UPDATE OF THE HL-LHC OPERATIONAL SCENARIOS FOR PROTON OPERATION

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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 and performance assessment. Two scenarios are discussed:

i) Baseline scenario (levelling at a luminosity of 5×10^{34} cm^{-2}s^{-1}).
ii) Ultimate scenario (levelling at a luminosity of 7.5×10^{34} cm^{-2}s^{-1}).

The value of the luminosity at which levelling is performed is calculated assuming a visible cross-section of 81 mb (corresponding to the inelastic proton-proton cross-section at a center of mass energy of 14 TeV), and the cross-section for the burn-off is conservatively assumed to be 111 mb (corresponding to the total proton-proton cross-section at a center of mass energy of 14 TeV) [1,2]. For both scenarios the main assumptions for the first version of this note [3] were:

i) ATS optics.
ii) New Mo-Gr (also called or written MoC) collimators with a 5 μm Mo coating are installed, in LSS7 only (to replace the secondary collimators). The electrical resistivity of Mo-Gr and Mo is assumed to be 1 μΩm and 0.05 μΩm respectively.
iii) Levelling with β* in IP1&5 and with parallel separation in IP2&8.
iv) Few non-colliding bunches for the experiments (for background studies).
v) Crab Cavities (CCs) are active providing full compensation of the crossing angle in IP1 and IP5. Continue the reduction of the impedance of the CCs to the required level (and good control of the impedance of new equipment, in particular at large β values).
vi) All the existing circuits should operate at their nominal performance (e.g. non-conformities observed so far should be repaired by Run 4).

An updated version of Ref. [3] is discussed in this note, in particular after four significant modifications [4]

i) CCs will not provide the full compensation of the crossing angle in IP1 and IP5 as their number has been halved [5]: 2 CCs/beam/IP side (i.e. 8 CCs per beam and 16 in total). A crabbing angle of ±190 μrad will be provided for the nominal voltage of 3.4 MV/cavity for optics version HL-LHCv1.3 [6], knowing that 2 CCs on one side of the IP provide the crabbing and 2 CCs on the other side of the IP provide the anti-crabbing. The work has been done to reduce the impedance of a remaining HOM at

920 MHz by a factor ~ 20 and no significant impedance effect is expected anymore for the baseline and ultimate scenarios discussed in this note [7].

ii) Based on the LHC experience a q-Gaussian distribution [8,9] has been considered to represent the longitudinal distribution (see also Appendix A) and its Full Width at Half Maximum (FWHM) at high energy has to be increased to avoid longitudinal instabilities due to loss of Landau damping [10]. In particular, at high energy the new bunch length is now defined as [9]

- RMS bunch length (q-Gaussian): 7.6 cm,
- FWHM bunch length (q-Gaussian): 21.2 cm.

The RMS bunch length of a Gaussian having the same FWHM is 9 cm. It should be noted that the influence of the potential-well distortion (due to the impedance) is rather small, both in the SPS and (HL)-LHC [8,10].

iii) New horizontal and vertical primary collimators is IR7 (2 per beam) are replaced by a new design based on un-coated Mo-Gr. This item has been recently approved by the consolidation project [11].

iv) It is assumed that β^* levelling will provide steps of 5% in luminosity to limit the number of matched optics while parallel separation will be used for finer luminosity levelling (at the level of 2%).

