Two Scenarios for the LHC Luminosity Upgrade

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outline

- beam parameters
- features, IR layout, merits and challenges of both scenarios
- beam-beam effect with transverse offset
- luminosity evolution
- bunch structures
- comments on S-LHCb
- luminosity leveling
- summary & recommendations

parameter	symbol	nominal	ultimate	12.5 ns, short
transverse emittance	ε [μm]	3.75	3.75	3.75
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7
bunch spacing	Δt [ns]	25	25	12.5
beam current	I [A]	0.58	0.86	1.72
longitudinal profile		Gauss	Gauss	Gauss
rms bunch length	σ_z [cm]	7.55	7.55	3.78
beta* at IP1&5	β* [m]	0.55	0.5	0.25
full crossing angle	θ_c [μrad]	285	315	445
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.64	0.75	0.75
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	2.3	9.2
peak events per crossing		19	44	88
initial lumi lifetime	τ_L [h]	22	14	7.2
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.46	0.91	2.7
	$T_{run,opt}$ [h]	21.2	17.0	12.0
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	0.56	1.15	3.6
	$T_{run,opt}$ [h]	15.0	12.0	8.5
e-c heat SEY=1.4(1.3)	P [W/m]	1.07 (0.44)	1.04 (0.59)	13.34 (7.85)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.17	0.25	0.5
image current heat	P_{IC} [W/m]	0.15	0.33	1.87
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.04 (0.38)	0.06 (0.56)	0.113 (1.13)
extent luminous region	σ_l [cm]	4.5	4.3	2.1
comment				partial wire c.

baseline upgrade parameters 2001-2005

abandoned at LUMI'06

(SR and image current heat load well known)

total heat far exceeds max. local cooling capacity of 2.4 W/m

W. Scandale/F. Zimmermann, 13.02.2007

parameter	symbol	25 ns, small β*	50 ns, long
transverse emittance	ε [μm]	3.75	3.75
protons per bunch	N_b [10^{11}]	1.7	4.9
bunch spacing	Δt [ns]	25	50
beam current	I [A]	0.86	1.22
longitudinal profile		Gauss	Flat
rms bunch length	σ_z [cm]	7.55	11.8
beta* at IP1&5	β* [m]	0.08	0.25
full crossing angle	θ_c [μrad]	0	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0	2.0
hourglass reduction		0.86	0.99
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	15.5	10.7
peak events per crossing		294	403
initial lumi lifetime	τ_L [h]	2.2	4.5
effective luminosity ($T_{turnaround}$=10 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	2.4	2.5
	$T_{run,opt}$ [h]	6.6	9.5
effective luminosity ($T_{turnaround}$=5 h)	L_{eff} [10^{34} cm^{-2}s^{-1}]	3.6	3.5
	$T_{run,opt}$ [h]	4.6	6.7
e-c heat SEY=1.4(1.3)	P [W/m]	1.04 (0.59)	0.36 (0.1)
SR heat load 4.6-20 K	P_{SR} [W/m]	0.25	0.36
image current heat	P_{IC} [W/m]	0.33	0.78
gas-s. 100 h (10 h) τ_b	P_{gas} [W/m]	0.06 (0.56)	0.09 (0.9)
extent luminous region	σ_l [cm]	3.7	5.3
comment		D0 + crab (+ Q0)	wire comp.

two new upgrade scenarios

compromises between heat load and # pile up events

for operation at beam-beam limit
with alternating planes of crossing at two IPs,
luminosity equation can be written as

$$L \approx \pi \gamma n_b \frac{(\gamma \varepsilon) f_{rev}}{r_p^2 \beta^*} \Delta Q_{bb}^2 \sqrt{1+\phi^2} F_{profile} F_{h-g}$$

$\downarrow$ 50 ns $\downarrow\downarrow$ 25 ns $\uparrow\uparrow$ 50 ns

$\downarrow$ 50 ns

where ΔQ_{bb} = total beam-beam tune shift

(hourglass effect is neglected above)

