HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Scientific / Technical Note

HL-LHC Operational Scenarios

Metral, Elias (CERN) *et al*

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HL-LHC OPERATIONAL SCENARIOS

G. Arduini, N. Biancacci, O. Brüning, R. De Maria, M. Giovannozzi, W. Höfle, K. Li, E. Métral, J.E. Muller, Y. Papaphilippou, T. Pieloni, B. Salvant, E. Shaposhnikova, D. Valuch (CERN, Geneva, Switzerland), C. Tambasco (CERN, Geneva, Switzerland and EPFL, Lausanne, Switzerland), D. Banfi, J. Barranco (EPFL, Lausanne, Switzerland), A. Valishev (FNAL, Batavia, USA), A. Wolski (UNILIV, Liverpool, UK)

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Abstract

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

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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 numerical 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 LSS7 only.
ii)   Levelling with parallel separation in IP8.
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 values).
v)   All the existing circuits should operate at their nominal performance (e.g. non-conformities observed so far should be repaired by Run 4).

Parameters at SPS[1] extraction [2]	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	0.45	
Particles per bunch, N [10^{11}]	2.30	
Maximum number of bunches	288	
ε_n [μm]	2.0	1.7
ε_L [eVs]	0.66	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	2.7	
r.m.s. bunch length (Gaussian fit) [cm]	13.7	

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[1] The Q20 optics is assumed, with a gamma transition of 17.951, 10 MV in the 200 MHz RF cavities and 1 MV in the 800 MHz RF cavities, in bunch shortening mode. The standard beam parameters are those requested by HL-LHC at injection and the BCMS beam emittance is extrapolated from Table 10 in Ref. [2] for the presently assumed acceptable space charge tune spread in the PS and SPS.

Parameters at the injection plateau after RF capture	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	0.45	
Particles per bunch, N [10^{11}]	2.30	
Maximum number of bunches per beam	2748	2604
Filling pattern	standard[2]	BCMS[3]
ε_n [µm]	2.0	1.7
Total RF voltage [MV]	8	
ε_L [eVs]	0.7	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	3.7	
r.m.s. bunch length (Gaussian fit) [cm]	10.4	
β^* [m] in IP1/2/5/8	6/10/6/10	
Optics	HL-LHCV1.1 injection[4]	
Tunes (H/V)	62.28/60.31	
Transition gamma (average B1/B2)	53.83	
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)[5] [µrad]	±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)[5] [µrad]	-170 (H)	
Half crossing angle at the IP for LHCb (IP8)[5] [µrad]	1930 (H)	
Half parallel angle at the IP for LHCb (IP8) [µrad]	±30 (V) [3]	
Half parallel separation at IP for LHCb (IP8) [mm]	±3.5 (V) [3]	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+3 [1]	
Landau octupole Current (LOF) [A]	-20 [1,4]	

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

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

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

[5] 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.

Parameters during ramp	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	0.45 - 7	
Particles per bunch, N [10^{11}]	2.30	
Maximum number of bunches per beam	2748	2604
Filling pattern	standard[2]	BCMS[3]
ε_n [μm]	2.0	1.7
Total RF voltage [MV]	8 (0.45 TeV) to 16 (7 TeV) linearly with time	
ε_L [eVs]	0.7 (0.45 TeV) to 2.5 (7 TeV)	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	3.7 (0.45 TeV) to 1.08 (7 TeV)	
r.m.s. bunch length (Gaussian fit) [cm]	10.4 (0.45 TeV) to 8.1 (7 TeV)	
β^* [m] in IP1/2/5/8	6/10/6/10	
Optics	HL-LHCV1.1 injection[6] (0.45 TeV) - HL-LHCV1.1 end of ramp[7] (7 TeV)	
Tunes (H/V)	62.28/60.31 to 62.31/60.32	
Transition gamma (average B1/B2)	53.83 to 53.86	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±2 (H) [5]	
Half external crossing angle at IP for ALICE (IP2) [μrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[5] [μrad]	±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) [5]	
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)[5] [μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[5][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) [3]	
Half parallel separation at IP for LHCb (IP8) [mm]	±3.5 to ±2.0 (V) [3]	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+3 [1]	
Landau octupole Current (LOF) [A]	-20 (0.45 TeV) to -570[8] (7 TeV) scaling with ~ p^2 [1,4]	

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

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

[8] This is the maximum operating current expected for the Landau Damping octupoles.

