Parameter update for the nominal HL-LHC: Standard, BCMS, and 8b+4e

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with input from WP4

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Current HL-LHC Parameters table [link]

HL-LHC Parameters V4.2.1 (Last updated 13-November-2015)

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)	HL-LHC 25ns (BCMS) 9	HL-LHC 8b+4e[12]
Beam energy in collision [TeV]	7	7	7	7
N_b	1.15E+11	2.2E+11	2.2E+11	2.3E+11
n_b	2808	2748	2604	1968
Number of collisions in IP1 and IP5 [1]	2808	2736	2592	1960
N_{tot}	3.2E+14	6.0E+14	5.7E+14	4.5E+14
beam current [A]	0.58	1.09	1.03	0.82
x-ing angle [μrad]	285	590	590	554 [10]
beam separation [σ] [11]	9.4	12.5	12.5	12.5 [10]
β^* [m]	0.55	0.15	0.15	0.15
ε_n [μm]	3.75	2.50	2.50	2.20
ε_L [eVs]	2.50	2.50	2.50	2.50
r.m.s. energy spread	1.13E-04	1.13E-04	1.13E-04	1.13E-04
r.m.s. bunch length [m]	7.55E-02	7.55E-02	7.55E-02	7.55E-02
IBS horizontal [h]	80 -> 106	18.5	18.5	13.1
IBS longitudinal [h]	61 -> 60	20.4	20.4	17.6
Piwinski parameter	0.65	3.14	3.14	3.14
Total loss factor R0 without crab-cavity	0.836	0.305	0.305	0.304
Total loss factor R1 with crab-cavity [13]	(0.981)	0.829	0.829	0.828
beam-beam / IP without Crab Cavity	3.1E-03	3.3E-03	3.3E-03	3.9E-03
beam-beam / IP with Crab cavity [13]	3.8E-03	1.1E-02	1.1E-02	1.3E-02
Peak Luminosity without crab-cavity [cm^{-2} s^{-1}]	1.00E+34	7.18E+34	6.80E+34	6.38E+34
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [cm^{-2} s^{-1}] [13]	(1.18E+34)	19.54E+34	18.52E+34	17.40E+34
Events / crossing without levelling and without crab-cavity	27	198	198	246
Levelled Luminosity [cm^{-2} s^{-1}]	-	5.00E+34 [5]	5.00E+34	3.63E+34
Events / crossing (with leveling and crab-cavities for HL-LHC) [8]	27	138	146	140
Peak line density of pile up event [event/mm] (max over stable beams) [13]	0.21	1.25	1.31	1.28
Leveling time [h] (assuming no emittance growth) [8, 13]	-	8.3	7.6	9.5

Assumptions I

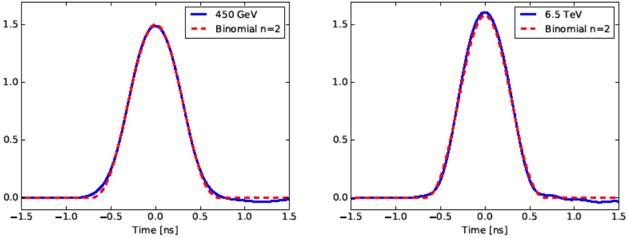
- Round optics: $\beta^* = 20\,\text{cm}$, 12.5σ.
- Two crab cavities (CCs): only partial compensation (380 μrad) of the crossing angle (510 μrad).
- Bunch length: 9 cm ($4\sigma = 1.2\,\text{ns}$) due to RF needs margin to ensure stability [E. Shaposhnikova, 78th HL-LHC WP2 Meeting].
- **New longitudinal bunch profile** [E. Shaposhnikova, 82th HL-LHC WP2 Meeting].

