Accelerator operation and luminous region scenarios

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Mode of operation

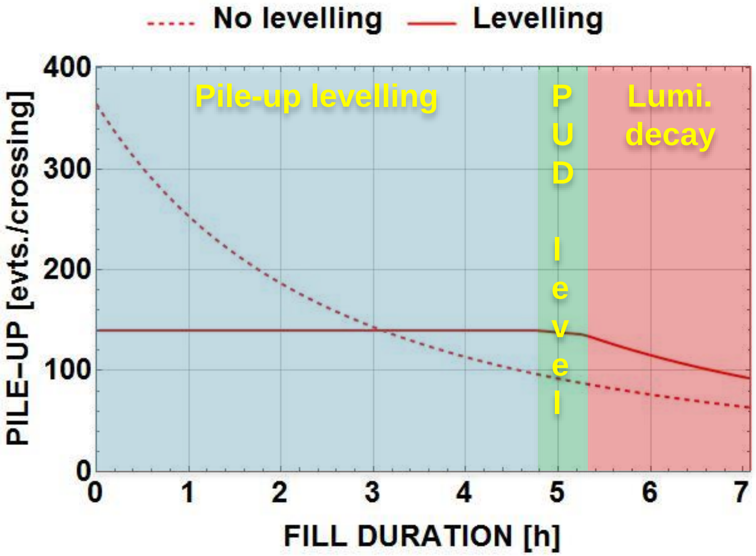
$$L = \frac{kN_b^2 f \gamma}{4\pi \beta^* \varepsilon^*} F$$

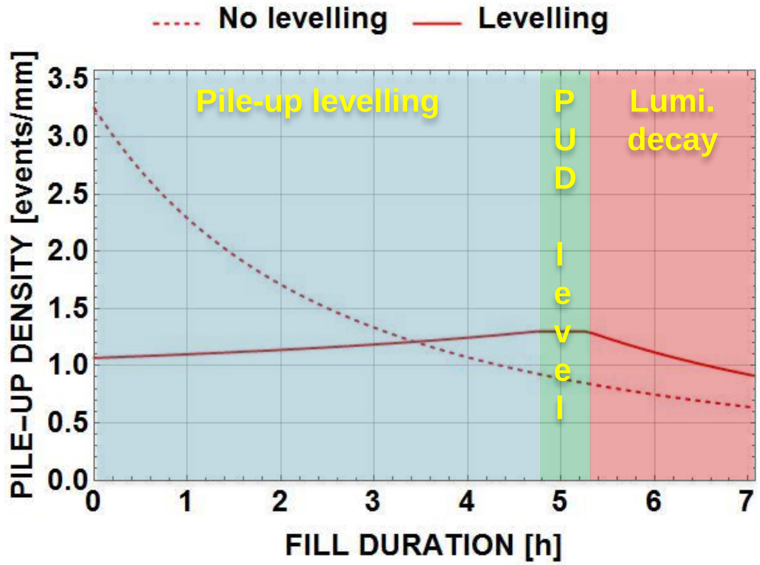
- Operation at pile-up/pile-up density limit (set by the experiments) by choosing parameters that allow higher than design pile-up (140 events) / pile-up density (<1.3 events/mm):
  - Beam brightness and in particular bunch population to sustain burn-off over long periods ➔ LHC Injector Upgrade
  - Maximize number of bunches to minimize pile-up ➔ 25 ns
  - Low β^* optics
  - Large crossing angle to minimize the beam-beam effects
  - Fight the reduction factor F by crab crossing

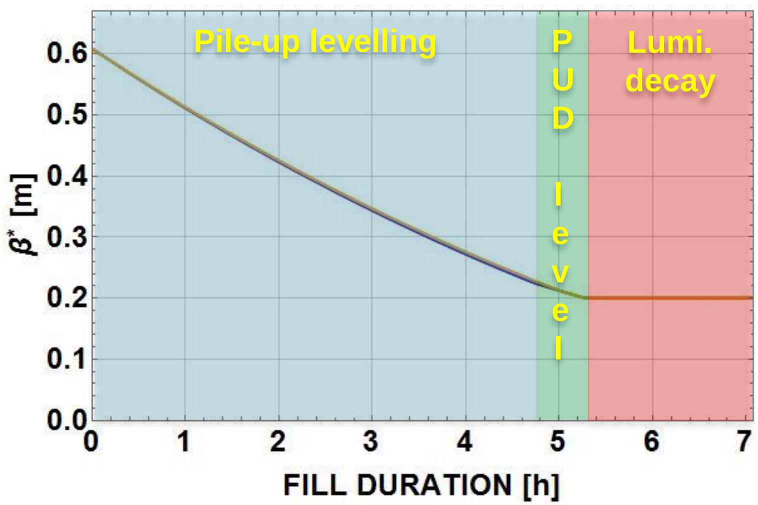
- Improve 'Machine Efficiency' ➔ minimize the number of unscheduled beam aborts

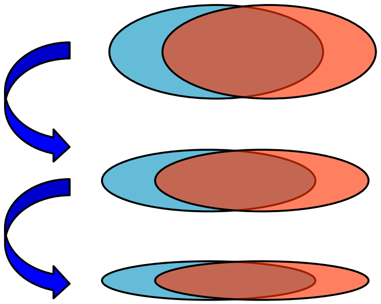
Mode of operation

$$L = \frac{kN_b^{\,2} f\gamma}{4\pi\beta^{*}\varepsilon^{*}}F$$



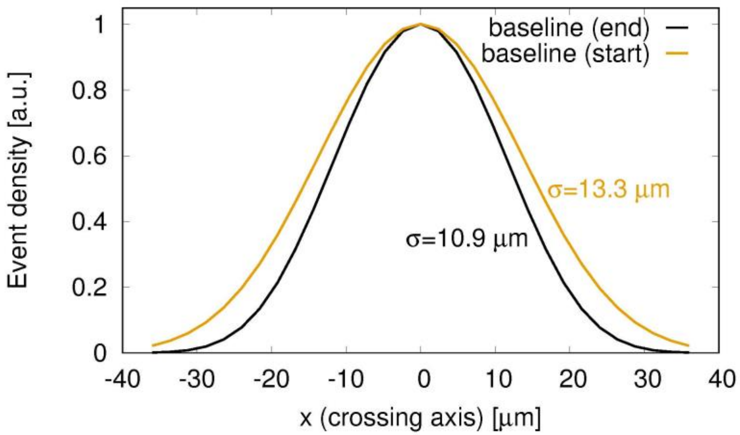






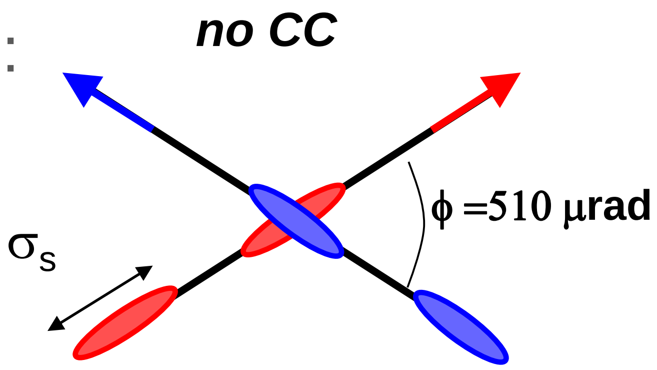
Luminous region

- 3D distribution of the collision event vertices
- Transverse sizes of the luminous region depends on:
  - β-function at the interaction point (varying during levelling ➔ β* is our nominal levelling mechanism for IP1 and IP5)
  - Transverse emittance
  - Transverse separation (levelling by separation is our nominal levelling mechanism in IP2 and IP8)
  - Crossing angle and crab cavity voltage

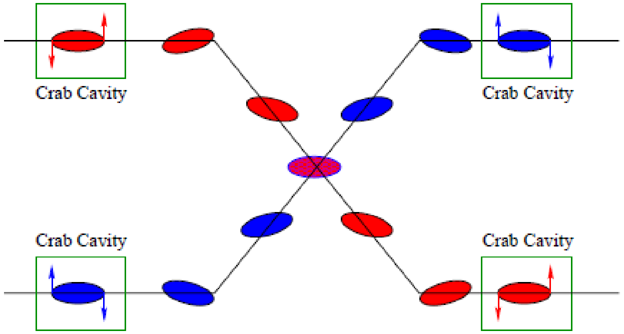


Luminous region

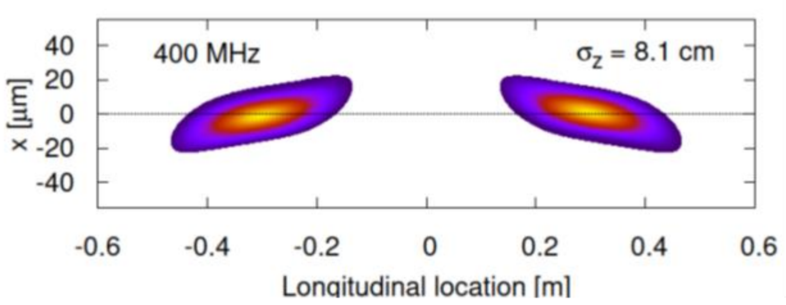
- 3D distribution of the collision event vertices
  - Longitudinal size σ_{LRz} depends on:
    - Crossing angle