Several other considerations have also been made, such as

- ATS optics V1.3 is now used (called HL-LHCV1.3) [6]. The new optics features an optimized phase advance between MKD and TCTs allowing to reduce the retraction of the TCTs with respect to the TCDQ and TCSP collimators in Point 6. Therefore, the protected aperture can be reduced from 14.6 to 11.9 beam σ [12]. This value of the protected aperture allows to operate the machine down to b* =15 cm and a full crossing angle of 500 mrad.
- At injection, a β^* of 6 m in Points 1 and 5 is assumed as it gives already plenty of aperture margins and it is not trivial to increase or decrease it. For the ramp and squeeze process we are currently limited by the ramp rate of the sextupoles, so starting with a lower β^* will help.
- At high energy, the β^* reach in Points 1 and 5 for a given choice of flat or round optics depends of the horizontal MKD-TCT1/5 phase advances that are not necessarily the best possible due to optics constraints in Point 6. In case one foresees a swap of the crossing plane between Run 4 and Run 5 as discussed in the TDR [5], there is no best choice a priori. On the contrary, there is a choice for the crossing plane in Point 1 and 5 that gives better performance and flexibility. For round optics, where the aperture bottleneck is in the crossing plane, the best choice is horizontal crossing in Point 1 and vertical crossing in Point 5. For flat optics, where the bottleneck is in the non-crossing plane, the best choice is vertical crossing in Point 1 and horizontal crossing in Point 5. This is because it is in general easier to optimize the MKD-TCT phase advance for Point 1 rather than Point 5. It has also be noted that an optimization of round optics with crab cavities implemented by squeezing the β^* in the non-crossing plane will be as effective as the MKD-TCT1/5 phase advance are close to ideal values. In the context of this note we make the assumption of “H/V crossing in Point 1/5” that gives the best performance for the nominal scenario of round optics with crab cavities. Furthermore we also assume that no swap of the crossing plane will be

performed to reduce the accumulated radiation dose in the triplets, as it would require the swap of the CCs.

- New injection working point (due to e-cloud and the high values of chromaticities and Landau octupoles current needed to reach beam stability) used since 2015: (0.27,0.295) instead of (0.28,0.31) [13].
- Laslett tune shifts at injection and linear coupling have to be well corrected to avoid transverse instabilities due to loss of Landau damping [13]. The intensity-dependent tune shifts have been measured in Ref. [14], confirming roughly the predictions [15]. However, it is worth reminding that only a simplified geometry was considered in Ref. [15] and the nominal LHC vertical Laslett tune shift was expected to be ~ - 1.7×10^{-2} at 450 GeV and ~ - 1.1×10^{-3} at 7 TeV (the horizontal tune shift is the same but with opposite sign). As the total beam current will be increased by a factor ~ 2 for HL-LHC, the HL-LHC Laslett tune shifts will be increased by a factor ~ 2. Linear coupling ($|C^-|$) should be corrected at the level of 0.002 for injection tunes and 0.001 for collision tunes. In case the tunes would be brought closer to each other, an even better coupling correction would be required as the ratio between the linear coupling strength (i.e. $|C^-|$) and the tune distance to the coupling resonance should be kept constant to avoid a loss of transverse Landau damping.
- The bunch length also changed in the SPS (taking into account the effect of the impedance and the planned impedance reduction). It is worth reminding that for the momentum spread and the emittance, the values are obtained by computing the trajectory in phase space, taking into account the non-linearities of the RF but without potential well distortion (as evaluated in operation).
- Halo cleaning is expected to be necessary for HL-LHC [16]. Scenarios for providing sufficient transverse Landau damping should be devised without relying on the transverse tails (as it was already the case for the LHC) and some margin should be kept to fight against e-cloud. It is thus very important to reduce the impedance of the secondary collimators in LSS7, as shown in Fig. 1 for the most critical horizontal plane, just before collision for the ultimate scenario [17]. In this case, the beam (with maximum bunch population and minimum transverse emittance of the beams delivered by the SPS) should be stable for a current in the Landau octupoles (LOF) of ~ 420 A, independently on the sign and even if the transverse tails would be cut down to ~ 3 σ (considering impedance only and no other destabilising effects).