Assumptions II

- β^*-levelling: a step is performed whenever the deviation from the target value reaches 2 %.
- Crossing angle (in µrad) is kept constant while the beam separation (in σ) is reduced.
- Constant bunch length.
- 40 h vertical emittance growth time.
- Conservative emittance blow-up for the BCMS beam.
- Efficiency: $\eta = 50\,\%$, for $3000\,\mathrm{fb}^{-1}$.
- Conservative cross section for burn-off: 111 mb (total).

Bunch profiles in a single RF system (measured and fitted)

Binomial line density distribution $\lambda(t) = \lambda_0(1 - 4t^2/\tau^2)^{2.5}$ fits well present LHC bunches (in a single RF) on flat bottom and at beginning of flat top (after controlled emittance with band-limited noise during ramp)

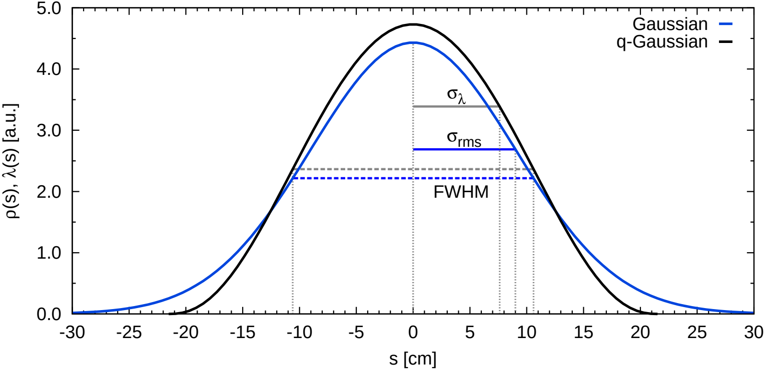


- Real bunch tails are more populated (also visible from the PD Schottky)
- Profiles become Gaussian after a few hours due to IBS and SR

E. Shaposhnikova, 78th HL-LHC WP2 Meeting

- Stability threshold is related to the *full width at half maximum* (FWHM) for different distributions.

q-Gaussian longitudinal bunch profile



- The new bunch profile can be derived as a particular case of the **q-Gaussian** distribution [Y. Papaphilippou].
- For $\sigma_{\text{rms}} = 9\,\text{cm}$ ($4\sigma = 1.2\,\text{ns}$),

$$\text{FWHM} \approx 2.355\sigma_{\text{rms}} = 21.2\,\text{cm}, \quad \text{and} \quad \sigma_\lambda = 7.6\,\text{cm}.$$

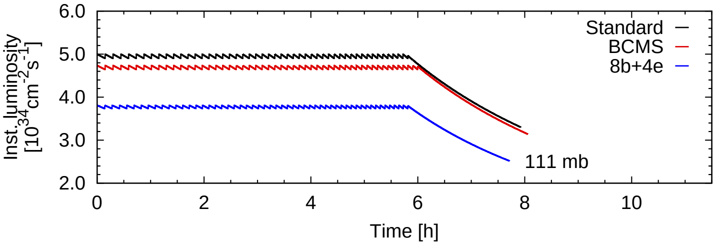
Nominal Parameter Table I

	Standard	BCMS	8b+4e
E [TeV]	7	7	7
N_b [10^{11}]	2.2	2.2	2.2
n_{bunches}	2748	2604	1968
No. collisions IP1&5	2736	2592	1960
N_{tot} [10^{14}]	6.05	5.73	4.33
Beam current [A]	1.10	1.04	0.79
x-sing angle [μrad]	512	512	480
Beam separation [σ]	12.5	12.5	12.5
β^* [m]	0.20	0.20	0.20
ϵ_n [μm]	2.5	2.5	2.2
E spread [10^{-4}]	1.2	1.2	1.2
Gaussian RMS bunch length [cm]	9.0	9.0	9.0
RMS bunch length [cm]	7.6	7.6	7.6
FWHM [cm]	21.2	21.2	21.2
IBS horizontal [h]	18.8	18.8	14.3
IBS longitudinal [h]	25.0	25.0	21.5
Piwinski parameter	2.4	2.4	2.4