    - Crab cavity voltage



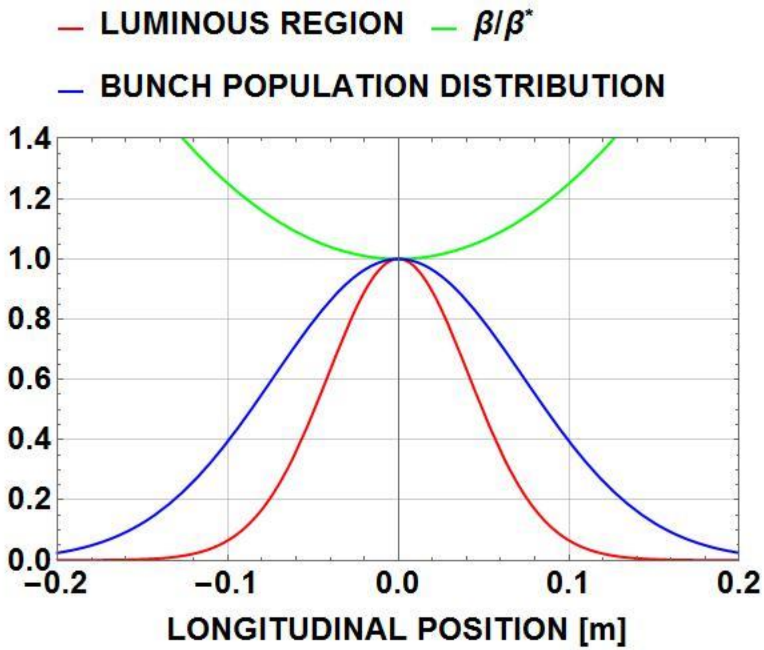
    - Crab cavity RF curvature



Luminous region

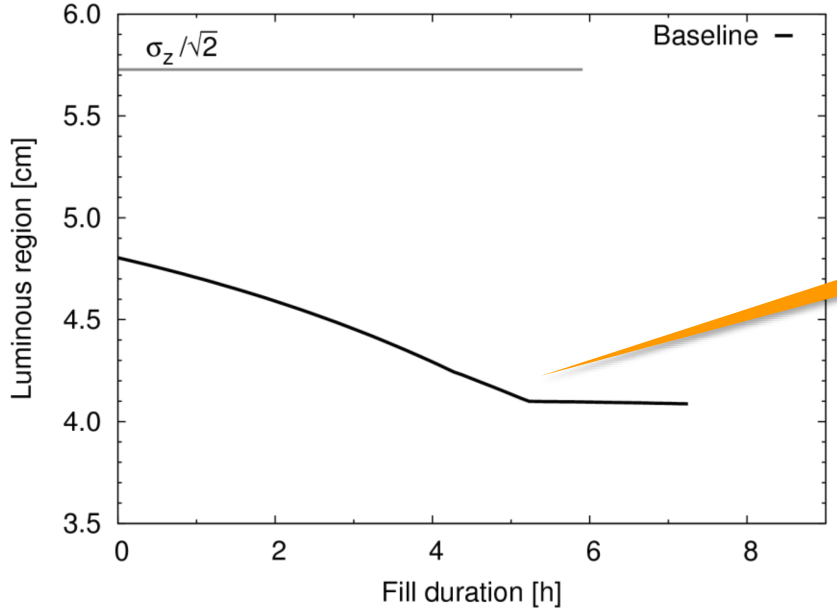
- 3D distribution of the collision event vertices
  - Longitudinal size σ_{LRz} depends on:
    - Bunch length σ_z (for head on collisions $\beta^* >> \sigma_z \rightarrow \sigma_{LRz} = \frac{\sigma_z}{\sqrt{2}}$)
    - Hourglass effect: varies during the fill because of the β^* levelling

Baseline scenario
Gaussian bunch longitudinal distribution (slightly pessimistic)
End of levelling



Luminous region

- r.m.s. length of the longitudinal distribution evolves during the levelling process. Because of the evolution of β*



Minimum β*

Baseline scenario

Pile-up

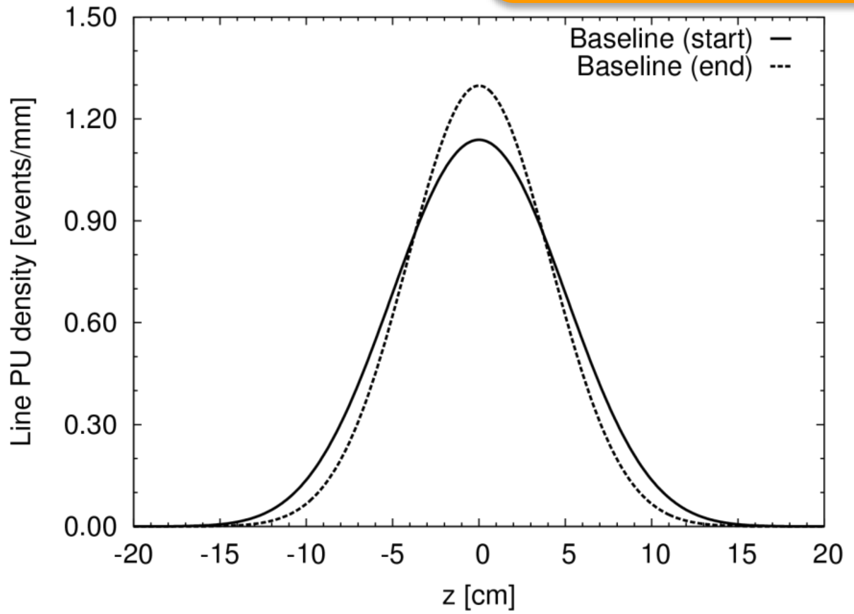
- Pile-up [events/crossing]:
  - A certain number of events can occur in a single bunch crossing
  - The number of events per crossing μ is distributed according to Poisson distribution with average $<\mu>$. We call pile-up the value

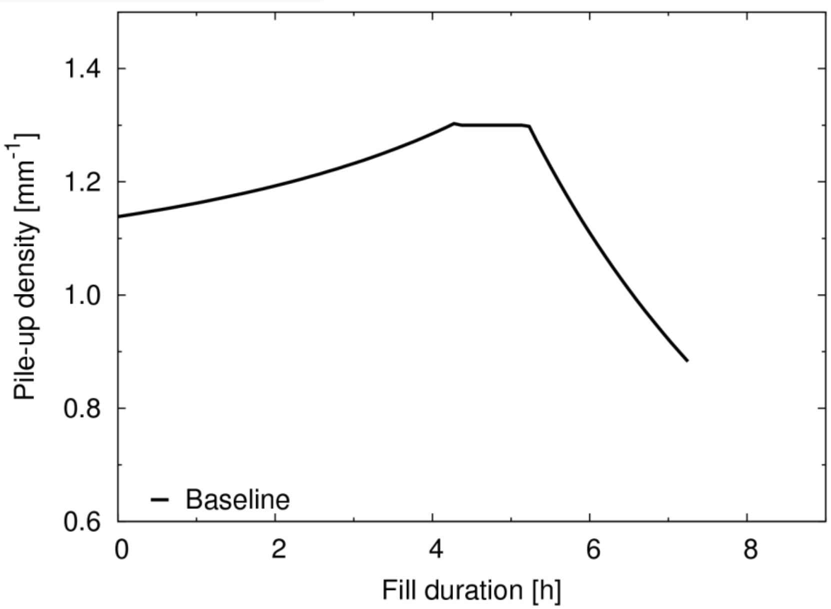
$$<\mu>(t)= \sigma_{inel} L_{inst}(t)$$

Line Pile-up Density

- Line Pile-up density [events/crossing/mm]:
  - Longitudinal density of the event distribution, evolves during the levelling process