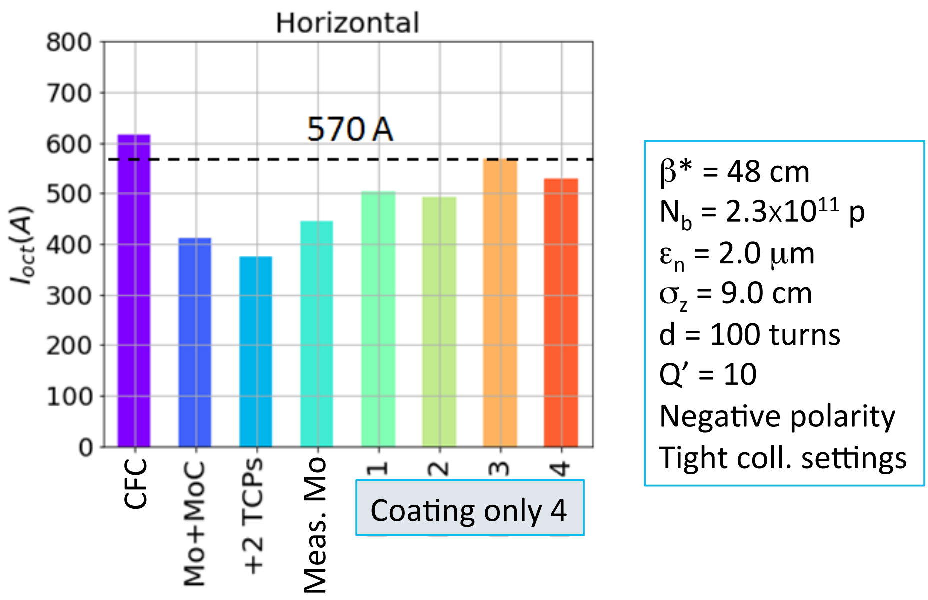

Figure 1: Required current in the Landau octupoles (whose maximum current is 570 A) to reach beam stability for several scenarios of collimator impedance reduction.

The stability limits are constantly being reviewed as a function of the observations made at the LHC: based on the past LHC operational experience, a margin in the Landau octupoles current by a factor at least 2 would be highly desirable, as the machine impedance can only be worse than in the idealistic model considered above and other destabilizing effects might appear (such as e.g. e-cloud or linear coupling already observed during Runs 1 and 2). During the fill the bunch intensity will decrease and it will be possible to decrease the Landau octupoles current accordingly, still preserving the beam stability of the non-colliding bunches. As concerns the colliding bunches in IP1&5, thanks to the beam-beam head-on tune spread providing much more Landau damping than the Landau octupoles, the Landau octupoles current could be significantly reduced (as well as the chromaticities). Therefore, in stable beams the constraints on the Landau octupoles current and chromaticities should come only from the non-colliding (in IP1&5) bunches. This is why they will be treated separately in the following Tables related to the "stable beams" process.

- Instabilities attributed to electron cloud have been observed in the LHC also in collision, which required increasing the vertical chromaticities to values slightly higher than 20 [18]. However, according to simulations [18], this mechanism should occur for bunch populations below ~ 1×10^{11} p/b and therefore it should not be an issue for HL-LHC [19].
- The destabilising effect of the (resistive) transverse damper for low chromaticities is under study as it could set a limit on the minimum chromaticity to be used [20].
- The effect of space charge was also recently investigated, revealing its beneficial effect on the intensity threshold for both TMCI and Head-Tail instability regimes, below a certain energy [21].
- Combined ramp and squeeze has been tested successfully during Run 2 in the LHC and it is proposed to be implemented in HL-LHC tentatively down to

64 cm (which is the β* at which the collisions will occur for the nominal scenario). This value will be refined when the final squeeze sequence will be validated taking into account the final ramp rate limitation of the HL-LHC circuits. This leads to a reduction of the minimum turn-around time compared to the 180 minutes mentioned in Ref. [5] (see Table 1).

Table 1: Minimum turn-around time.

