HL-LHC OPERATIONAL SCENARIOS

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The main aim of this document is to have a clearly identified set of beam and machine parameters to be used for the simulations.

Two scenarios are discussed [1]:

i) Baseline scenario.
ii) Ultimate scenario.

For both scenarios the main assumptions are [1]:

i) New Mo-Gr collimators with a 5 μm Mo coating are installed (in both IR3 and IR7).
ii) Levelling with parallel separation in point 8.
iii) Few non-colliding bunches for the experiments (for background studies)
iv) Crab cavities are active providing full compensation of the crossing angle in IP1 and IP5. Reduction of the impedance of the Crab Cavities to the required level (and good control of the impedance of new equipment, in particular at large β)

Parameters at SPS extraction (2)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	0.45	0.45
Particles per bunch, N [10^{11}]	2.30	2.30
Max. Number of bunches per batch	288	288
ε_n [μm]	2.00	1.40
ε_L [eVs]	0.6	0.6
r.m.s. energy spread [0.0001]	?	?
r.m.s. bunch length [cm]	?	?

Parameters at the injection plateau after capture	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	0.45	0.45
Particles per bunch, N [10^{11}]	2.30	2.30
Maximum number of bunches per beam	2748	2604
Filling pattern	standard[1]	BCMS[2]
ε_n [μm]	2.0	1.6
Total RF Voltage [MV]	?	?
ε_L [eVs]	?	?
r.m.s. energy spread [0.0001]	?	?
r.m.s. bunch length [cm]	?	?
β* [m] in IP1/2/5/8	6/10/6/10	
Optics	HL-LHCV1.1 injection[3]	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	-2.0 (H)	
Half external crossing angle at IP for ALICE (IP2) [μrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±1259 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	+2.0 (H)	
Half crossing angle at the IP for CMS (IP5) [μrad]	+295 (H)	
Half parallel separation at the IP for CMS (IP5) [mm]	±2.0 (V)	
Half external crossing angle at the IP for LHCb (IP8)[4] [μrad]	-170(H)	
Half crossing angle at the IP for LHCb (IP8)[4] [μrad]	1930(H)	
Half parallel angle at the IP for LHCb (IP8) [μrad]	±30(V) [3]	
Half parallel separation at IP for LHCb (IP8) [μrad]	±3.5(V) [3]	
Transverse damper damping time [turns]	50 [2]	
Chromaticity Q' (dQ/(dp/p))	+2 [2]	
Second order chromaticity Q"($d^2Q/(dp/p)^2$)	? [2]	
Landau Octupole Current (LOF) [A]	-20 [2][5]	

[1] https://espace.cern.ch/HiLumi/WP2/Shared Documents/Filling Schemes HL-LHC/25ns_2748b_2736_2452_2524_288bpi12inj.txt

[2] https://espace.cern.ch/HiLumi/WP2/Shared Documents/Filling Schemes HL-LHC/25ns_2604b_2592_2288_2396_288bpi12inj.txt

[3] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc11/inj/index.html

[4] The crossing angle in IP2 and IP8 is the sum of an external crossing angle bump and an 'internal' spectrometer compensation bump and it depends on the spectrometer polarity. The values quoted above correspond to the configuration with the spectrometer ON providing the minimum long-range beam-beam normalized separation. The external bump extends over the triplet and D1 and D2 magnets. The internal spectrometer compensation bump extends only over the long drift space between the two Q1 quadrupoles left and right from the IP. For IP2 the vertical external crossing angle sign can be changed and therefore the same sign of the internal and external angle can be chosen to be the same. This is not possible for IP8 as the sign of the external crossing angle must be compatible with the recombination scheme.

[5] The plus sign was initially proposed to avoid any reduction of the stability diagram during the betatron squeeze (in the presence of both octupoles and beam-beam long range), but detailed simulations revealed that the stability diagram is almost preserved and that it can be fully preserved by optimizing the ATS optics [4]. The negative sign should therefore be fine during the squeeze, it should also be much better for single-beam stability and much better for dynamic aperture considerations in the presence of both beams.