$$\frac{d\langle\mu\rangle}{ds}(s,t) = \sigma_{inel}\frac{dL_{inst}(s,t)}{ds}$$

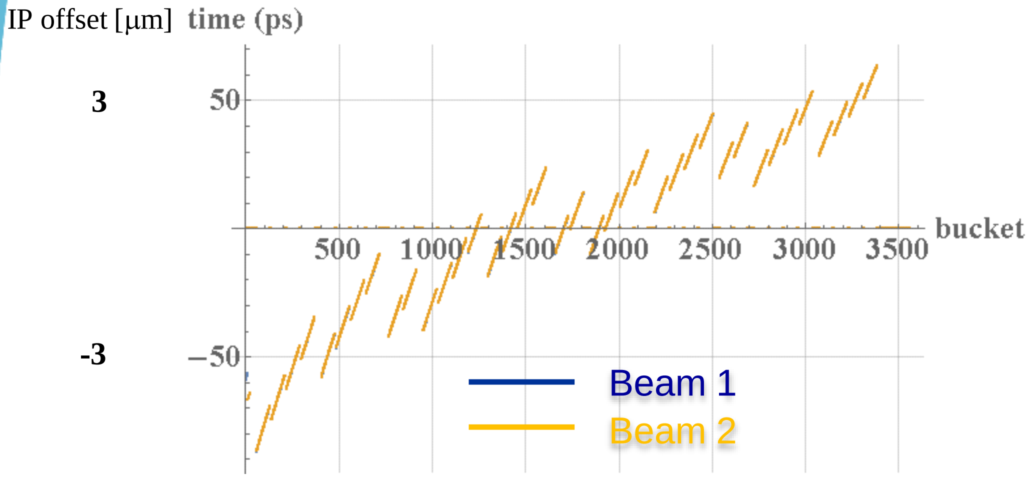


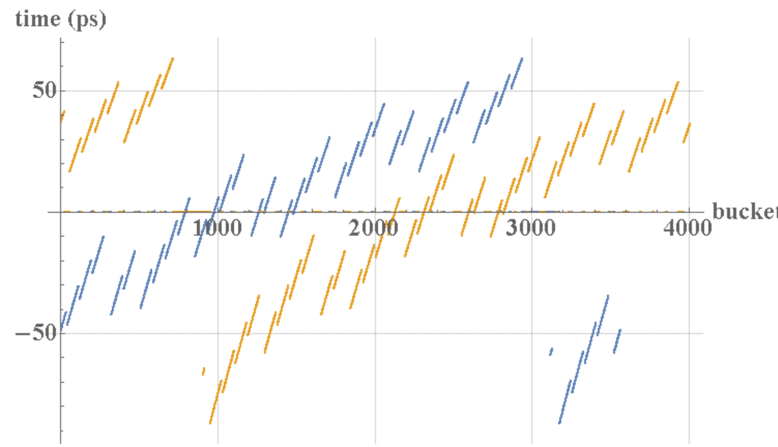


Baseline scenario

Other features

- In order to operate at double current as compared to LHC with the available klystron power we will have to operate in the so-called “full detuning mode” the main 400 MHz RF system ➔ Modulation of the bunch arrival time over the machine turn ~ ±70 ps





IP1/5 – symmetric for symmetric filling patterns

IP2/8 – asymmetric even for symmetric filling patterns

- modulation of the transverse position of the collision point at IP1-5 in the crossing plane and modulation of the longitudinal position of the collision point in IP2-8 (~ ±1 cm) ➔~ 1% lumi. modulation

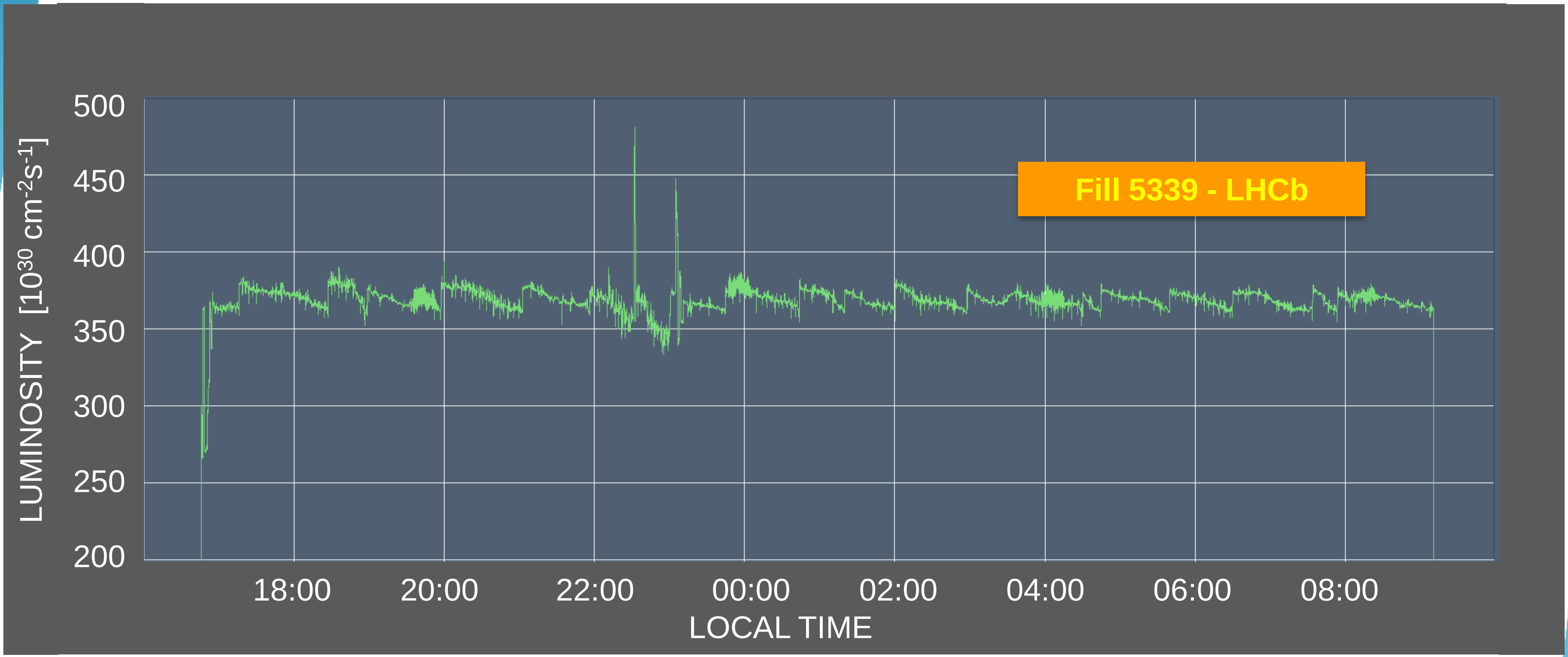
Levelling

- Any form of levelling implies:
  - Getting the observable(s) on which we need to level
  - Having a variable to act on the observable

- At present we are counting on:
  - Luminosity

- In the future we will need information on
  - Luminosity ~ proportional to pileup for a given number of colliding pairs
  - Pile-up density (or luminosity density: i.e. r.m.s. luminous region length and luminosity)

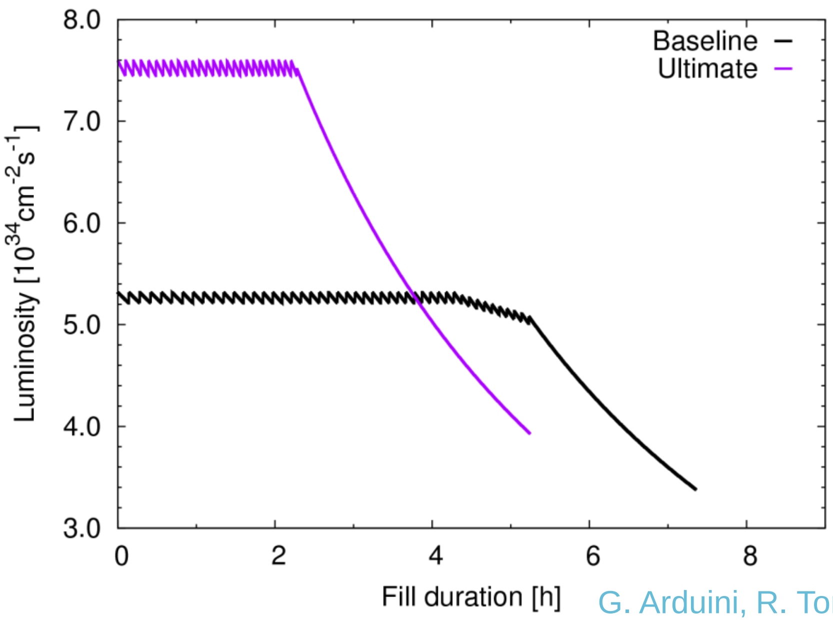
How does it look like today?