Phase	Time [minutes]
Ramp-down	40
Pre-injection set-up	15
Set-up with beam	15
Nominal injection	30
Prepare ramp	5
Ramp & Squeeze	25
Flat-top	5
Squeeze	0 (baseline) / 5 (ultimate)
Adjust/collide	10
TOTAL	145 (baseline) / 150 (ultimate)

This might require the commissioning of the Main Sextupole and Landau Octupole circuits to higher ramp and acceleration rates as compared to the lower ones tested during HWC and operation. It should be noted that in the above table the time for a pre-cycle (30 min) has not been included as the latter is supposed to be performed only sporadically. Furthermore, it is worth mentioning that with an upgrade of the IR2&8 triplet circuits the ramp-down time could be reduced from 40 min down to 25 min, gaining therefore 15 min.

- Following the successful commissioning of IR non-linear correctors, it is proposed to operate the non-linear correctors in HL-LHC by ramping their strength to the nominal value during the energy ramp.
- The spacing between PS/SPS trains has been reduced to 200/800 ns following the 2017 operational experience [22,23] and the maximum number of bunches per beam and colliding pairs have been updated accordingly as reported in the following tables. Concerning the BCMS beam, the compatibility of these beam parameters with the protection devices involved in the SPS-LHC transfer still needs to be validated within the LIU project [24].
- Detailed Dynamic Aperture (DA) simulations (successfully benchmarked in the LHC) were performed to optimize the relevant beam parameters [25]. The DA can be improved by reducing both the Landau octupoles current (as shown in Fig. 2 for the most critical case of the β* of 15 cm at the end of the fill) and chromaticities. In this plot, the luminosity of LHCb is at 2×10^{33} cm^{-2} s^{-1}, β* = 3m with 1.25 σ of beam-beam head-on separation (and with the Main Sextupoles in cell 10 - MS10 - also in). A half crossing angle of 250 μrad looks feasible with Landau octupoles at ~ - 100 A (which is not that small considering the teleindex of 3.333 at 15 cm). It might be possible to gain some more margins by reducing the chromaticities to 10 or less and/or refining the tunes.

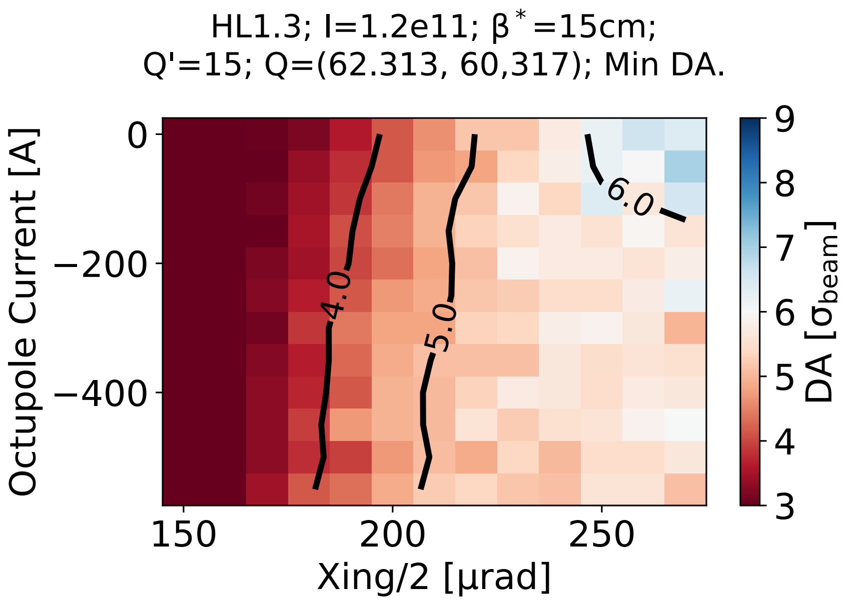

Figure 2: DA simulations for the most critical case of β* = 15 cm at the end of the fill.