25-ns low-β upgrade scenario

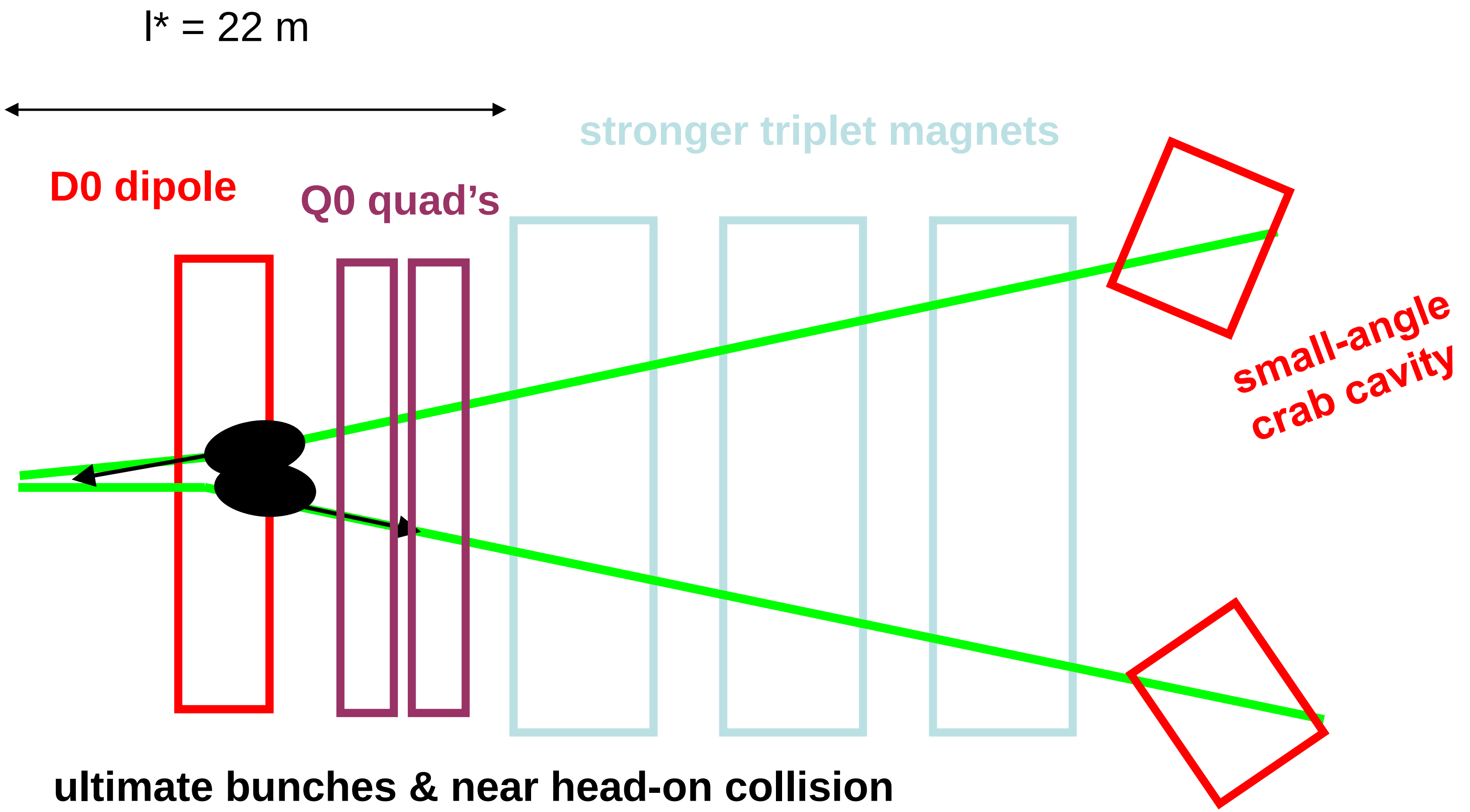
- stay with ultimate LHC beam (1.7×10^{11} protons/bunch, 25 spacing)
- squeeze β* below ~10 cm in ATLAS & CMS
- add early-separation dipoles in detectors, one at ~ 3 m, the other at ~ 8 m from IP
- possibly also add quadrupole-doublet inside detector at ~13 m from IP
- and add crab cavities ($\phi_{Piwinski} \sim 0$), and/or shorten bunches with massive addt'l RF

→ new hardware inside ATLAS & CMS,

→ first hadron-beam crab cavities

(J.-P. Koutchouk et al)

CMS & ATLAS IR layout for 25-ns option



ultimate bunches & near head-on collision

25-ns scenario assessment (accelerator view point)

merits:

negligible long-range collisions,
no geometric luminosity loss,
no increase in beam current beyond ultimate

challenges:

D0 dipole deep inside detector (~3 m from IP),
Q0 doublet inside detector (~13 m from IP),
crab cavity for hadron beams (emittance growth),
4 parasitic collisions at 4-5σ separation,
"chromatic beam-beam" $Q'_{eff} \sim \sigma_z/(4\pi\beta^*\sigma_\delta)$,
poor beam and luminosity lifetime ~β*

