [σ]	12 (CC)	



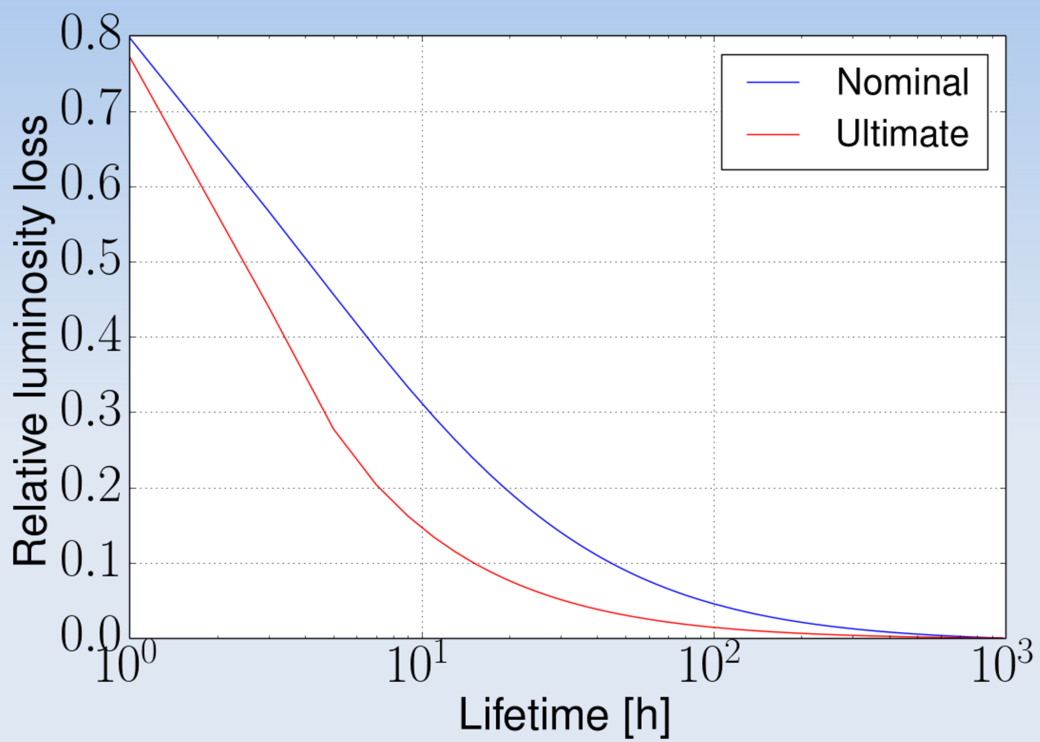
- Similar performance can be achieved with the 5 ns option

Performance

Configuration	Average luminosity production rate [fm^{-1}/day]	Integrated luminosity [fm^{-1}]*
Nominal	2.3	8'050
+ lower β* *(0.3 m)*	3.2 (+39%)	11'200
+ Higher levelled luminosity ($2 \cdot 10^{35}$ [cm-2/s-1])	5.0 (x2.1)	17'500
+ higher beam-beam tune shift (0.03)	5.4 (x2.3)	18'900
+ Crab crossing	7.3 (x3.2)	25'550
+ Shorter turn around (4h) → Ultimate 25 ns	8.2 (x3.7)	28'700
Ultimate 5 ns	8.0 (x3.5)	28'000

* Assuming 25 years of run, with 140 effective days per year (D. Schulte @ FCC Week 2015)