- Levelling by separation within ±2%
- β* levelling more complex but first MD results positive
  ➔ Need to gain operational experience

Levelling

- Granularity of 2% assumed for HL-LHC fill simulations:
  - Possible hybrid schemes with feedforward based on expected evolution and feedback based on levelling by separation could be considered ➔ we need to work out the details

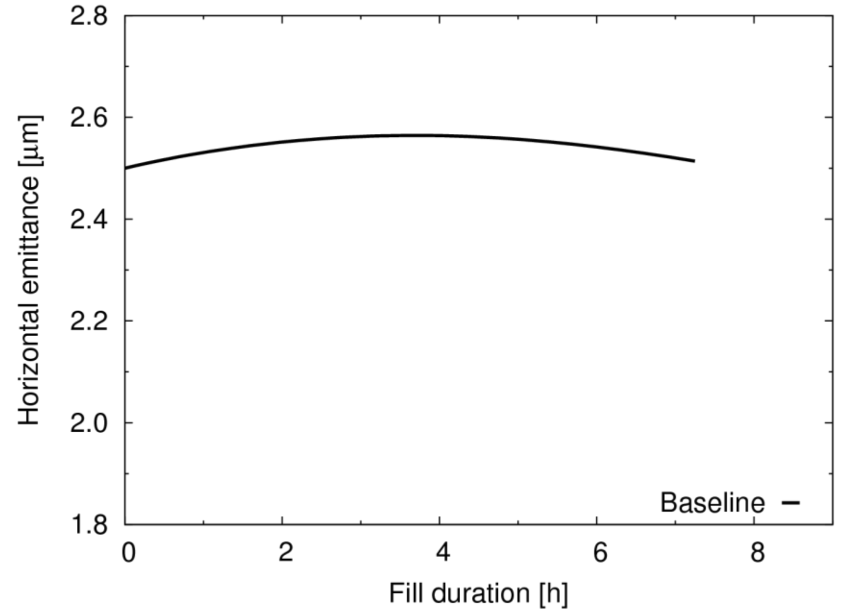


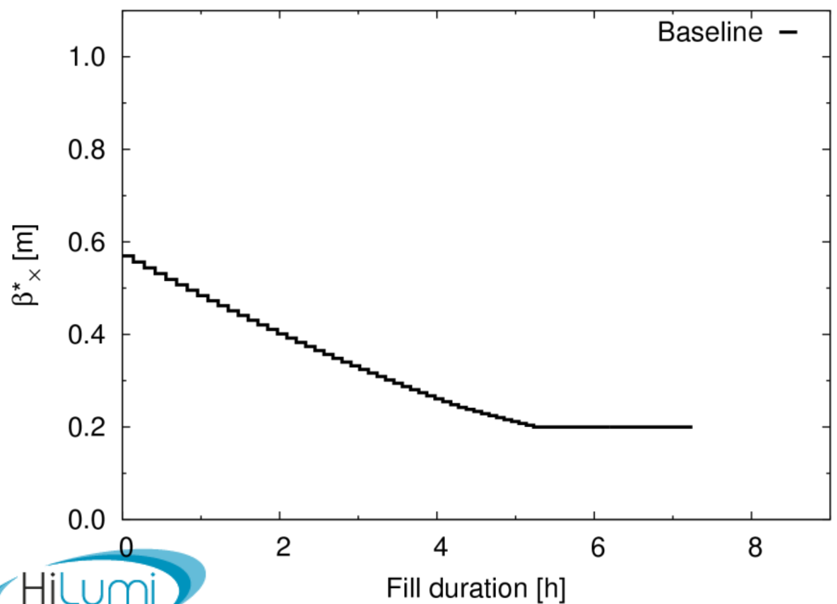
HL-LHC Parameters

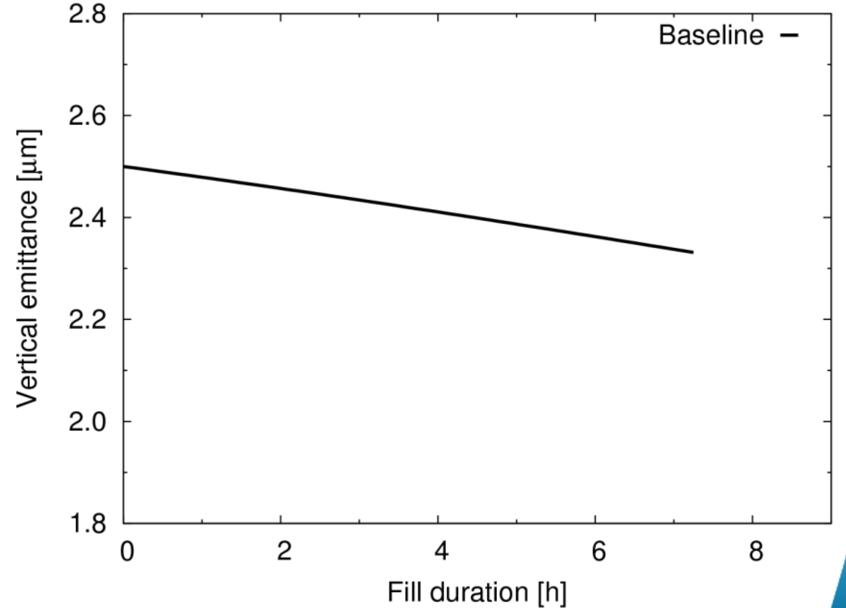
Parameter	Nominal	HL-LHC updated
Bunch population N_b [10^{11}]	1.15	2.2
Number of bunches	2808	2748
Beam current [A]	0.58	1.12
Stored Beam Energy [MJ]	362	677
Full crossing angle [μrad]	285	510
Beam separation [σ]	9.4	12.5
Min β^* [m]	0.55	0.2
Normalized emittance ε_n [μm]	3.75	2.5
r.m.s. bunch length [m]	0.075	0.081
Peak Luminosity (w/o CC) [10^{34} cm^{-2}s^{-1}]	1.2 (1.2)	12.6 (6.5)
Max. Luminosity [10^{34} cm^{-2}s^{-1}]	1	5.3
Levelled Pile-up|Pile-up density [evt. | evt./mm]	26/0.2	140/1.3

Baseline

- Round optics:
  - Constant crossing angle 510 μrad
  - Min β* = 20 cm
  - Partial (~75%) compensation of crossing angle with two CCs per IP side per beam (2×3.4 MV)