4 parasitic collisions at 4-5σ offset
in 25-ns low-β case

<u>concerns:</u>

- poor beam lifetime
- enhanced detector background

discouraging experience at RHIC, SPS, HERA and Tevatron

50-ns higher β* upgrade scenario

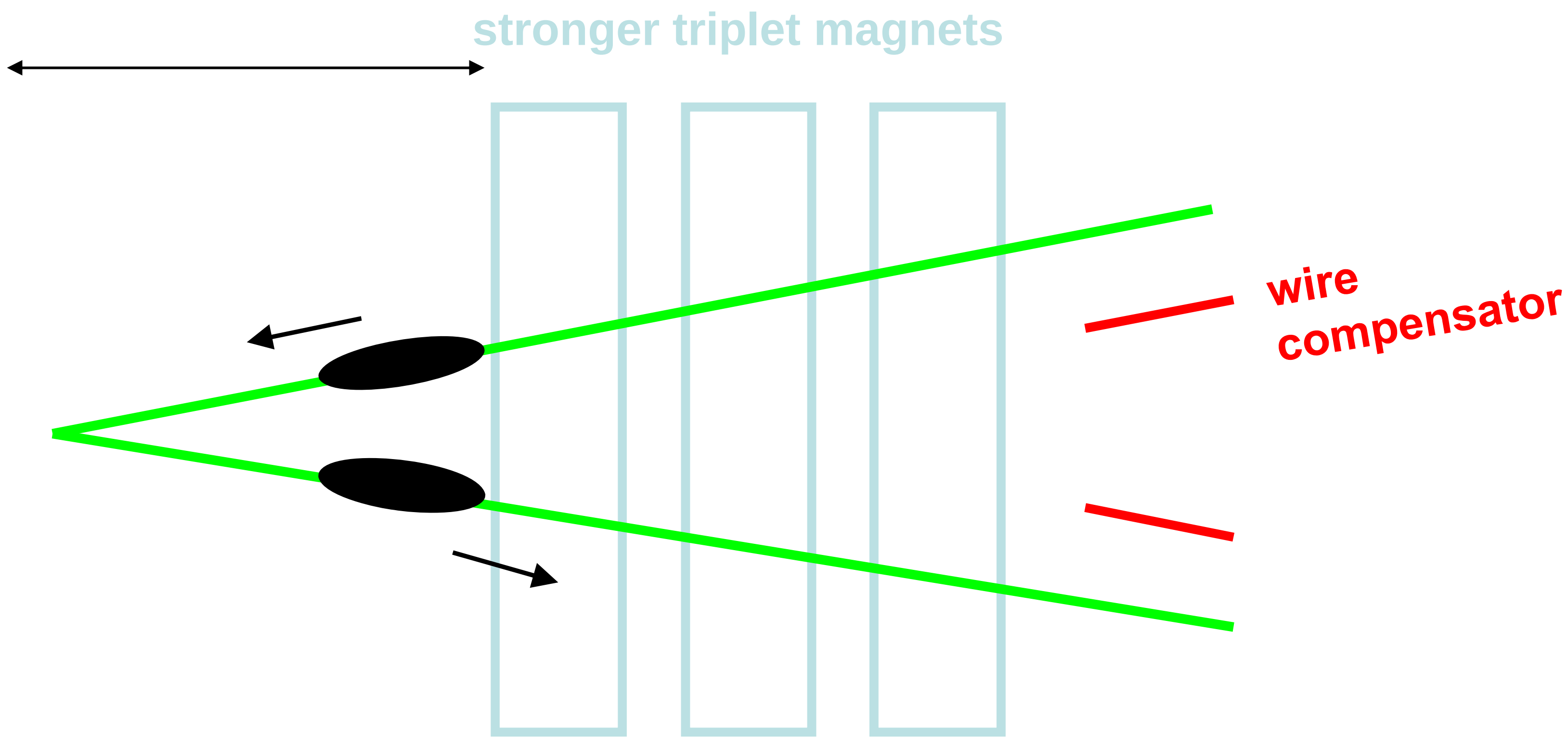
- double bunch spacing
- longer & more intense bunches with $\phi_{\mathrm{Piwinski}} \sim 2$
- keep β*~25 cm (achieved by stronger low-β quads alone)
- do not add any elements inside detectors
- long-range beam-beam wire compensation

→ novel operating regime for hadron colliders

(W. Scandale, F.Zimmermann & PAF)

CMS & ATLAS IR layout for 50-ns option

l* = 22 m



long bunches & nonzero crossing angle & wire compensation

50-ns scenario assessment (accelerator view point)

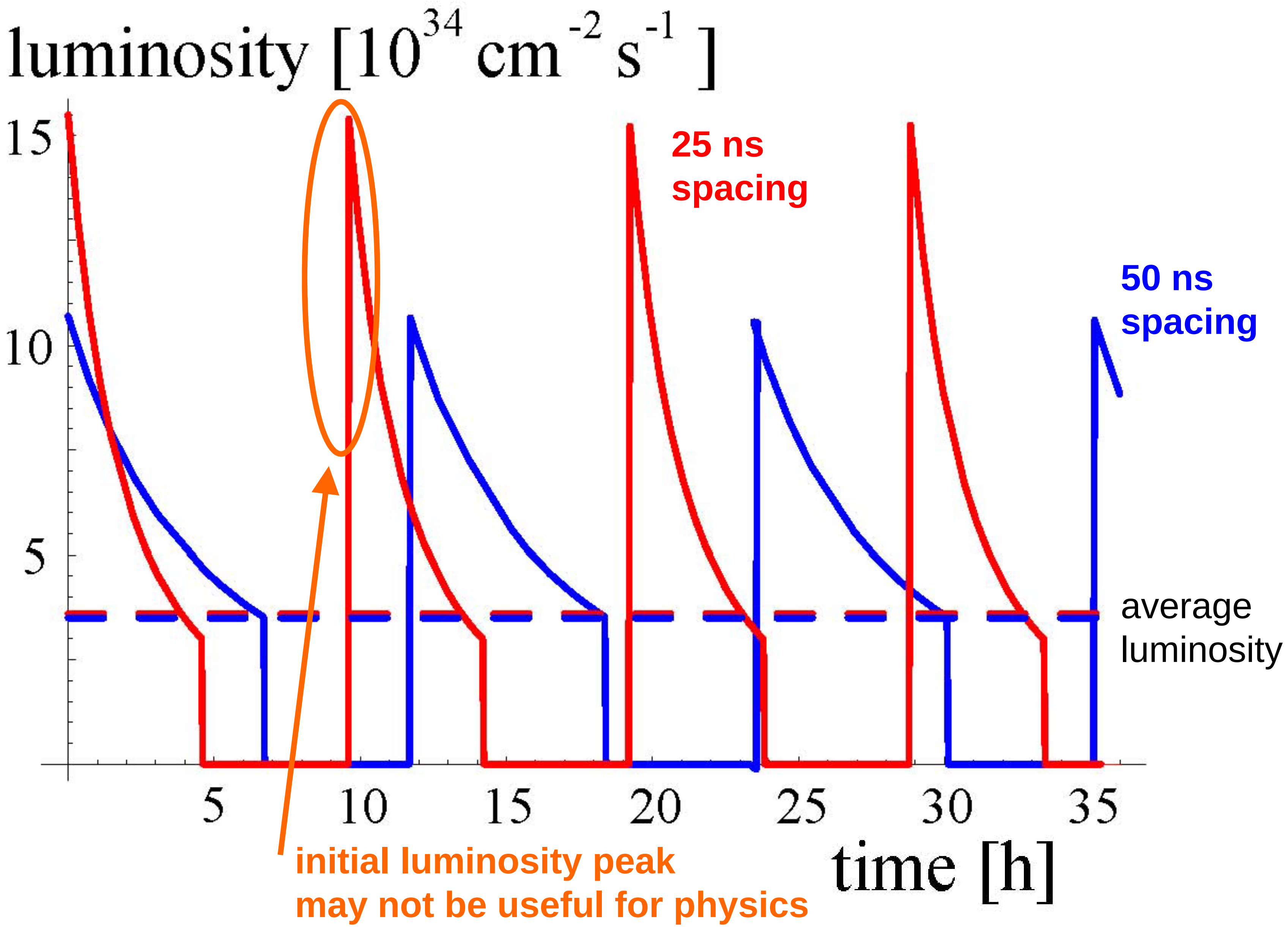
merits:

no elements in detector, no crab cavities,
lower chromaticity,
less demand on IR quadrupoles (NbTi possible)

challenges:

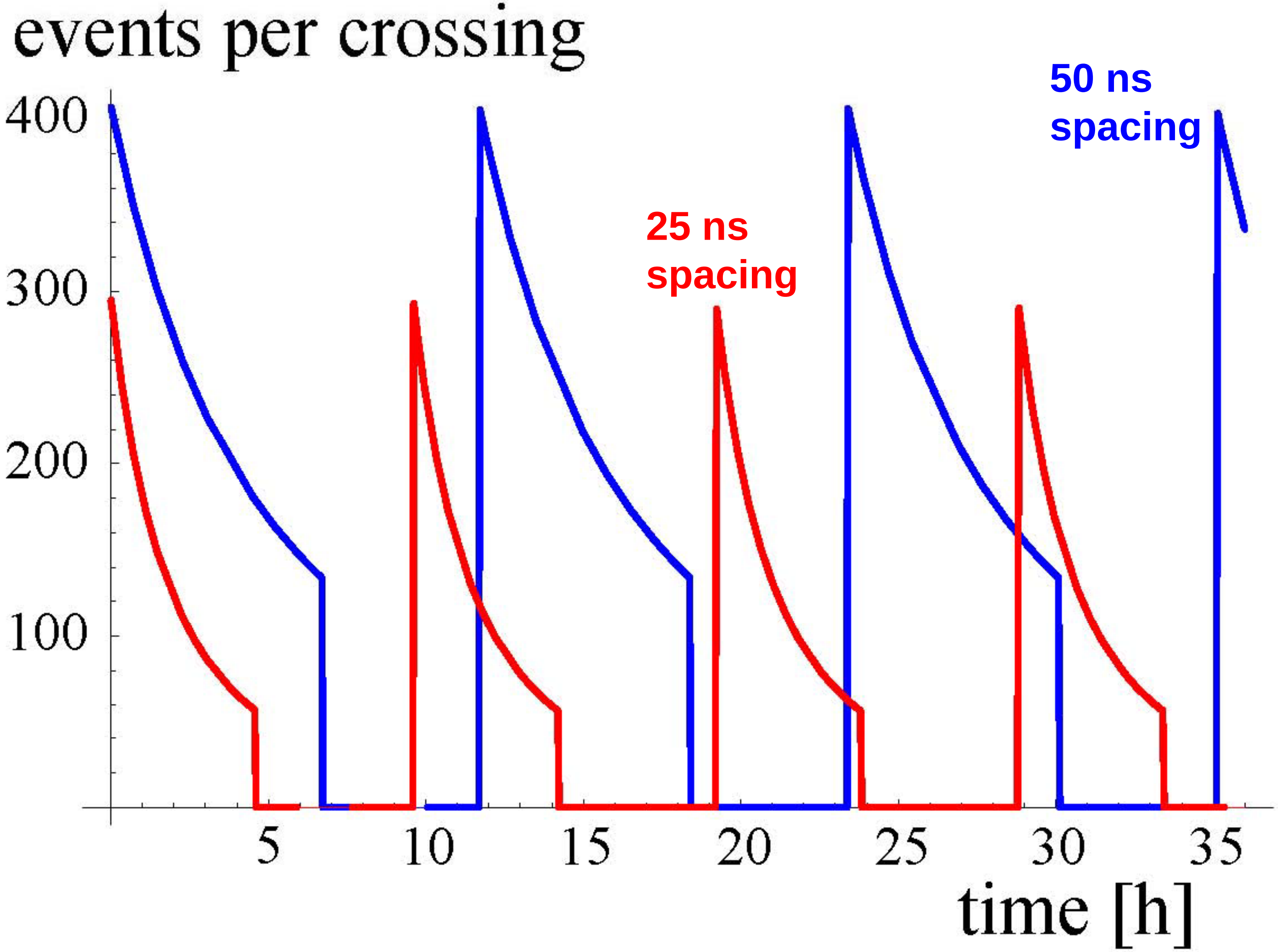
operation with large Piwinski parameter unproven for hadron beams,
high bunch charge,
beam production and acceleration through SPS,
"chromatic beam-beam" $Q'_{eff} \sim \sigma_z/(4\pi\beta^*\sigma_\delta)$,
larger beam current,
wire compensation (almost etablished)