- In case limitations from e-cloud effects are encountered (e.g. heat loads, instabilities) the 8b+4e filling pattern [26] will be employed to mitigate the e-cloud formation at the expense of a reduction in number of bunches. With this configuration, a maximum of 1972 bunches can be stored in the LHC [27]. The injected bunch population will be the same as for the baseline scenario (2.3×10^{11} p/b), and the normalized transverse emittance will be 1.7 μm. In order to adapt the heat loads on the beam screens to the available cooling capacity while maximizing the number of colliding bunches, 8b+4e trains can be mixed with standard trains in the same filling scheme. This possibility was successfully tested in MD during 2016 [28].
- Concerning the operation with the CCs, the strategy is
  - CCs are on-tune at all times: the RF is ON with strong RF feedback and tune controls at all times. At injection, with 0.25 MV per CC, 2 mm of beam displacement (injection oscillations) will require 19 kW from the amplifier (out of 40 kW maximum) to compensate for the beam loading (if the displacement is in the wrong direction).
  - During filling, ramping or operation with transparent CCs
    - small cavity field as required for the active tuning system,
    - we use counter-phasing to make the total field invisible to the beam,
    - a strong RF feedback keeps the beam-induced voltage to zero if the beam is off-centred.
  - Before the collision process
    - we drive counter-phasing to zero,
    - any adiabatic field manipulation is possible by synchronously changing the voltage or phase in each cavity (luminosity levelling for example).
  - In stable beam

   - The studies of emittance growth in the presence of the transverse damper (ADT) noise and beam-beam should be done assuming an RMS tune spread due to head-on beam-beam interaction, which is 0.17 times the beam-beam tune shift [29]. The noise requirements should be based on a total beam-beam tune shift of ~ 0.02 (as the beam-beam tune shift per IP is ~ 0.01 and IP8 will not collide head-on), and therefore a RMS tune spread of ~ 0.0034.
   - For the current baseline, the maximum acceptable transverse emittance blow-up to avoid less than ~ 1% of luminosity loss is ~ 1.5%/h (at $\beta^* = 15$ cm), i.e. ~ 0.04 μm/h as the CCs should provide an additive (and not multiplicative) source of blow-up [30] (see also Appendix B).
- For the longitudinal beam loading compensation, the half-detuning scheme was used in the LHC between 2008 and 2016. In this scheme, the voltage is kept constant (amplitude and phase) over the turn and the required power from the klystrons to compensate the beam-induced voltage scales with the beam current. Since 2017, the full-detuning scheme is used [31], where the cavity voltage amplitude is kept constant but a phase modulation caused by the beam loading is accepted. Like this, the required power from the klystron is constant and independent of the beam current. Without the full detuning scheme it would not be possible to accelerate the future high-intensity beams without major upgrades of the RF system. The procedure is to use the old scheme (half detuning, i.e. without phase modulation) for the injection process, as the bunch spacing from SPS is constant, and switch to the new scheme (full detuning, i.e. with phase modulation) at the start of the ramp.
- The power loss due to synchrotron radiation reaches 34 W per half-cell and per beam at 7 TeV, i.e. it is ~ 0.32 W/m/beam [32].
- In the four experimental insertion regions, a low SEY (Secondary Emission Yield) coating (< 1.1) of the inner triplets is foreseen in the baseline: in IR1&5, which will be changed (and will be equipped with dedicated cryoplants) and in IR2&8, where the coating will have to be done in-situ. The total length of non-coated parts should be minimized (as much as possible); and as the heat load in IR2 and IR8 will affect the neighboring arcs, it is desirable to have also a low SEY coating of the matching sections (stand-alones) [5]. Amorphous carbon (a-C) performances have to be validated at cryogenics temperature and an in-situ a-C coating of the triplets in Points 2 and 8 is foreseen during LS3 [33]. The temperature of the new a-C coated shielded beam screens in Points 1 and 5 will be higher than the usual 5-20 K: 60-80 K is currently contemplated [34].
- As concerns the LHC arcs, taking into account the effect of the photoelectrons we can conclude that measurements for the cells with the current lowest heat loads (S34, S45, S56 and S67) are compatible with a low SEY parameter (SEY < 1.2, corresponding to a full surface conditioning) [35,36]. The measurements for the half-cells with the largest load (S12, S23, S78 and S81), instead, correspond to SEY parameters in the range between 1.4 and 1.5. The priority is therefore to identify and suppress the source of large heat loads in S12, S23, S78 and S81, and to preserve the performance in the other arcs since they are compatible with HL-LHC but there is no much margin available. It is worth reminding that the sectors 23 and 78 will be the weakest even after the HL-LHC new cooling installations [37].