Nominal Parameter Table II

	Standard	BCMS	8b+4e
Loss factor no CC	0.38	0.38	0.38
Loss factor with CC	0.74	0.77	0.77
Beam-beam no CC [10^{-3}]	3.6	3.6	4.1
Beam-beam with CC [10^{-2}]	0.87	0.87	1.05
Peak lumi no CC [$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	6.67	6.32	5.43
Virtual lumi with CC [$10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	1.31	1.29	1.11
Pile-up without lev CC	176	176	200
Levelled lumi [$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	5.0	4.7	3.8
Pile-up with lev CC	132	132	140
Peak line pile-up density [mm^{-1}]	1.3	1.3	1.3
Eff. line pile-up density [mm^{-1}]	0.79	0.77	0.81
Levelling time [h]	5.8	6.0	5.8
N_b at injection [10^{11}]	2.3	2.3	2.3
Emittance at injection [µm]	2.1	1.7	1.7

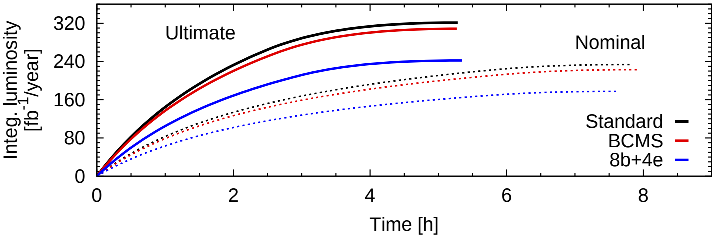
Luminosity



	Standard	BCMS	8b+4e
Fill duration [h]	7.8	8.0	7.6
Integrated luminosity [fb^{-1}/160 days]	234	223	177
Effective line pile-up dens. [mm^{-1}]	0.79	0.77	0.81

- For the standard HL-LHC with the q-Gaussian bunch profile: increments of 11 %, 2 %, and 3 %, on the virtual lumi, integrated lumi, and effective line PU density, respectively, w.r.t. Gaussian.

200 Pile-up



	Standard	BCMS	8b+4e
Fill duration [h]	5.3	5.3	5.3
Integrated luminosity [fb^{-1}/160 days]	321	309	242
Levelled lumi [$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]	7.5	7.1	5.4
Peak pile-up density [mm^{-1}]	1.9	1.9	1.8
Effective line pile-up dens. [mm^{-1}]	1.14	1.11	1.13

- Ultimate performance increased by $\sim 40\,\%$ with $\eta = 58\,\%$ and $\sigma_{\text{burn-off}} = 111\,\text{mb}$.

Summary I

- The q-Gaussian bunch profile yields, for the **standard HL-LHC** w.r.t. to the Gaussian case:
  - An increment of 2 % on the integrated lumi (**234 $\mathbf{fb^{-1}}$/160 days**).
  - An increment from 0.76 events/mm to **0.79 events/mm** on the effective line pile-up density.
- **BCMS** reduces the standard integrated lumi by $\sim 5\,\%$
- The integrated lumi of the **8b+4e** scenario is 24 % lower than the standard
- 200MHz scenario to be further studied.

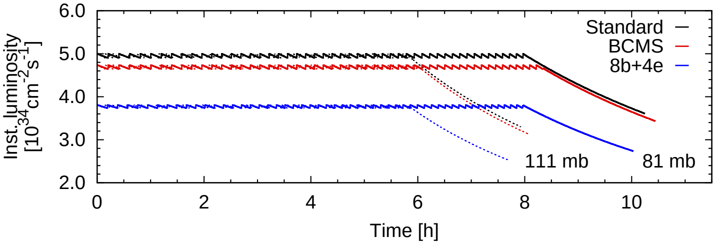
Summary II

To recover the performance:

- Reduction of the protected aperture by improved collimation settings and reduction of β^* to 15 cm.
- Variation of the crossing angle (adapting to intensity).
- Study of the origin of the additional losses observed in LHC at the beginning of the fill and scaling with bunch population.
  - Understanding and controlling this phenomena can yield up to a 9 % gain on integrated luminosity.
- BCMS+ increasing the number of bunches towards the standard beam: Pending studies on robustness of the TCDI collimators within LIU.
- Emittance preservation studies that would allow us to profit of the smaller emittances of the BCMS beam.