IP1& 5 luminosity evolution for 25-ns and 50-ns spacing

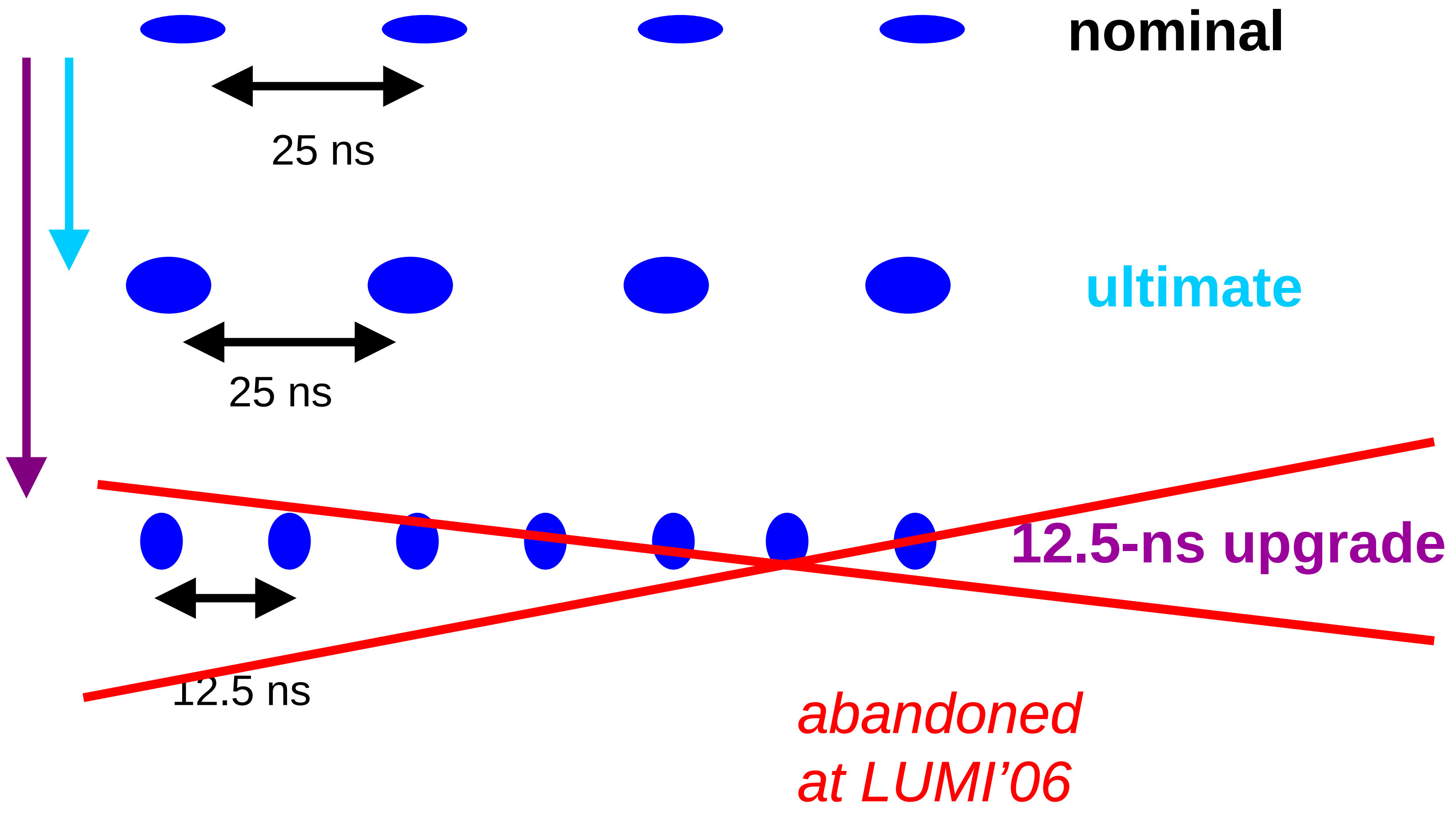


W. Scandale/F. Zimmermann, 19.03.2007

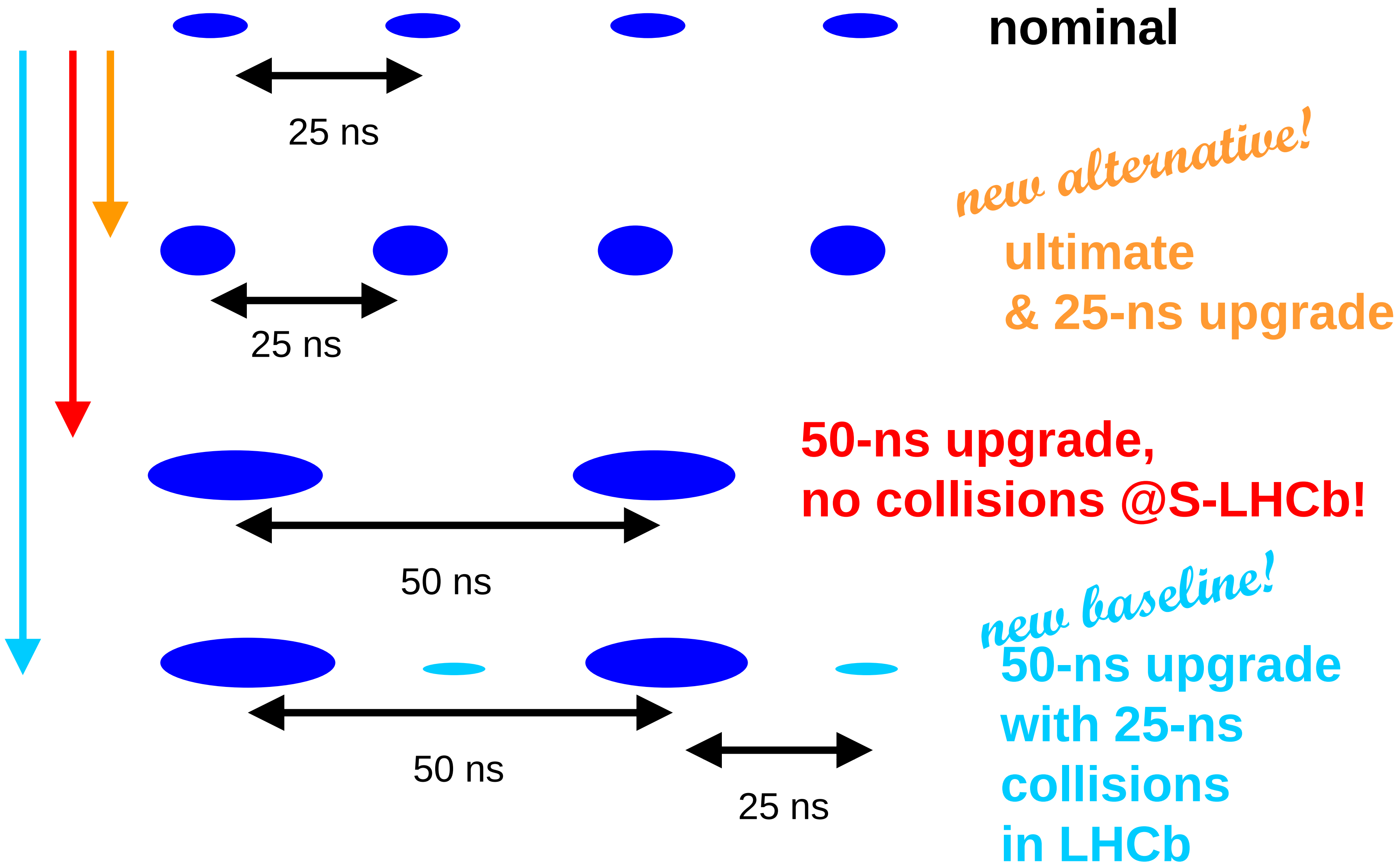
IP1& 5 event pile up for 25-ns and 50-ns spacing



old upgrade bunch structure



new upgrade bunch structures



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S-LHCb collision parameters

parameter	symbol	25 ns, offset	25 ns, late collision	50 ns, satellites
collision spacing	T_{coll}	25 ns	25 ns	25 ns
protons per bunch	N_b [10^{11}]	1.7	1.7	4.9 & 0.3
longitudinal profile		Gaussian	Gaussian	flat
rms bunch length	σ_z [cm]	7.55	7.55	11.8
beta* at LHCb	$\beta*$ [m]	0.08	3	3
rms beam size	$\sigma_{x,y}$* [μm]	6	40	40
rms divergence	$\sigma_{x',y'}$* [μrad]	80	13	13
full crossing angle	θ_c [urad]	550	180	180
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	3.3	0.18	0.28
peak luminosity	L [10^{33} cm^{-2}s^{-1}]	1.13	2.1	2.4
effective luminosity (5 h turnaround time)	L_{eff} [10^{33} cm^{-2}s^{-1}]	0.25	0.35	0.67
initial lumi lifetime	τ_L [h]	1.8	2.8	9
length of lum. region	σ_l [cm]	1.6	5.3	8.0

rms length of luminous region: $$\boxed{\frac{1}{\sigma_l^2} \approx \left(\frac{2}{\sigma_z^2} + \frac{\theta_c^2}{2\sigma^{*2}_{x,y}}\right)}$$

F. Zimmermann, W. Scandale, 19.03.2007

luminosity leveling in IP1&5

experiments prefer more constant luminosity, less pile up at the start of run, higher luminosity at end

how could we achieve this?