- The effect of beam-beam head-on interactions is about 5% β-beating (with a beam-beam parameter of $\xi = 0.01$) for LHC and 10% for HL-LHC ($\xi = 0.02$). The impact of the β-beating on the luminosity has been computed confirming that the effect is at the few percent level for the typical beam-beam parameters. A possible strategy would be leave the effect uncorrected and recover the loss or gain of luminosity with separations [38].
- Several levelling techniques are available [39]:
  - Levelling by transverse offset is operational since Run 1.
  - The crossing angle levelling has been made operational since June 2017.
  - The β* levelling has been tested in MDs. In between the matching points some β-beating and tune shift appear, which are observed as losses, which should be reduced by additional smoothing. As concerns beam stability, the beam-beam separation should remain below 1 σ (RMS beam size).
- Bunch-by-bunch capabilities are required to perform measurements with high intensity beams by exciting a single bunch and measuring it for instance with all the BPMs (e.g. for coupling measurement).
- Finally, it is worth emphasizing that in the whole document the positions of the collimators are expressed in RMS beam sizes assuming a normalized transverse emittance of 2.5 μm (instead of the 3.5 μm used for the LHC).

In the following tables the beam parameters at SPS extraction and the main HL-LHC nominal machine and beam parameters during the various phases of the cycle are provided (the crossing angle and separation offset refer to Beam 1).

Table 2: Parameters at SPS extraction[1] [4]	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]	0.57	
RMS bunch length (q-Gaussian) [cm]	10.5	
RMS bunch length (Gaussian fit) [cm]	12.4	
FWHM bunch length [cm]	29.2	
RMS energy spread (q-Gaussian) [10^{-4}]	2.2	
RMS energy spread (Gaussian fit) [10^{-4}]	2.6	
FWHM energy spread [10^{-4}]	6.1	

[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 [1].

Table 3: 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	2760	2748
Filling pattern	standard[2]	BCMS[3]
ε_n (x,y) [µm] at start of injection plateau and before the ramp (with IBS)	Initial: 2.0, 2.0 Final: 2.2, 2.0	Initial: 1.7, 1.7 Final: 1.93, 1.71
Total RF voltage [MV]	8	
Longitudinal beam loading compensation	Half detuning (without phase modulation)	
ε_L [eVs]	0.57	
RMS bunch length (q-Gaussian) [cm]	7.8	
RMS bunch length (Gaussian fit) [cm]	9.2	
FWHM bunch length [cm]	21.7	
RMS energy spread (q-Gaussian) [10^{-4}]	3.1	
RMS energy spread (Gaussian fit) [10^{-4}]	3.7	
FWHM energy spread [10^{-4}]	8.7	
β* [m] in IP1/2/5/8	6/10/6/10	
Optics	HL-LHCV1.3 injection	
Tunes (H/V)	62.27/60.295	
Transition gamma (B1/B2)	53.8/53.9	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	+250[4] (H[5])	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±2.0 (V)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2)[6] [µrad]	±1089 (V) ±170 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±3.5 (H)	
Parallel angle at the IP for Alice (IP2) [µrad]	±40 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	±250 (V)	
Half parallel separation at the IP for CMS (IP5) [mm]	±2.0 (H)	
Half external crossing angle at the IP for LHCb (IP8) [µrad]	-170 (H)	
Half crossing angle at the IP for LHCb (IP8)[6] [µrad]	±2100 (H) -170 (H)	

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[2] https://espace.cern.ch/HiLumi/WP2/Shared%20Documents/Filling%20Schemes%20HL-LHC/25ns_2760b_2748_2494_2572_288bpi_13inj.csv.