Parameters during ramp	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	0.45 - 7	0.45 - 7
Particles per bunch, N [10^{11}]	2.30	2.30
Maximum number of bunches per beam	2748	2604
Filling pattern	standard	BCMS
ε_n [µm]	2.0	1.6
Total RF Voltage [MV]	to 16 (7 TeV) scaling with ?	
ε_L [eVs]	to 2.5 (7 TeV)	
r.m.s. energy spread [0.0001]	to 1.13 (7 TeV)	
r.m.s. bunch length [cm]	to 7.55 (7 TeV)	
β^* [m] in IP1/2/5/8	6/10/6/10	
Optics	HL-LHCV1.1 injection[8] (0..45 TeV) - HL-LHCV1.1 end of ramp[9] (7 TeV)	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	-2 (0.45 TeV) to -0.75 (7 TeV) (H) scaling with $1/\sqrt{p}$?	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±1259 (0.45 TeV) to ±240 (7 TeV) (V) scaling with p	
Half parallel separation at the IP for ALICE (IP2) [mm]	+2.0 (H) No scaling?	
Half crossing angle at the IP for CMS (IP5) [µrad]	+295 (H)	
Half parallel separation at the IP for CMS (IP5) [mm]	±2 (0.45 TeV) to ±0.75 (7 TeV) (V) scaling with $1/\sqrt{p}$?	
Half external crossing angle at the IP for LHCb (IP8)[4] [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[4] [µrad]	1930 (0.45 TeV) to -115 (7 TeV) (H) scaling with p	
Half parallel angle at the IP for LHCb (IP8) [µrad]	±30 (0.45 TeV) to 0 (7 TeV) (V) (1)	
Half parallel separation at IP for LHCb (IP8) [µrad]	±3.5 (V) (1) No scaling?	
Transverse damper damping time [turns]	50 (2)	
Chromaticity Q' (dQ/(dp/p))	+2 (0.45 TeV) to +15 (7 TeV) (2) Scaling?	
Second order chromaticity Q"($d^2Q/(dp/p)$)	? (2)	
Landau Octupole Current (LOF) [A]	-20 (0.45 TeV) to -590[11] (7 TeV) scaling with p (2)	

From here onwards we have to distinguish between nominal and ultimate HL-LHC scenarios

Nominal Scenario (levelling at a pile-up of 140)

[8] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc11/inj/index.html

[9] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc11/endoframp/index.html

[11] This is the maximum operating current expected for the Landau Damping Octupoles

Parameters during pre-squeeze (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	7	7
Particles per bunch, N [10^{11}]	2.30	2.30
Maximum number of bunches per beam	2748	2604
Filling pattern	standard	BCMS
ε_n [µm]	2.0	1.6
Total RF Voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread [0.0001]	1.13	
r.m.s. bunch length [cm]	7.55	
β^* [m] in IP1/2/5/8	6/10/6/10 to 0.7/10/0.7/3	
Optics	HL-LHCV1.1 end of ramp[14] to HL-LHCV1.1 pre-squeeze (0.7 m)	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	-0.75 (H)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±240 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	+2.0 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	+295 (H)	
Half parallel separation at the IP for CMS (IP5) [mm]	±0.75(V)	
Half external crossing angle at the IP for LHCb (IP8)[4] [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[4] [µrad]	-115 (H)	
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) (1)	
Half parallel separation at IP for LHCb (IP8) [µrad]	±2 (V) (1)	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+15 [1]	
Second order chromaticity Q"($d^2Q/(dp/p)$)	? [1]	
Landau Octupole Current (LOF) [A]	-590 [1]	

Parameters for the collision process (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	7	7
Particles per bunch, N [10^{11}]	2.2	2.2
Maximum number of bunches per beam	2748	2604
Number of collisions in IP1/2/5/8 (at the end of the collision process)[16]	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	140/140/4.5	140/140/4.5
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8[17]	5.1/0.001/5.1/0.17	4.8/0.001/4.8/0.16
ε_n [µm]	2.5	2.5
Total RF Voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread [0.0001]	1.13	

[14] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc11/endoframp/index.html

[16] Assuming one batch less from the PS for machine protection (pilot injection, TL steering with 12 nominal bunches) and non-colliding bunches for experiments. Note that due to RF beam loading the abort gap length must not exceed the 3µs design value.

[17] The value of the luminosity at which levelling is performed is calculated assuming a visible cross-section of 85 mb for point 1/2/5 and 75 mb for IP8.