25-ns low-β scheme:
dynamic β squeeze

Novel proposal under investigation
Change the crossing angle
G. Sterbini

50-ns higher-β scheme:
dynamic β squeeze, and/or
dynamic reduction in bunch length
(less invasive)

leveling equations

$$events/Xing = \frac{L_0 \sigma_{inel}}{n_b} \approx const \qquad L = L_0 \approx const$$

$$N = N_0 - \frac{L_0 \sigma_{tot} n_{IP}}{n_b} t$$

beam intensity decays linearly

length of run

$$t_{run} = \frac{\Delta N_{\max} n_b}{L \sigma_{tot} n_{IP}}$$

average luminosity

$$L_{ave} = \frac{L_0}{1 + \frac{L_0 \sigma_{tot} n_{IP}}{\Delta N_{\max} n_b} T_{turn-around}}$$

	25 ns, low β*, with leveling	50 ns, long bunches, with leveling
events/crossing run time av. luminosity	300 N/A N/A	300 2.5 h $2.6\times10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity	150 2.5 h $2.6\times10^{34}s^{-1}cm^{-2}$	150 14.8 h $2.9\times10^{34}s^{-1}cm^{-2}$
events/crossing run time av. luminosity	75 9.9 h $2.6\times10^{34}s^{-1}cm^{-2}$	75 26.4 h $1.7\times10^{34}s^{-1}cm^{-2}$