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

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

Parameters during pre-squeeze (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.30	
Maximum number of bunches per beam	2748	2604
Filling pattern	standard[2]	BCMS[3]
ε_n [μm]	2.0	1.7
Total RF voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	1.08	
r.m.s. bunch length (Gaussian fit) [cm]	8.1	
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[9] to HL-LHCV1.1 pre-squeeze (0.7 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.86 to 53.78	
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)[5] [μrad]	±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]	±2.0(V)	
Half external crossing angle at the IP for LHCb (IP8)[5][μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[5][μrad]	-115(H)	
Half parallel angle at the IP for LHCb (IP8) [μrad]	0 (V) [3]	
Half parallel separation at IP for LHCb (IP8) [mm]	±2 (V) [3]	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+3 [6,8]	
Landau octupole Current (LOF) [A]	-570 [1,4,8]	

Parameters for the collision process (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.2	
Maximum number of bunches per beam	2748	2604
Number of colliding pairs in IP1/2/5/8 (at the end of the collision process)[10]	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard[2]	BCMS[3]
Levelled pile-up in IP1/5/8	140/140/4.5	
Levelled luminosity [10^{34} cm^{-2}s^{-1}] in IP1/2/5/8[11]	5.1/0.001/5.1/0.17	4.8/0.001/4.8/0.16
ε_n [µm]	2.5	
Total RF voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	1.08	
r.m.s. bunch length (Gaussian fit)[cm]	8.1	
β^* [m] in IP1/2/5/8	0.7/10/0.7/3	
Optics	HL-LHCV1.1 pre-squeeze (0.7 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.78	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±2.0 to 0 (H)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[5] [µrad]	±240 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±2.0 to ±0.138[12] (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 to 0 (V)	
Half external crossing angle at the IP for LHCb (IP8)[5] [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[5] [µrad]	-115 (H)	
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) [3]	
Half parallel separation at IP for LHCb (IP8) [mm]	±2 to ±0.043[13] (V)	
Delay in the start of the collision process in IP1/2/5/8	Synchronised IP1 and IP5 to full head-on collision first, and then IP2 and IP8	
Time to go in collision in IP1/5 (from 2 σ full separation to 0 σ) [s]. No time constraint for IP2/8	< 1	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+3 [6,8]	
Landau octupole Current (LOF) [A]	-570 [1,4,8]	

[10] 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.

[11] 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.

[12] 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.

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

Parameters in stable beams (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.2 (start of fill)	
ε_n [µm]	2.5 (start of fill)	
Maximum number of bunches per beam	2748	2604
Number of colliding pairs in IP1/2/5/8[10]	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard[2]	BCMS[3]
Levelled pile-up in IP1/5/8	140/140/4.5	
Levelled luminosity [10^{34} cm^{-2}s^{-1}] in IP1/2/5/8[11]	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 (Gaussian fit) [10^{-4}]	1.08 (start of fill)	
r.m.s. bunch length (Gaussian fit) [cm]	8.1 (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)[14] to HL-LHCV1.1 collision round (0.15 m)[15]	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.78 to 53.73	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V) [7]	
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)[5] [µrad]	±240 (V) [7]	
Half parallel separation at the IP for ALICE (IP2) [mm]	±0.138[16] to 0 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	+295 (H) [7]	
Half parallel separation at the IP for CMS (IP5) [mm]	0 (V)	
Half external crossing angle at the IP for LHCb (IP8)[5] [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[5] [µrad]	-115 (H) [7]	
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) [3]	
Half parallel separation at IP for LHCb (IP8) [mm]	±0.043[17] to 0 (V) [1]	
Transverse damper damping time [turns]	50[18] [1]	
Chromaticity Q' (dQ/(dp/p))	+3[18] [6,8]	
Landau octupole Current (LOF) [A]	-570[18] [1,4,8]	

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

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

[16] 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.

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

[18] The transverse damper gain, chromaticity and the octupoles should be reduced (in absolute values) "as much as possible" as soon as the beams are in collision in IP1 and IP5.