r.m.s. bunch length [cm]	7.55
β^* [m] in IP1/2/5/8	0.7/10/0.7/3
Optics	HL-LHCV1.1 pre-squeeze (0.7 m)
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)
Half parallel separation at the IP for ATLAS (IP1) [mm]	-0.75 to 0 (H)
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)
Half crossing angle at the IP for ALICE (IP2)[4]	±240 (V)
Half parallel separation at the IP for ALICE (IP2) [mm]	+2.0 to +0.138[21] (H)
Half crossing angle at the IP for CMS (IP5) [µrad]	+295 (H)
Half parallel separation at the IP for CMS (IP5) [mm]	±0.75 to 0 (V)
Half external crossing angle at the IP for LHCb (IP8)[4] [µrad]	-250(H)
Half crossing angle at the IP for LHCb (IP8)[4] [µrad]	-115 (H)
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) [3]
Half parallel separation at IP for LHCb (IP8) [µrad]	±2 to ±0.043[22] (V)
Delay in the start of the collision process in IP1/2/5/8 [s]	Synch. or staggered (in this case specify delay between points)
Time to go in collision in IP1/2/5/8 [s]	Specify
Transverse damper damping time [turns]	50 (2)
Chromaticity Q' (dQ/(dp/p))	+15 (2)
Second order chromaticity Q"($d^2Q/(dp/p)$)	? (2)
Landau Octupole Current (LOF) [A]	-590 (2)

Parameters in stable beams (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	7	7
Particles per bunch, N [10^{11}]	2.2 (start of fill)	2.2 (start of fill)
ε_n [µm]	2.5 (start of fill)	2.5 (start of fill)
Maximum number of bunches per beam	2748	2604
Number of collisions in IP1/2/5/8	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	140/140/4.5	
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8[24]	5.1/0.001/5.1/0.17	4.8/0.001/4.8/0.16
Levelling method in IP1/2/5/8	β^*/separation/β^*/separation	
Total RF Voltage [MV]	16	
ε_L [eVs]	2.5 (start of fill)	
r.m.s. energy spread [0.0001]	1.13 (start of fill)	
r.m.s. bunch length [cm]	7.55 (start of fill)	
β^* [m] in IP1/2/5/8	0.7 to 0.15/10/0.7 to 0.15/3	
Optics	HL-LHCV1.1 pre-squeeze (0.7 m) to HL-LHCV1.1 pre-squeeze (0.44 m)[27] to HL-LHCV1.1 collision round (0.15 m)[28]	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	0 (H)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±240 (V)	

[21] This corresponds to the half-separation of 2.39/2.38 σ to level the luminosity to 10^{31} $cm^{-2}s^{-1}$ for the standard and BCMS beams respectively.

[22] This corresponds to the half-separation of 1.35 σ to level the pile-up to 4.5 events/crossing

[24] The value of the luminosity at which levelling is performed is calculated assuming a visible cross-section of 85 mb for point 1/2/5 and 75 mb for IP8.

[27] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc11/presqueeze/index.html

[28] http://lhc-optics.web.cern.ch/lhc-optics/www/hllhc11/round/index.html

Half parallel separation at the IP for ALICE (IP2) [mm]	+0.138[30] to 0 (H)
Half crossing angle at the IP for CMS (IP5) [µrad]	+295 (H)
Half parallel separation at the IP for CMS (IP5) [mm]	0 (V)
Half external crossing angle at the IP for LHCb (IP8)[4] [µrad]	-250(H)
Half crossing angle at the IP for LHCb (IP8)[4] [µrad]	-115 (H)
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) [3]
Half parallel separation at IP for LHCb (IP8) [µrad]	±0.043[31] to 0 (V) [1]
Transverse damper damping time [turns]	50 [1]
Chromaticity Q' (dQ/(dp/p))	+15 to 2[32] [1]
Second order chromaticity Q"($d^2Q/(dp/p)$)	? [1]
Landau Octupole Current (LOF) [A]	-590 to ? [1]

Ultimate Scenario (levelling at a pile-up of 210)

[30] This corresponds to the half-separation of 2.39/2.38 σ to level the luminosity to 10^{31} $cm^{-2}s^{-1}$ for the standard and BCMS beams respectively.

[31] This corresponds to the half-separation of 1.35 σ to level the pile-up to 4.5 events/crossing

[32] The chromaticity and the octupoles should be reduced (in absolute values) as soon as the beams are in collision in IP1 and IP5

Parameters during pre-squeeze (ultimate)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	7	7
Particles per bunch, N [10^{11}]	2.30	2.30
Maximum number of bunches per beam	2748	2604
Filling pattern	standard	BCMS
ε_n [µm]	2.0	1.6
Total RF Voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread [0.0001]	1.13	
r.m.s. bunch length [cm]	7.55	
β^* [m] in IP1/2/5/8	6/10/6/10 to 0.46/10/0.46/3	
Optics	HL-LHCV1.1 end of ramp to HL-LHCV1.1 pre-squeeze (0.46 m)	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	-0.75 (H)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±240 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	+2.0 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	+295 (H)	
Half parallel separation at the IP for CMS (IP5) [mm]	±0.75(V)	
Half external crossing angle at the IP for LHCb (IP8)4 [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)4 [µrad]	-115 (H)	
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) (1)	
Half parallel separation at IP for LHCb (IP8) [µrad]	±2 (V) (1)	
Transverse damper damping time [turns]	50 (2)	
Chromaticity Q' (dQ/(dp/p))	+15 (2)	
Second order chromaticity Q"($d^2Q/(dp/p)$)	? (2)	
Landau Octupole Current (LOF) [A]	-590 (2)	