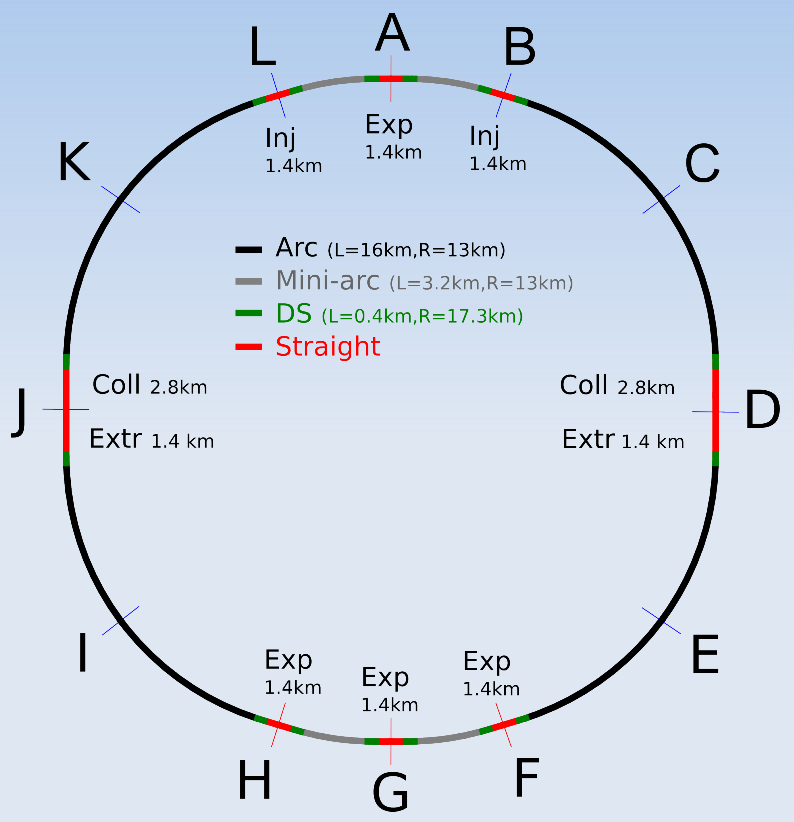
Effect of the lifetime



- A beam lifetime degradation due processes above 50 h reduces the performance by > 10%
  - Less critical in the ultimate scenario, due to the fast luminosity burn off

Effect of other interactions points

- The presence of lower luminosity experiments in Point H and F will :
  - Have a weak impact on the losses due to luminosity burn-off
  - Increase the total head-on beam-beam tune shift