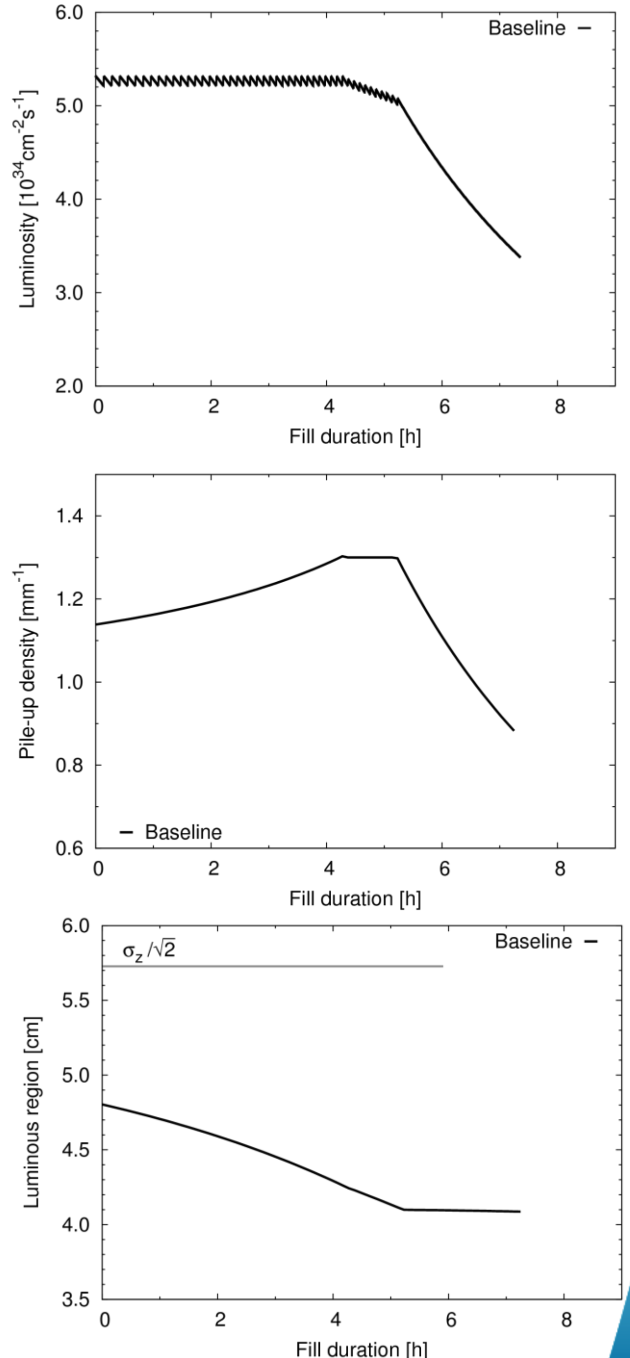






Baseline

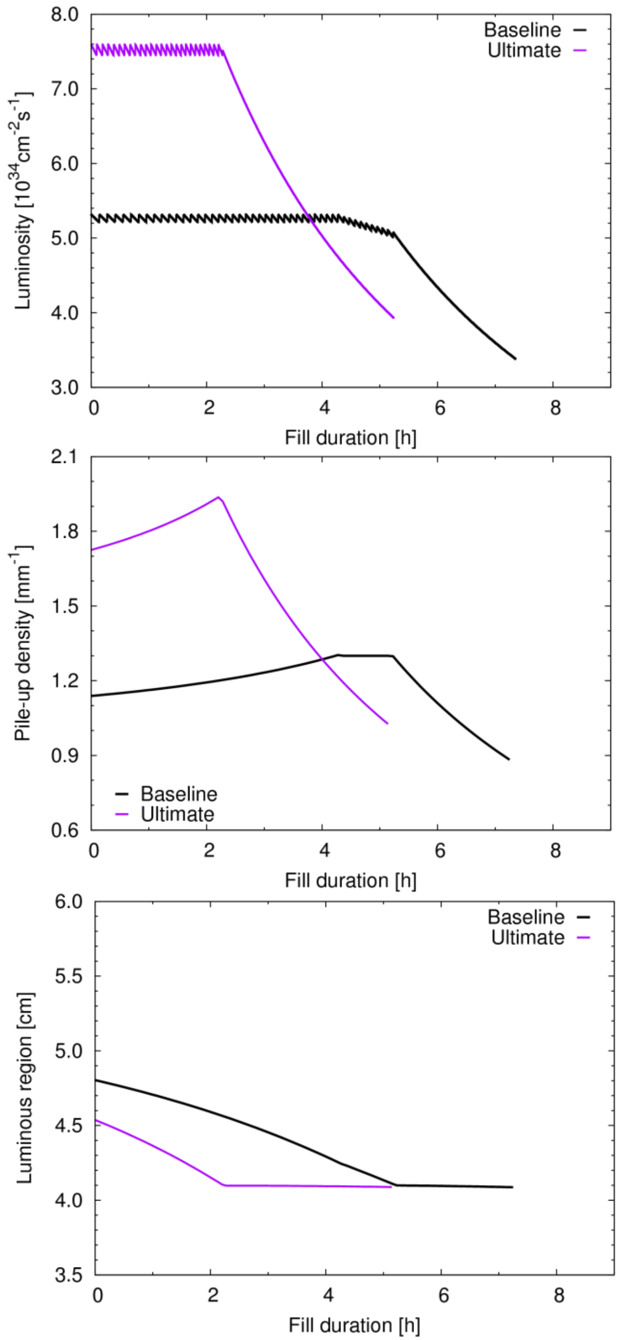
- Levelled luminosity at 5.3×10^{34} $cm^{-2}s^{-1}$ for pile-up =140 events/xing
- Peak line pile-up density limited to 1.3 events/mm/xing.
- 3000 fb^{-1} during HL-LHC period
- Assumptions:
  - Min. turn-around time: 3 h
  - Performance Efficiency: 50% (60.1 % in 2016 – so far)
  - 160 days of proton physics (this number increases in Run 5 (200 days) and Run 6 (220 days)



Ultimate

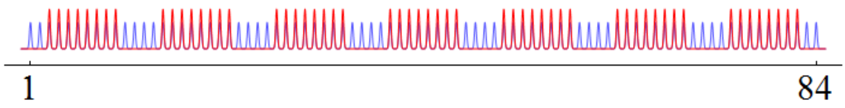
- Differences w.r.t. baseline
  - levelling at pile-up = 200 events/xing ➔ Luminosity levelling at $7.6\times10^{34}\ cm^{-2}s^{-1}$
  - Peak line pile-up density up to 1.9 events/mm/xing
  - Beam parameters are the same

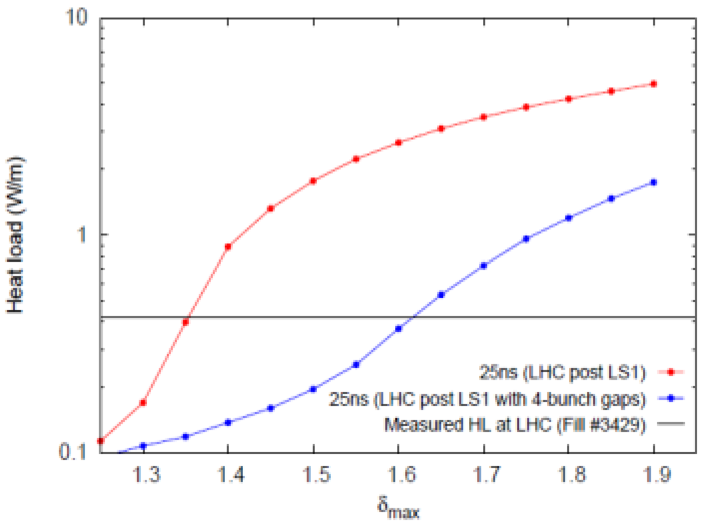
  - Up to 4000 fb^{-1} during HL-LHC period compatibly with engineering margins assuming 58% performance efficiency (2016 so far ~60%)



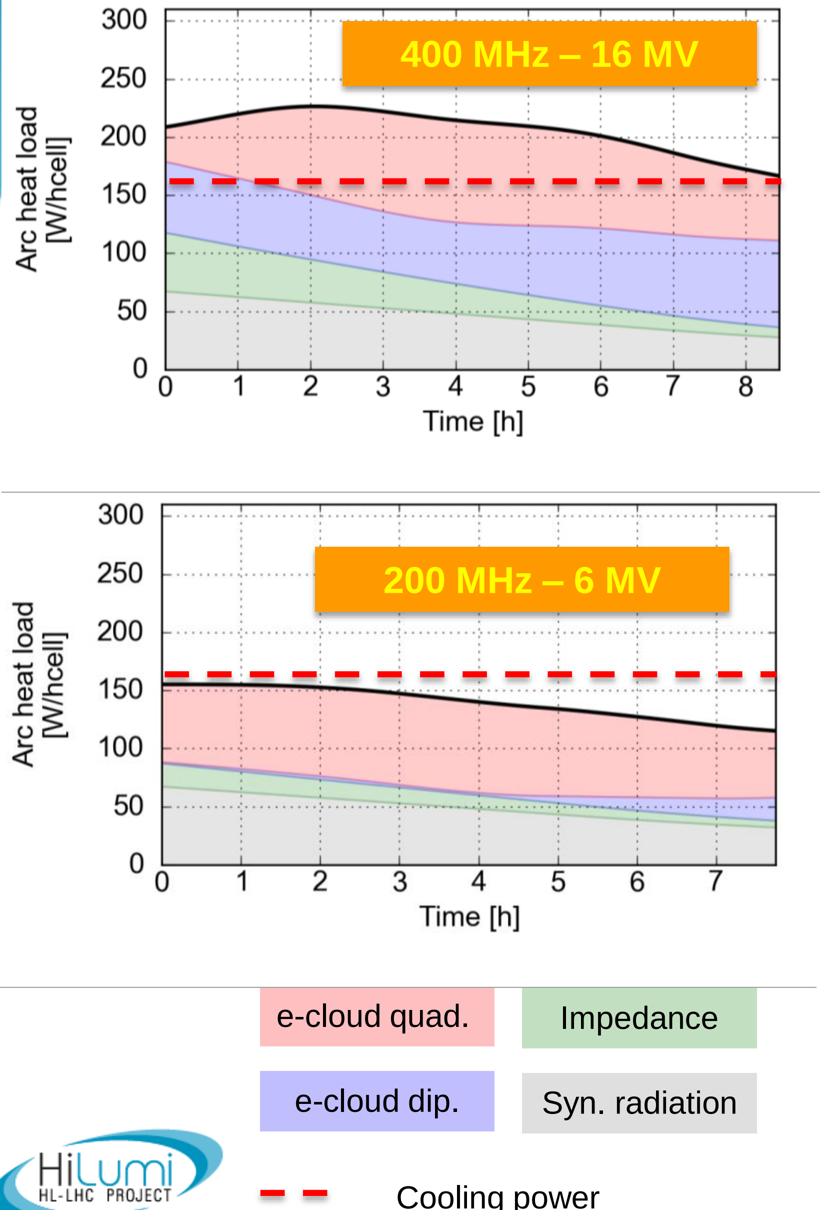
Back-up scenario (e-cloud mitigation): 8b+4e

- Relies on scrubbing to suppress electron cloud in the dipoles (heat load and beam stability)
- Alternatives to mitigate electron cloud:
  - ‘ad-hoc’ 25 ns filling schemes to minimize electron cloud build-up (e.g. 8b+4e scheme)
  - No additional HW but reduced number of bunches (1968 as compared to 2748)