Backup

Luminosity ($\sigma_{\text{burn-off}} = 81\,\text{mb}$)



	Standard	BCMS	8b+4e
Fill duration [h]	10.1	10.3	9.9
Integrated luminosity [fb^{-1}/160 days]	254	242	193
Effective line pile-up dens. [mm^{-1}]	0.80	0.77	0.82

- When the cross section for burn-off is assumed to be 81 mb, the integrated luminosities increase by 9 % w.r.t. to their counterparts for 111 mb.

New longitudinal bunch profile I

The function

$$\lambda(s) = \frac{32}{5\pi S}\left(1 - \frac{4s^2}{S^2}\right)^{5/2},$$

can be derived as a particular case of the *Tsallis* **q-Gaussian** *distribution*

$$f(s) = \frac{\sqrt{\beta}}{C_q} \mathrm{e}_q[-\beta(s-\mu)^2],$$

where the mean, *deformation parameter*, and *scale parameters* are

$$\mu = 0, \quad q = \frac{3}{5} \quad \text{and} \quad \beta = \frac{10}{S^2},$$

respectively, and

$$C_q = \begin{cases} \frac{2\sqrt{\pi}\,\Gamma\left(\frac{1}{1-q}\right)}{(3-q)\sqrt{1-q}\,\Gamma\left(\frac{3-q}{2(1-q)}\right)} & \text{for } -\infty < q < 1 \\ \sqrt{\pi} & \text{for } q = 1 \\ \frac{\sqrt{\pi}\,\Gamma\left(\frac{3-q}{2(q-1)}\right)}{\sqrt{q-1}\,\Gamma\left(\frac{1}{q-1}\right)} & \text{for } 1 < q < 3 \end{cases}$$

is the normalization factor, and

$$\mathrm{e}_q(s) = \begin{cases} \exp(x) & \text{if } \begin{cases} q = 1 \end{cases} \\ [1 + (1-q)s]^{\frac{1}{1-q}} & \text{if } \begin{cases} q \neq 1 \\ 1 + (1-q)s > 0 \end{cases} \\ 0^{\frac{1}{1-q}} & \text{if } \begin{cases} q \neq 1 \\ 1 + (1-q)s \leq 0 \end{cases} \end{cases}$$

the *q-exponential* function.

New longitudinal bunch profile II

	Gaussian	q-Gaussian
Distribution	$\rho(s) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{s^2}{2\sigma^2}\right)$	$\lambda(s) = \frac{32}{5\pi S}\left(1 - \frac{4s^2}{S^2}\right)^{5/2}$
RMS	$\sigma_{\text{rms}} = \sigma$	$\sigma_\lambda = \frac{S}{4\sqrt{2}} \approx 0.177S$
FWHM	$\text{FWHM}(\rho) = 2\sigma\sqrt{2\ln 2} \approx 2.355\sigma \approx 2.355\sigma_{\text{rms}}$	$\text{FWHM}(\lambda) = S\sqrt{1-2^{-2/5}} \approx 0.492S \approx 2.784\sigma_\lambda$

- In order to make the *full width at half maximum* of both distributions to be equal,

$$\text{FWHM}(\lambda) = \text{FWHM}(\rho)$$

we have to take

$$S = 2\sigma\sqrt{\frac{2\ln 2}{1-2^{-2/5}}} \approx 4.785\sigma_{\text{rms}}, \quad \text{and then} \quad \sigma_\lambda \approx 0.846\sigma_{\text{rms}}.$$