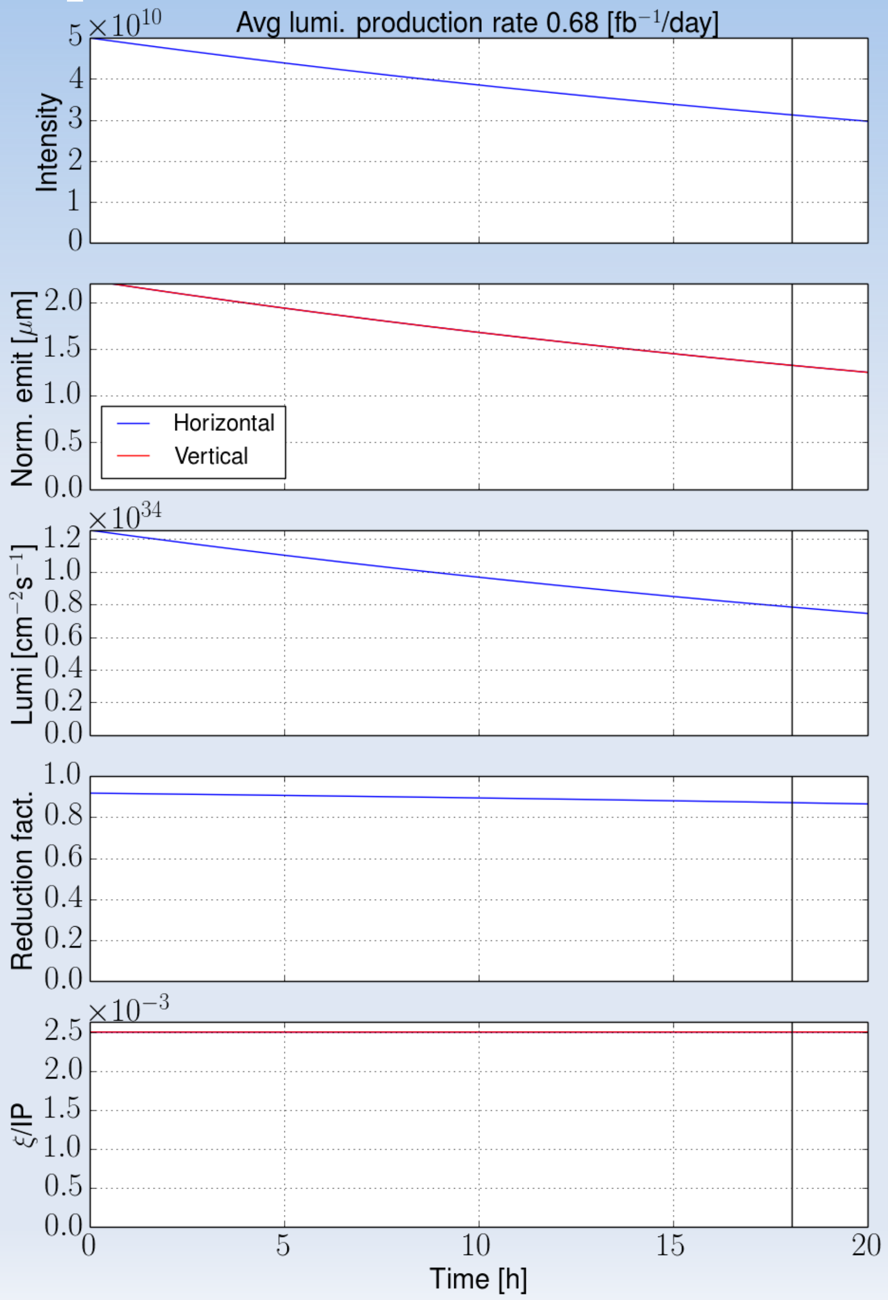


Effect of other interactions points

- The presence of lower luminosity experiments in Point H and F will :
  - Have a weak impact on the losses due to luminosity burn-off
  - Increase the total head-on beam-beam tune shift