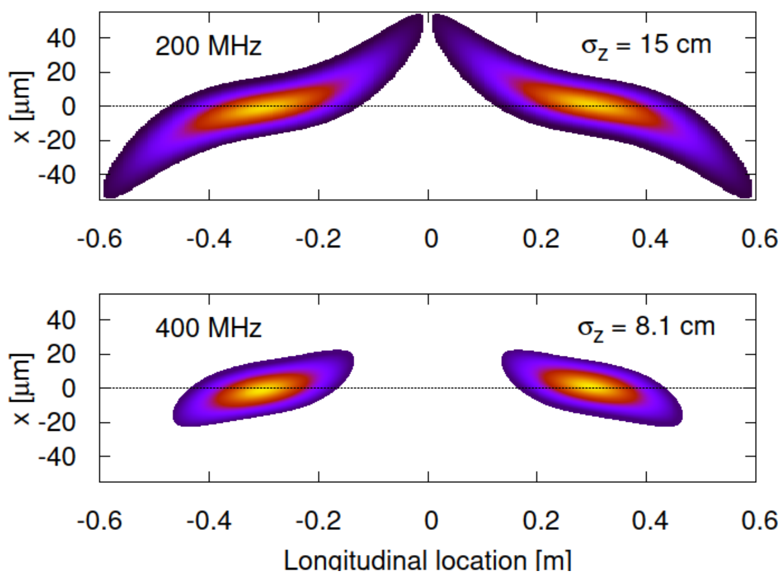




Alternative scenario (e-cloud mitigation): 200 MHz

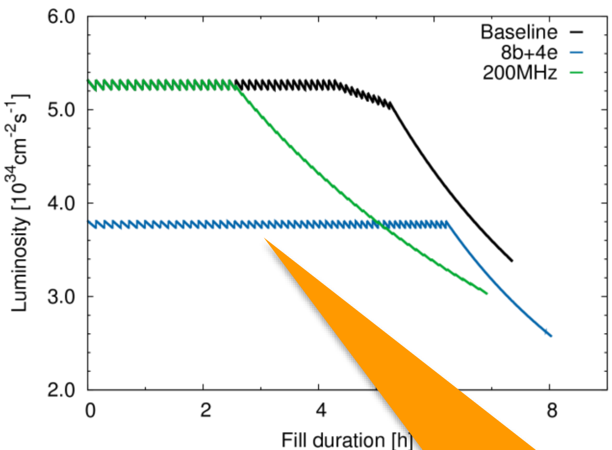


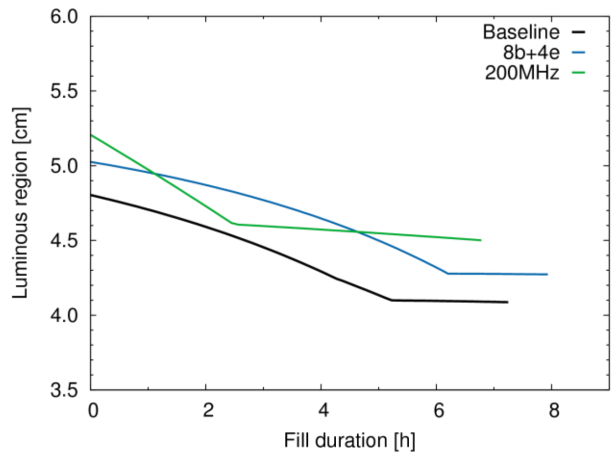
- In case scrubbing cannot reduce SEY_{dip} = SEY_{quad} below 1.40 ➔ Heat load exceeds the available cooling capacity for 400 MHz system
- Long bunches provided by 200 MHz system would allow operating within the cryo limits
- Crab cavities less efficient ➔ stronger effect of the RF curvature
- Requires new HW – not in baseline

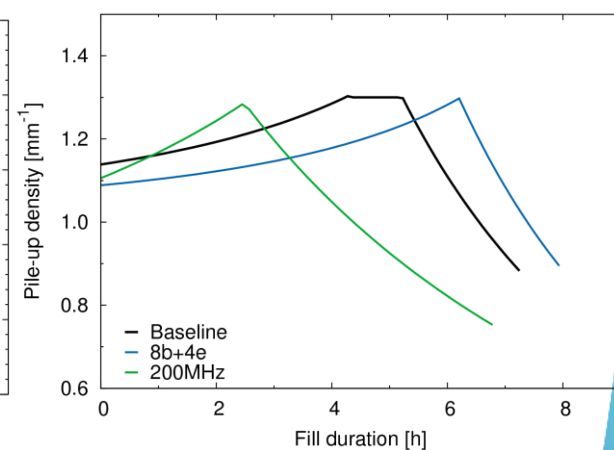


Luminous region/performance 8b+4e and 200MHz

- Scenarios for mitigation of electron cloud effects:
  - 8b+4e ➔ -25% integrated luminosity wrt baseline
  - 200 MHz ➔ -14% integrated luminosity wrt baseline



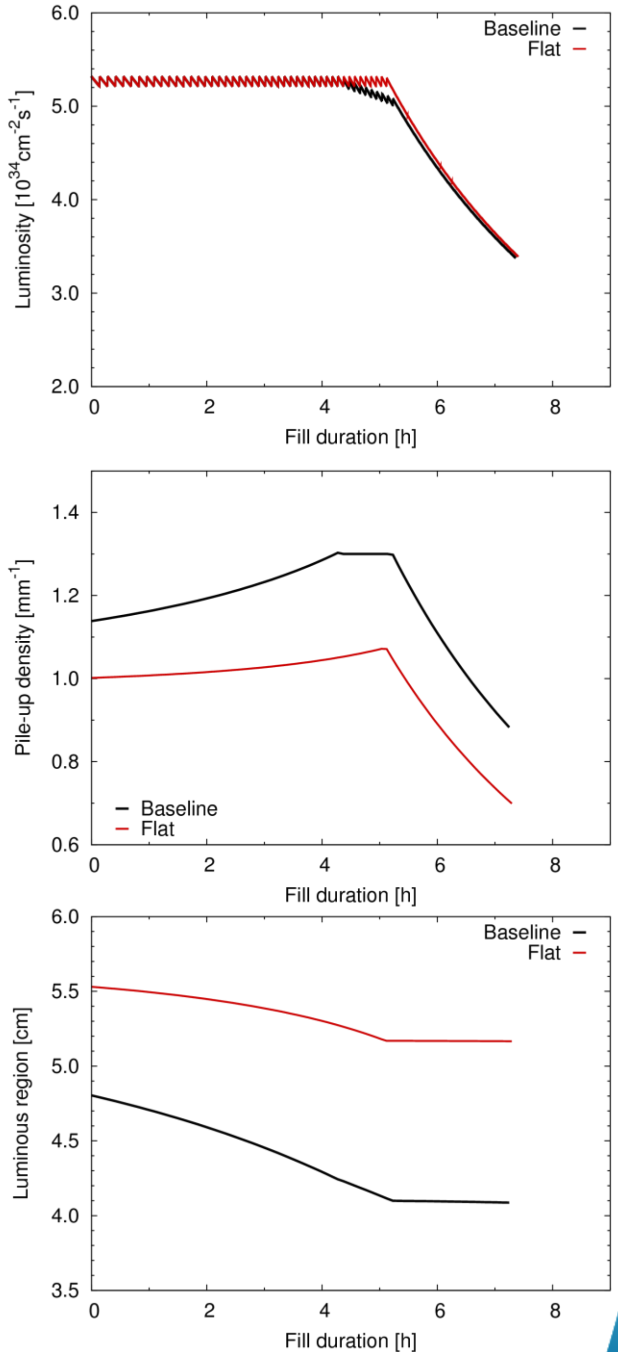




8b+4e: Lower number of bunches – 5% larger bunch population

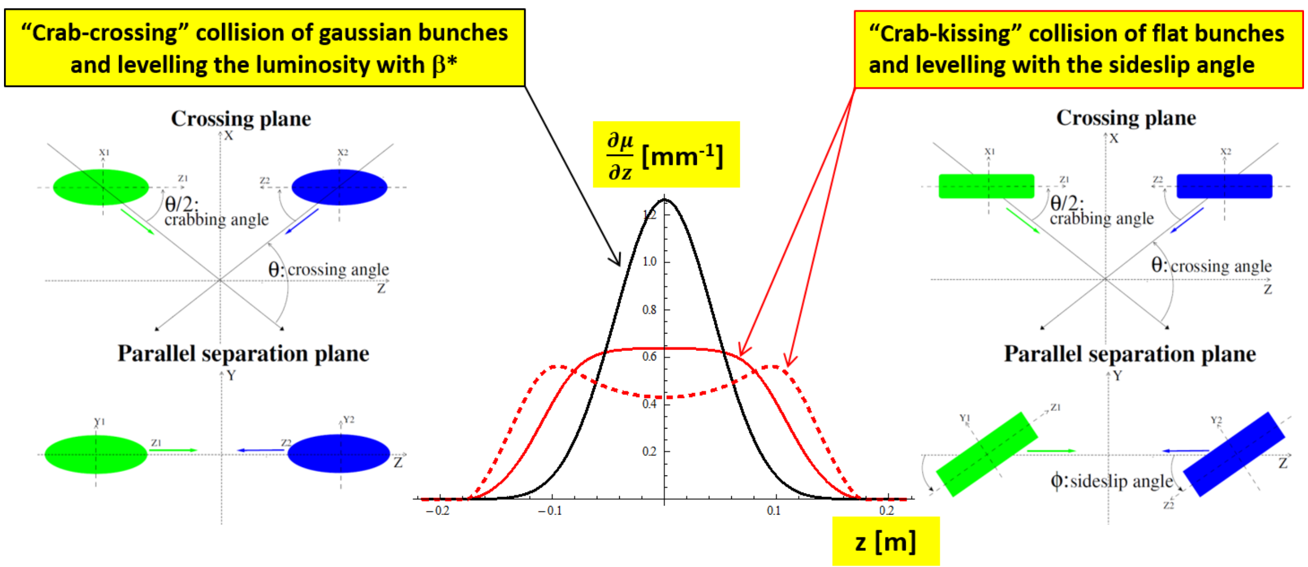
Flat Optics

- Flat optics with β^* = 40 cm / 15 cm and 12 σ beam separation ➔ pushed scenario to be proven by experience with flat optics (not baseline). Might require beam-beam long range compensation.
- Lower peak pile-up density w.r.t. baseline
- Integrated luminosity comparable to nominal but reduction of the peak pile-up density