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

Parameters during pre-squeeze (ultimate)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.30	
Maximum number of bunches per beam	2748	2604
Filling pattern	standard[2]	BCMS[3]
ε_n [µm]	2.0	1.7
Total RF voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	1.08	
r.m.s. bunch length (Gaussian fit) [cm]	8.1	
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)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.86 to 53.78	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±2 (H)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[5] [µrad]	±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]	±2 (V)	
Half external crossing angle at the IP for LHCb (IP8)[5] [µrad]	-250 (H)	
Half crossing angle at the IP for LHCb (IP8)[5] [µrad]	-115 (H)	
Half parallel angle at the IP for LHCb (IP8) [µrad]	0 (V) [3]	
Half parallel separation at IP for LHCb (IP8) [mm]	±2 (V) [3]	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+3 [6,8]	
Landau octupole Current (LOF) [A]	-570 [1,4,8]	

Parameters for the collision process (ultimate)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.2	
Maximum number of bunches per beam	2748	2604
Number of colliding pairs in IP1/2/5/8 (at the end of the collision process)[10]	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard[2]	BCMS[3]
Levelled pile-up in IP1/5/8	210/210/4.5	
Levelled luminosity [10^{34} cm^{-2}s^{-1}] in IP1/2/5/8[11]	7.6/0.001/7.6/0.17	7.2/0.001/7.2/0.16
ε_n [μm]	2.5	
Total RF voltage [MV]	16	
ε_L [eVs]	2.5	
r.m.s. energy spread (Gaussian fit) [10^{-4}]	1.08	
r.m.s. bunch length (Gaussian fit) [cm]	8.1	
β^* [m] in IP1/2/5/8	0.46/10/0.46/3	
Optics	HL-LHCV1.1 pre-squeeze (0.46 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.78	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	±295 (V)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±2 to 0 (H)	
Half external crossing angle at IP for ALICE (IP2) [μrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[5] [μrad]	±240 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±2.0 to ±0.138[19] (H)	
Half crossing angle at the IP for CMS (IP5) [μrad]	+295 (H)	
Half parallel separation at the IP for CMS (IP5) [mm]	±2 to 0 (V)	
Half external crossing angle at the IP for LHCb (IP8)[5] [μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[5] [μrad]	-115 (H)	
Half parallel angle at the IP for LHCb (IP8) [μrad]	0 (V) (1)	
Half parallel separation at IP for LHCb (IP8) [mm]	±2 to ±0.043[20] (V)	
Delay in the start of the collision process in IP1/2/5/8	Synchronised IP1 and IP5 to full head-on collision first, and then IP2 and IP8	
Time to go in collision in IP1/5 (from 2 σ full separation to 0 σ) [s]. No time constraint for IP2/8	< 1	
Transverse damper damping time [turns]	50 [1]	
Chromaticity Q' (dQ/(dp/p))	+3 [6,8]	
Landau octupole Current (LOF) [A]	-570 [1,4,8]	

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[19] 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.

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

Parameters in stable beams (ultimate)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.2 (start of fill)	
ε_n [μm]	2.5 (start of fill)	
Maximum number of bunches per beam	2748	2604
Number of colliding pairs in IP1/2/5/8[10]	2736/2452/2736/2524	2592/2288/2592/2396
Filling pattern	standard[2]	BCMS[3]
Levelled pile-up in IP1/5/8	210/210/4.5	
Levelled luminosity [10^{34} cm^{-2}s^{-1}] in IP1/2/5/8[11]	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 (Gaussian fit) [10^{-4}]	1.08 (start of fill)	
r.m.s. bunch length (Gaussian fit) [cm]	8.1 (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)[14] to HL-LHCV1.1 collision round (0.15 m)[15]	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.78 to 53.73	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	±295 (V) [7]	
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)[5] [μrad]	±240 (V) [7]	
Half parallel separation at the IP for ALICE (IP2) [mm]	±0.138[19] to 0 (H)	
Half crossing angle at the IP for CMS (IP5) [μrad]	+295 (H) [7]	
Half parallel separation at the IP for CMS (IP5) [mm]	0 (V)	
Half external crossing angle at the IP for LHCb (IP8)[5] [μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8)[5] [μrad]	-115 (H) [7]	
Half parallel angle at the IP for LHCb (IP8) [μrad]	0 (V) (1)	
Half parallel separation at IP for LHCb (IP8) [mm]	±0.043[20] to 0 (V)	
Transverse damper damping time [turns]	50[18] [1]	
Chromaticity Q' (dQ/(dp/p))	+3[18] [6,8]	
Landau octupole Current (LOF) [A]	-570[18] [1,4,8]	

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