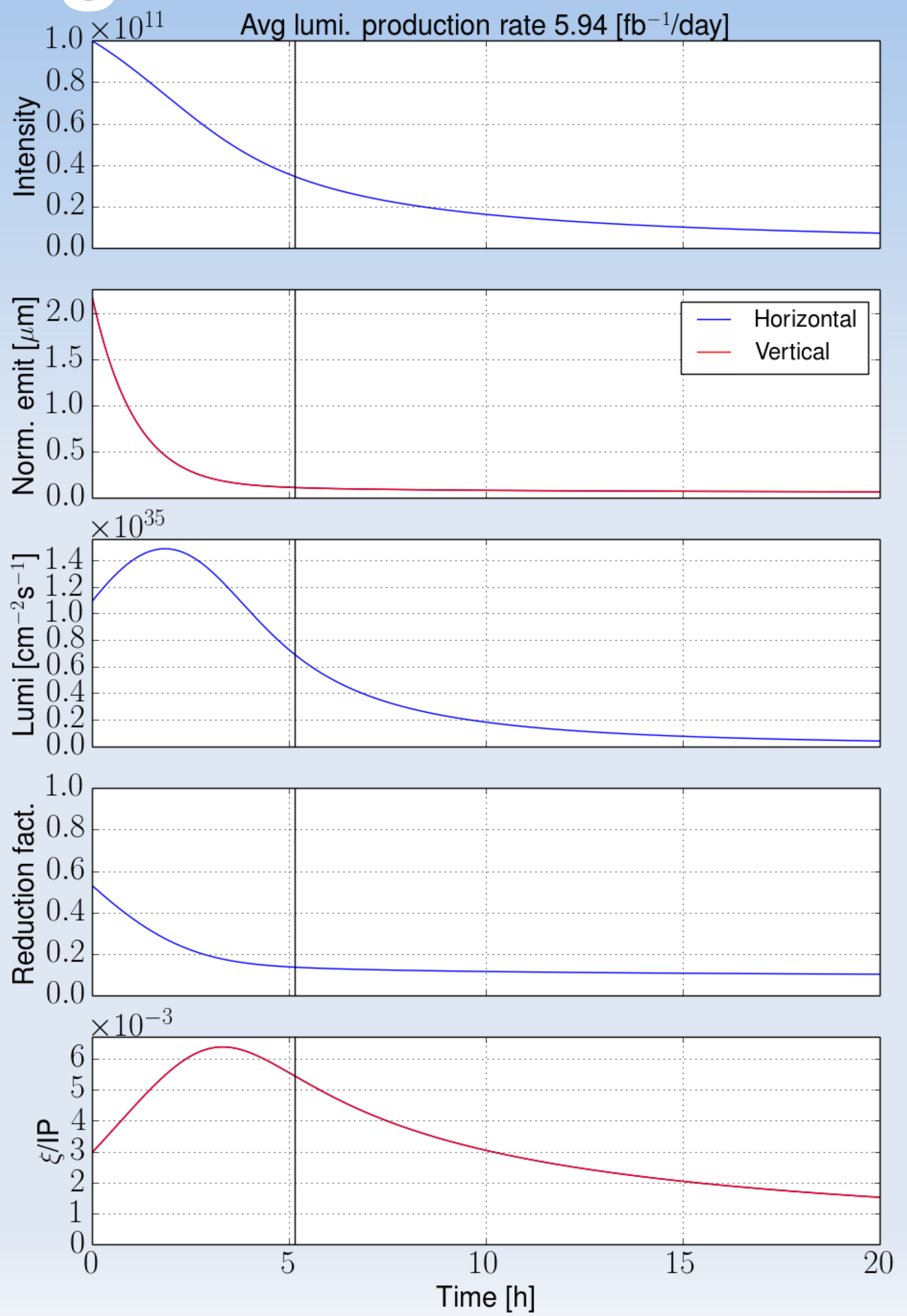
→ Need to reduce the bunch intensity

→ x3.4^{-1} reduction of the performance



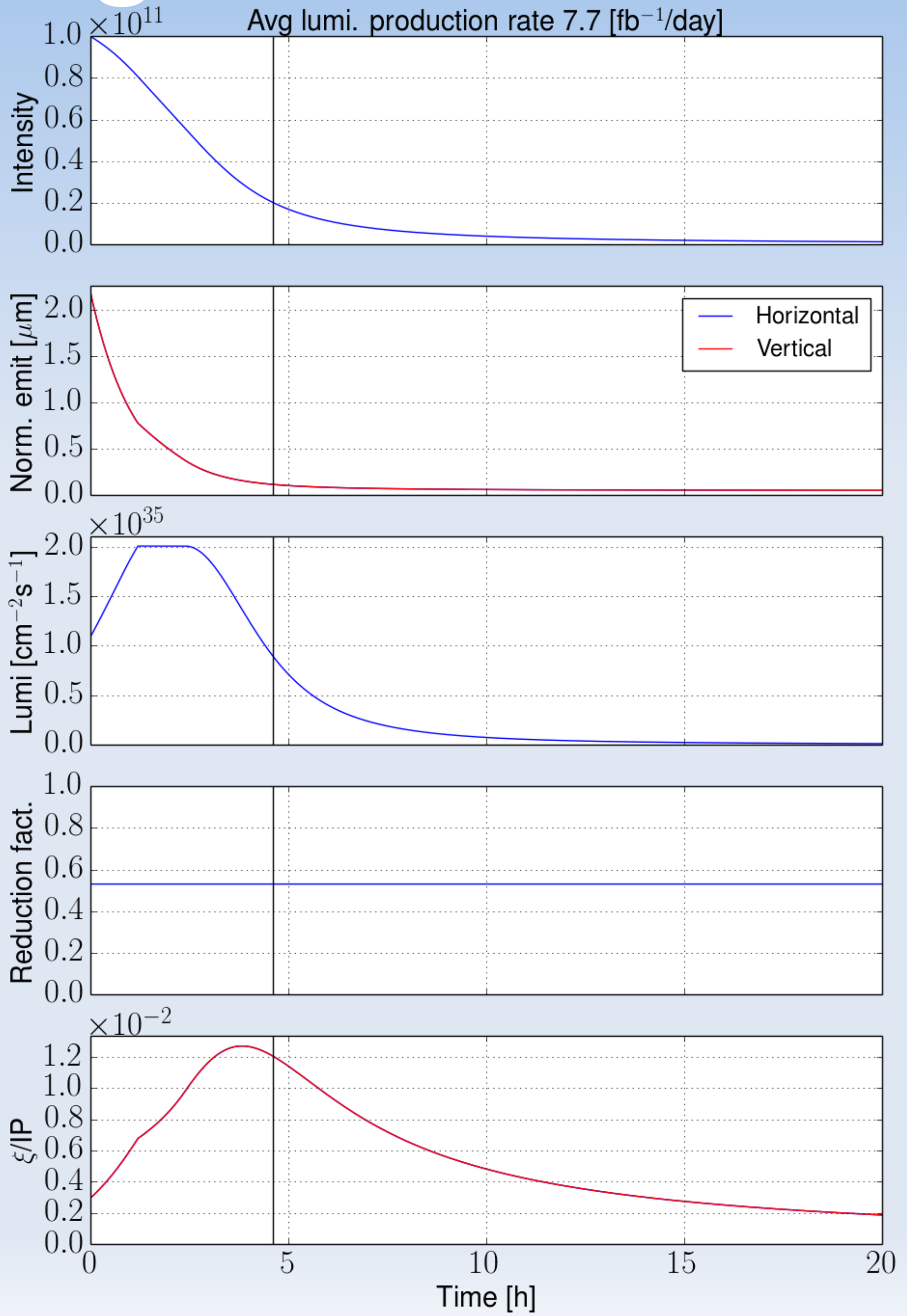
Effect of the crab crossing

- The ultimate configuration without crab crossing is limited by the geometric reduction factor