Crab Kissing

- Scenario studied (S. Fartoukh) to reduce pile-up density. Requires:
  - Crab-cavities in both || and X-sing planes (levelling with both sets of CCs)
  - Flat optics
  - Bunch charge distribution as flat as possible for more PU density flatness (800 MHz or longitudinal profile shaping by RF noise)
  - Requires additional HW (not in baseline)



  - Provides the lowest peak pile-up density of ~0.6-0.65 events/xing/mm with little reduction on integrated luminosity (~5%)

Summary Table

Scenario	Max. PU [events/xing]	Max. PU density [events /xing/mm]	Luminous Region long. r.m.s. size [cm]	$\Delta L_{int}/L_{nom}$ [%]	Additional HW [Y/N]
Nominal	**140**	**1.3**	**<4.8**	**0**	**N**
Ultimate	**200**	**1.9**	**<4.5**	**+33**	**N**
8b+4e	140	1.3	<5	-25	N
200 MHz	140	1.3	<4.8	-14	Y
Flat	140	1.1	<5.5	0	May be
Crab kissing	140	0.6-0.65	<7	-5	Y

Summary

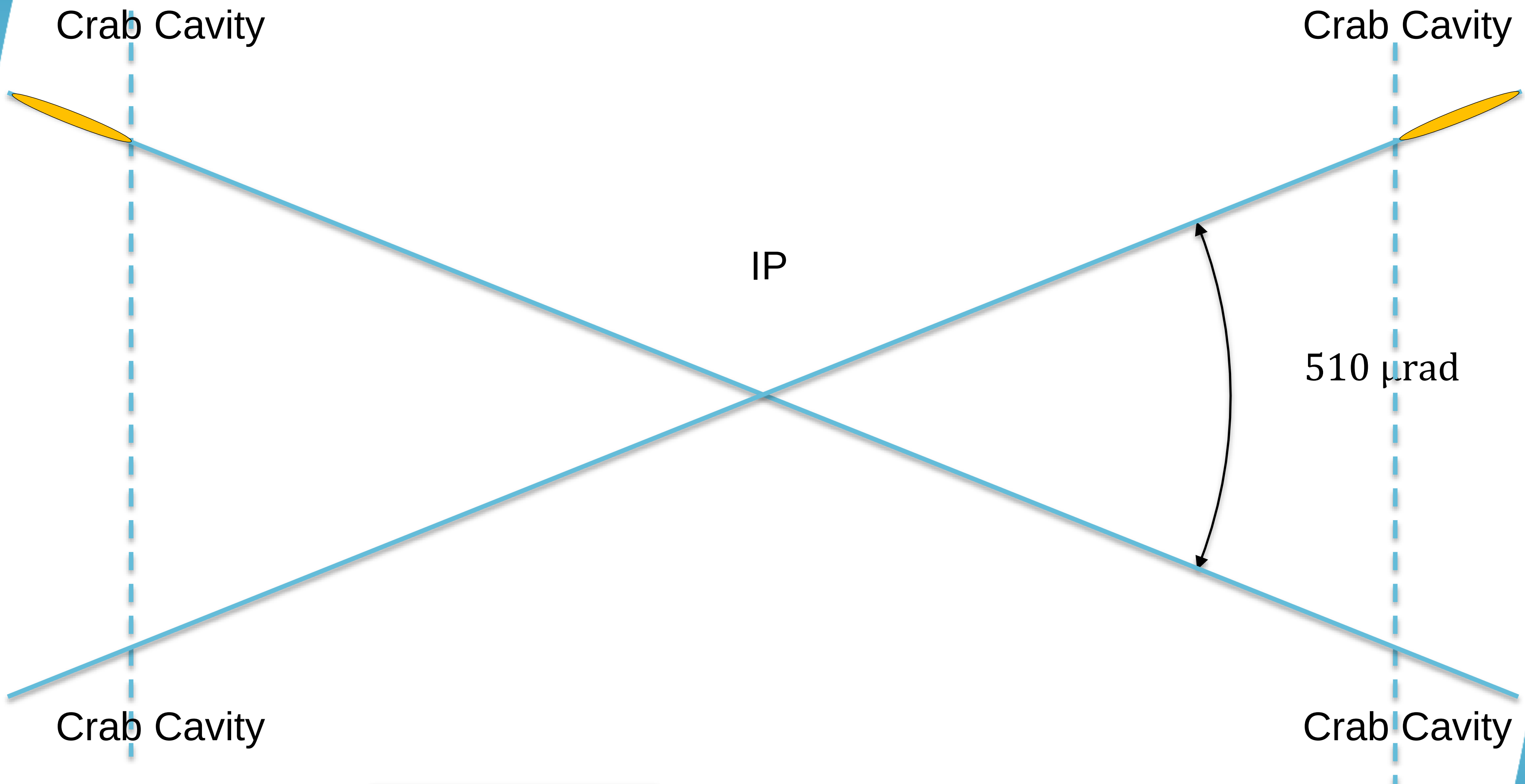
- An overview of the parameters affecting luminous region has been sketched
- The range of parameters for the nominal and ultimate parameters has been given
- A few non baseline scenarios have been sketched with the aim of providing the luminous region parameter space for the estimate of the performance of the detectors
- Basis for understanding detector performance and devise improved scenarios

HiLumi
HL-LHC PROJECT

Thank you for your attention!

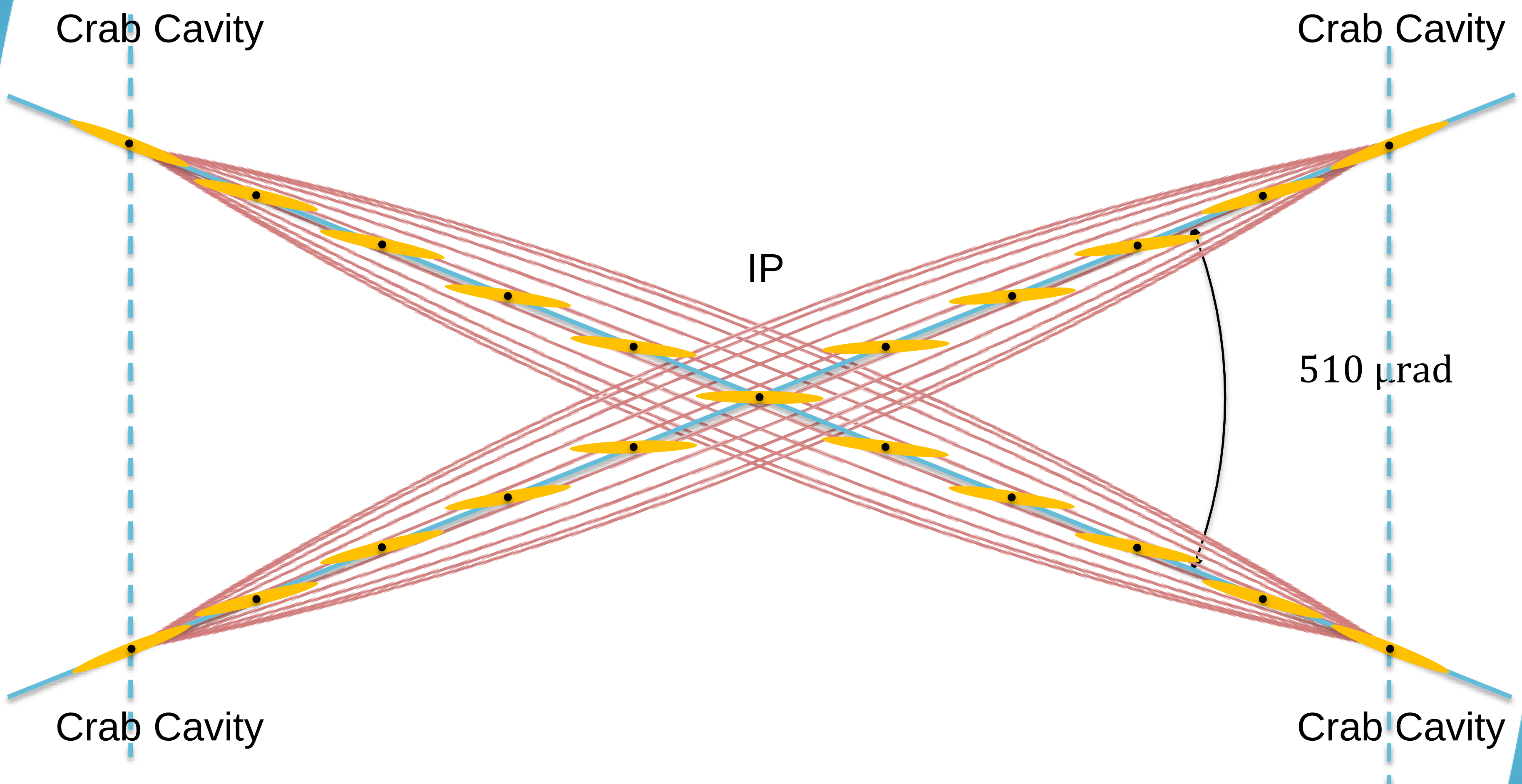
Acknowledgements: EDQ Working Group Members