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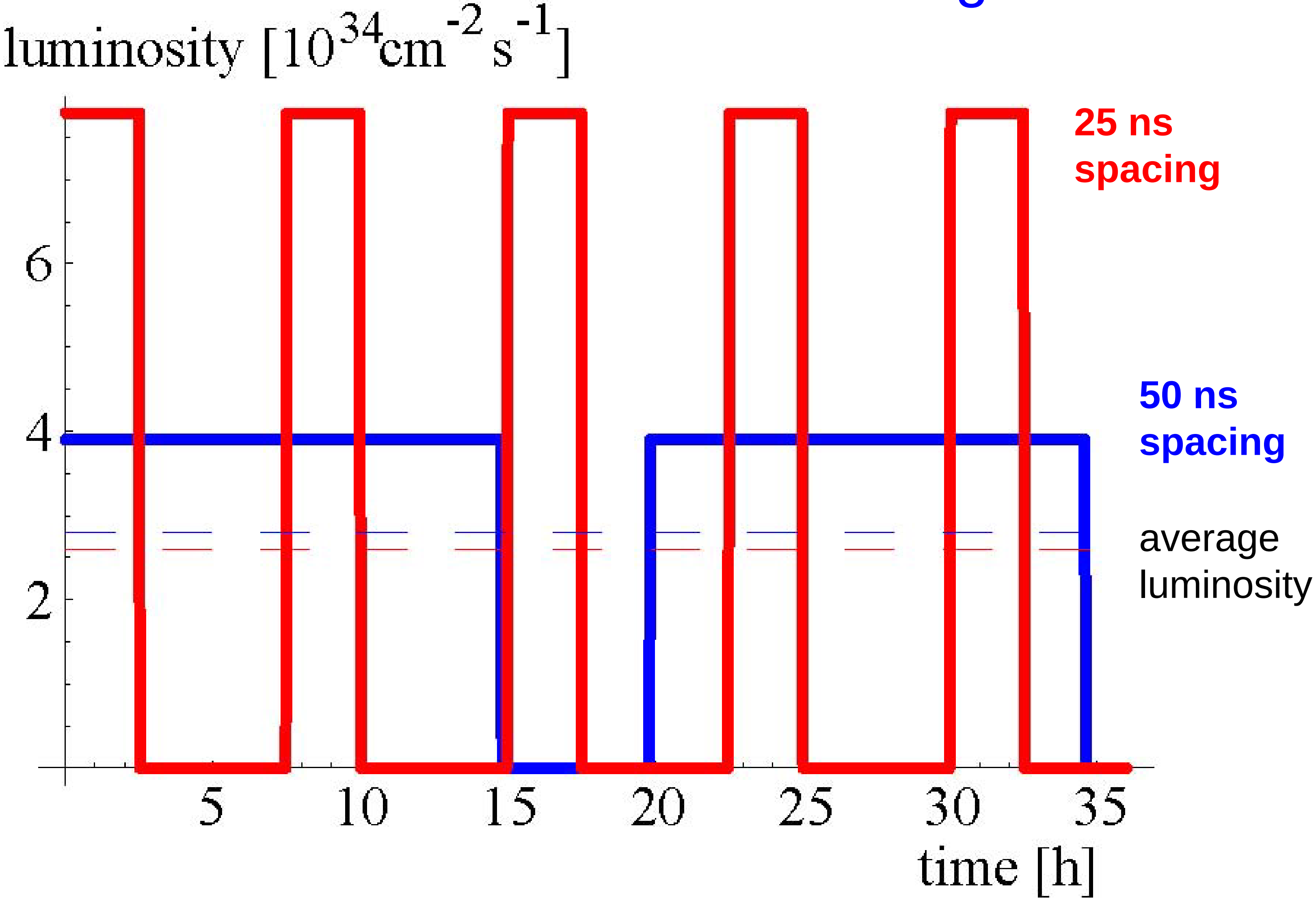
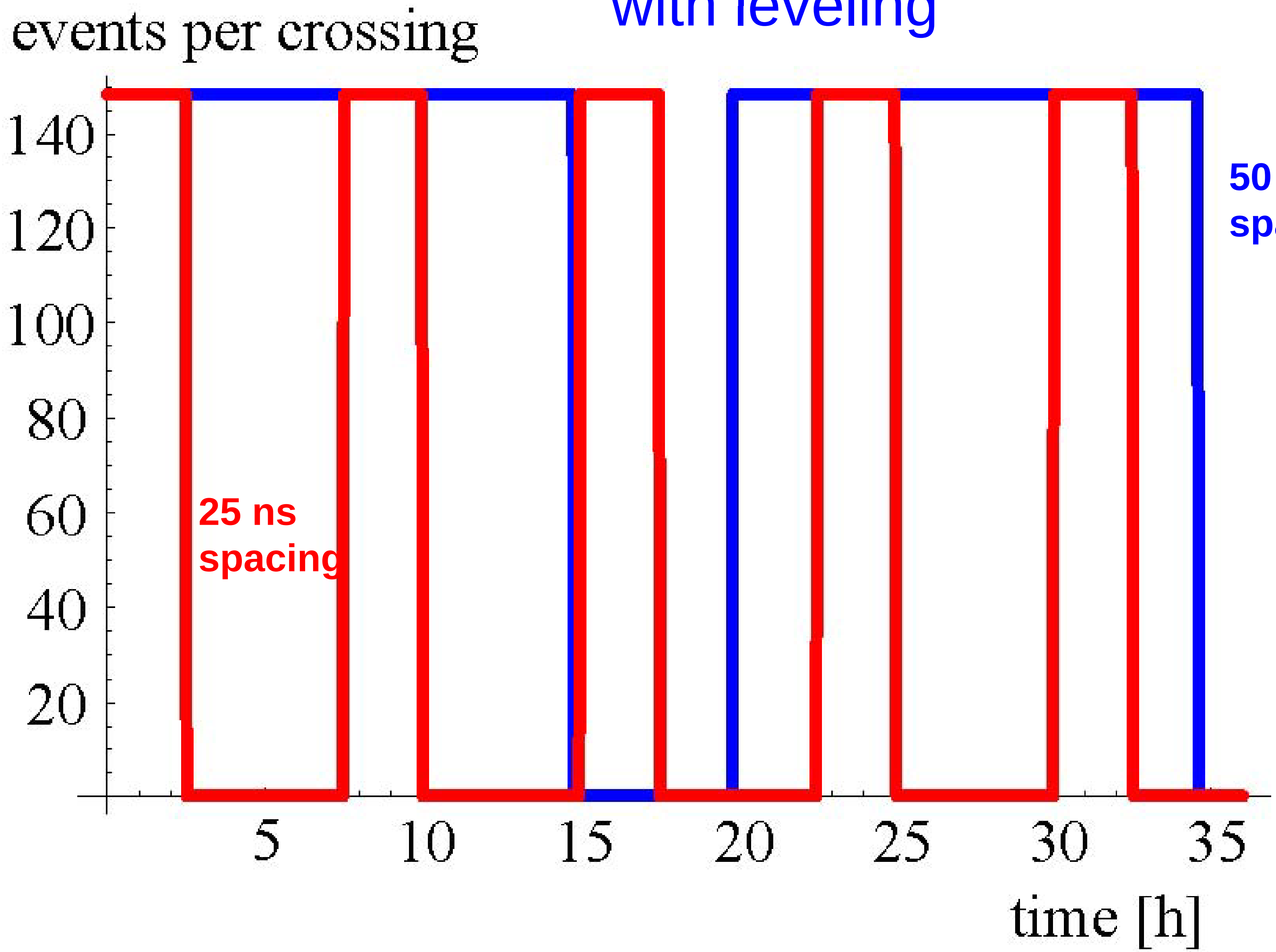
assuming 5 h turn-around time

IP1& 5 luminosity evolution for 25-ns and 50-ns spacing with leveling



IP1& 5 event pile up for 25-ns and 50-ns spacing with leveling



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summary

- two scenarios of L~10^{35} $cm^{-2}s^{-1}$ for which heat load and #events/crossing are acceptable
- 25-ns option: pushes β*; requires slim magnets inside detector, crab cavities, & Nb_3Sn quadrupoles and/or Q0 doublet; attractive if total beam current is limited; transformed to a 50-ns spacing by keeping only 1/2 the number of bunches
- 50-ns option: has fewer longer bunches of higher charge ; can be realized with NbTi technology if needed ; compatible with LHCb ; open issues are SPS & beam-beam effects at large Piwinski angle; luminosity leveling may be done via bunch length and via β*

recommendations

- **luminosity leveling** should be seriously considered: → higher quality events,

  → moderate decrease in average luminosity
- it seems **long-bunch 50-ns option entails less risk** and less uncertainties; however not w/o problems
- leaving the **25-ns option as back up** until we have gained some experience with the real LHC may be wise
- needed for both scenarios are **concrete optics solutions**, **beam-beam tracking studies**, and **beam-beam machine experiments**