Effect of the crab crossing

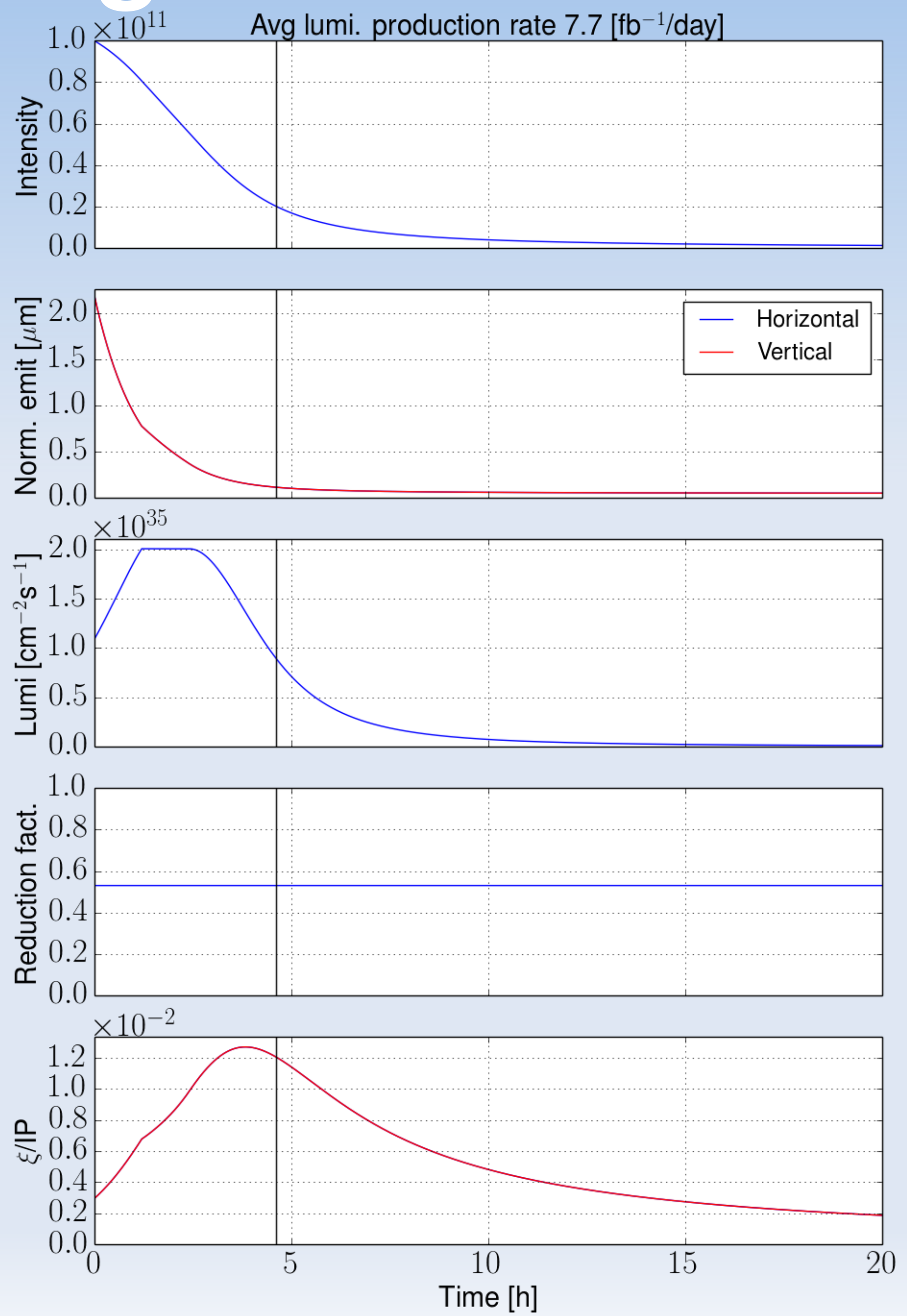
- The ultimate configuration without crab crossing is limited by the geometric reduction factor
- One could adjust the crossing angle during the fill, keeping constant the normalised separation between the beams



Effect of the crab crossing

- The ultimate configuration without crab crossing is limited by the geometric reduction factor
- One could adjust the crossing angle during the fill, keeping constant the normalised separation between the beams
  - Only 6% difference in performance between the two scenarios

    → The non-linear dynamic needs to be studied to fully assess both scenarios



Conclusion

- The nominal configuration is limited by the head-on beam-beam tune shift
  - Actual limit and compensation schemes need to be studied (ξ_{tot}=0.034 achieved in the LHC*)
- The nominal configuration rely on long fills (~ 12h), i.e. high reliability (6h in average for the LHC in 2012**)

* R. Alemany, et al, Head-on beam-beam tune shifts with high brightness beams in the LHC, CERN-ATS-Note-2011-029 MD
**A. Macpherson, LHC Availability and Performance in 2012, Proceedings of the 2012 Evian Workshop on LHC Beam Operation

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- The ultimate scenario is mainly limited by the turn around time
  - A scenario with 5 ns bunch spacing could provide a similar performance with a lower pile up

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  - A scenario with 5 ns bunch spacing could provide a similar performance with a lower pile up
- Assuming 2 runs of 5 years with nominal parameters and 3 with ultimate parameters, one integrates >~ 17'500 fm^{-1}
- The design need to take into account the slow, yet large, variation of the transverse emittance during the fill (Adaptive β* and crossing angle, collimation, beam instrumentation, beam stability, ...)

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