Other features

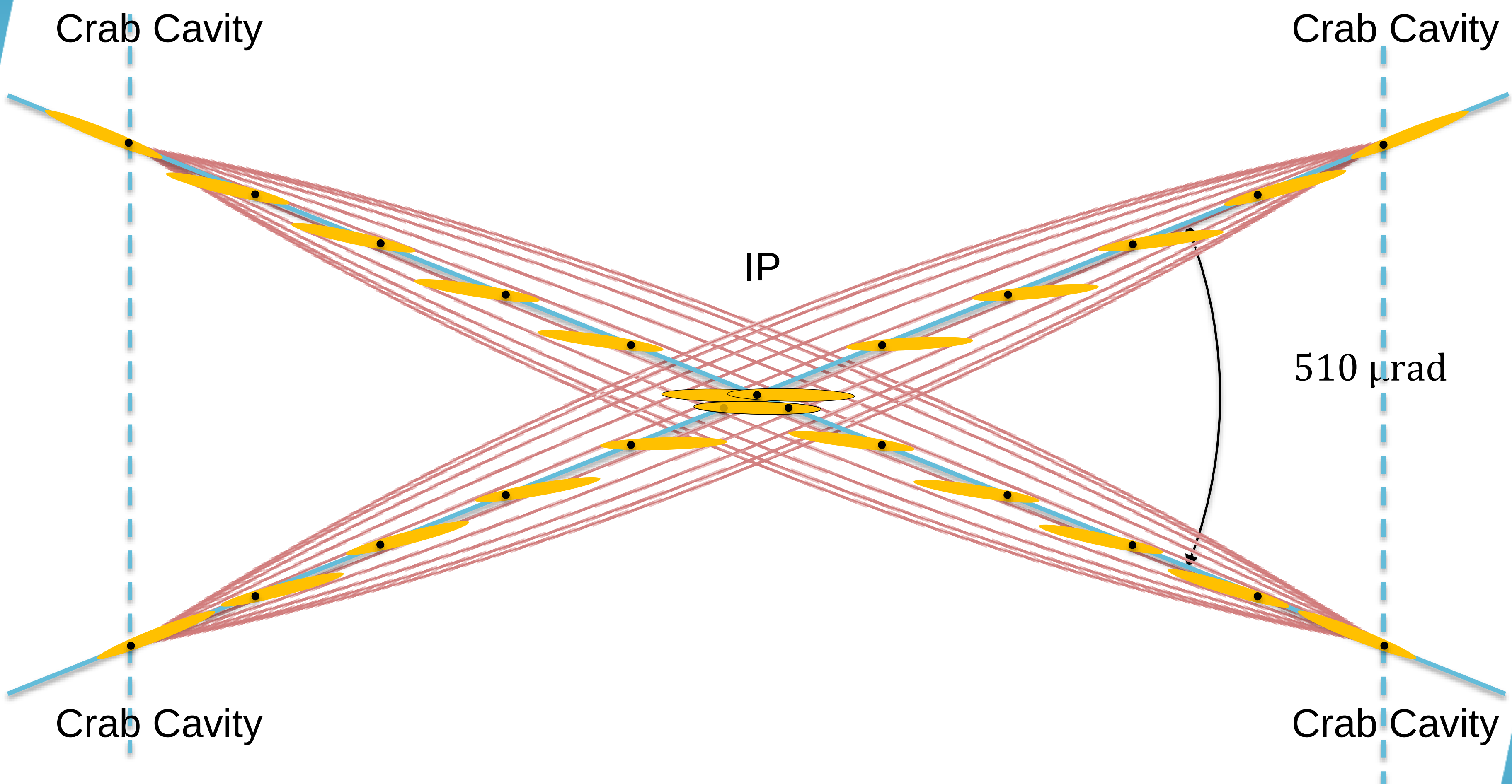


E. Jensen

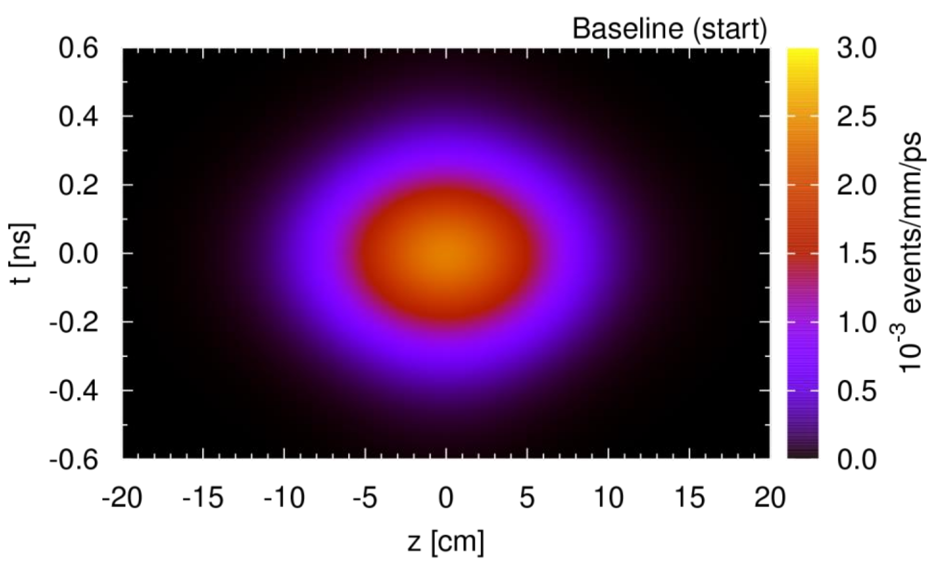
Other features

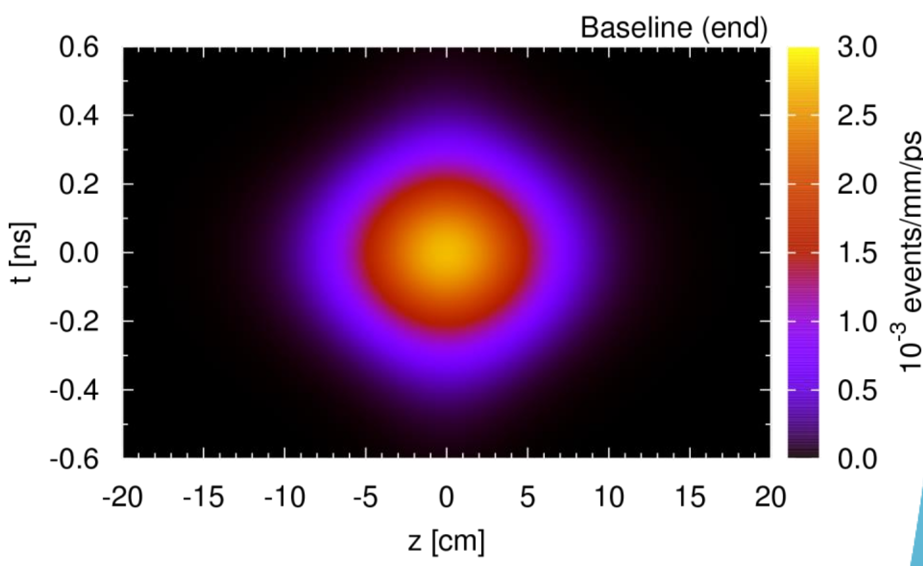


Other features



Baseline


Baseline (start)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
t [ns]
-20
-15
-10
-5
0
5
10
15
20
z [cm]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^{-3} events/mm/ps


Baseline (end)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
t [ns]
-20
-15
-10
-5
0
5
10
15
20
z [cm]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^{-3} events/mm/ps