Parameters for the collision process (ultimate)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	7	7
Particles per bunch, N [10^{11}]	2.2	2.2
Maximum number of bunches per beam	2748	2604
Number of collisions in IP1/2/5/8 (at the end of the collision process)	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	210/210/4.5	
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8	7.6/0.001/7.6/0.17	7.2/0.001/7.2/0.16
ε_n [µm]	2.5	2.5
Total RF Voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread [0.0001]	1.13	
r.m.s. bunch length [cm]	7.55	
β^* [m] in IP1/2/5/8	0.46/10/0.46/3	
Optics	HL-LHCV1.1 pre-squeeze (0.46 m)	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	-0.75 to 0 (H)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±240 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	+2.0 to +0.138[33] (H)	

[33] This corresponds to the half-separation of 2.39/2.38 σ to level the luminosity to 10^{31} $cm^{-2}s^{-1}$ for the standard and BCMS beams respectively.

Half crossing angle at the IP for CMS (IP5) [μrad]	+295 (H)
Half parallel separation at the IP for CMS (IP5) [mm]	±0.75 to 0 (V)
Half external crossing angle at the IP for LHCb (IP8)[4] [μrad]	-250(H)
Half crossing angle at the IP for LHCb (IP8)[4] [μrad]	-115 (H)
Half parallel angle at the IP for LHCb (IP8) [μrad]	0 (V) (1)
Half parallel separation at IP for LHCb (IP8) [μrad]	±2 to ±0.043[34] (V)
Delay in the start of the collision process in IP1/2/5/8 [s]	Synch. or staggered (in this case specify delay between points)
Time to go in collision in IP1/2/5/8 [s]	Specify
Transverse damper damping time [turns]	50 (2)
Chromaticity Q' (dQ/(dp/p))	+15 (2)
Second order chromaticity Q"($d^2Q/(dp/p)$)	? (2)
Landau Octupole Current (LOF) [A]	-590 (2)

Parameters in stable beams (ultimate)	HL-LHC (standard)	HL-LHC (BCMS)
Beam Total Energy [TeV]	7	7
Particles per bunch, N [10^{11}]	2.2 (start of fill)	2.2 (start of fill)
ε_n [μm]	2.5 (start of fill)	2.5 (start of fill)
Maximum number of bunches per beam	2748	2604
Number of collisions in IP1/2/5/8	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	210/210/4.5	
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8[35]	7.6/0.001/7.6/0.17	7.2/0.001/7.2/0.16
Levelling method in IP1/2/5/8	β^*/separation/β^*/separation	
Total RF Voltage [MV]	16	
ε_L [eVs]	2.5 (start of fill)	
r.m.s. energy spread [0.0001]	1.13 (start of fill)	
r.m.s. bunch length [cm]	7.55 (start of fill)	
β^* [m] in IP1/2/5/8	0.46 to 0.15/10/0.46 to 0.15/3	
Optics	HL-LHCV1.1 pre-squeeze (0.46 m) to HL-LHCV1.1 pre-squeeze (0.44 m)[36] to HL-LHCV1.1 collision round (0.15 m)[37]	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	0 (H)	
Half external crossing angle at IP for ALICE (IP2) [μrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[4]	±240 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	+0.138[38] to 0 (H)	
Half crossing angle at the IP for CMS (IP5) [μrad]	+295 (H)	
Half parallel separation at the IP for CMS (IP5) [mm]	0 (V)	
Half external crossing angle at the IP for LHCb (IP8)[4] [μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[4] [μrad]	-115 (H)	
Half parallel angle at the IP for LHCb (IP8) [μrad]	0 (V) (1)	
Half parallel separation at IP for LHCb (IP8) [μrad]	±0.043[39] to 0 (V)	
Transverse damper damping time [turns]	50 (2)	
Chromaticity Q' (dQ/(dp/p))	+15 to 2[40] (2)	
Second order chromaticity Q"($d^2Q/(dp/p)$)	? (2)	
Landau Octupole Current (LOF) [A]	-590 to ? (2)	

References

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