[3] https://espace.cern.ch/HiLumi/WP2/Shared%20Documents/Filling%20Schemes%20HL-LHC/25ns_2748b_2736_2258_2374_288bpi_12inj.csv.

[4] Detailed DA studies still need to be performed.

[5] In the horizontal plane there is no choice of sign as it is defined by the geometry.

[6] 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 sum of the two, noting that one configuration provides a 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.

Parallel angle at the IP for LHCb (IP8) [μrad]	±40 (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±3.5 (V)	
Transverse damper damping time [turns]	10	
Transverse damper bandwidth	Fully bunch-by-bunch	
IBS growth-times (x,y,z) [h]	4.2, 93.5, 3.3	3.0, 65.6, 2.8
Damping times from synchrotron radiation (x,y,z) [10^3 h]	194.7, 194.7, 97.4	
Power loss due to synchrotron radiation (W/m/beam)	~ 0	
Chromaticity Q' (dQ/(dp/p))	+20[7]	
Landau octupole Current (LOF) [A]	-40[7]	
Collimators: TCP IR7 [σ]	6.7	
Collimators: TCSG IR7 [σ]	7.9	
Collimators: TCLA IR7 [σ]	11.8	
Collimators: TCLD IR7 [σ]	20	
Collimators: TCP IR3 [σ]	9.5	
Collimators: TCSG IR3 [σ]	11.0	
Collimators: TCLA IR3 [σ]	11.8	
Collimators: TCSG IR6 [σ]	8.3	
Collimators: TCDQ IR6 [σ]	9.5	
Collimators: TCT IR1/5 [σ]	15.4	
Collimators: Protected Aperture 1/5 [σ]	12.6 (not related anymore to TCT settings)	
Collimators: TCT IR2 [σ]	15.4	
Collimators: TCT IR8 [σ]	15.4	
TDIS [in mm]	± 3.9	
Crab Cavities: frequency [MHz]	400.788	
Crab Cavities: voltage per cavity [MV]	0.25	
Crab Cavities: phase between the 2 cavities [deg]	±90	
Crab Cavities: total voltage [MV]	0 (as the 2 CCs are counter-phased)	
Crab Cavities: crabbing angle [μrad]	0	
Crab Cavities: max. transverse emittance blow-up [μm/h]	Should be small wrt blow-up from IBS (which is ~ 0.4 μm/h in H-plane) => < ~ 0.04	

[7] The scaling with intensity remains to be studied in detail but similar values were used until now for Run 2.

Table 4: Parameters during ramp and squeeze	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	2760	2748
Filling pattern	standard	BCMS
ε_n [μm]	2.0	1.7
Total RF voltage [MV]	8 (0.45 TeV) to 16 (7 TeV) linearly with time	
Longitudinal beam loading compensation	Full detuning (with phase modulation)	
Peak-to-peak RF phase modulation due to full detuning scheme [40] for the considered filling pattern and maximum bunch population [ps]	111	
ε_L [eVs]	0.57 (0.45 TeV) to 3.03 (7 TeV)	
RMS bunch length (q-Gaussian) [cm]	7.8 (0.45 TeV) to 7.6 (7 TeV)	
RMS bunch length (Gaussian fit) [cm]	9.2 (0.45 TeV) to 9.0 (7 TeV)	
FWHM bunch length [cm]	21.7 (0.45 TeV) to 21.2 (7 TeV)	
RMS energy spread (q-Gaussian) [10^{-4}]	3.1 (0.45 TeV) to 1.1 (7 TeV)	
RMS energy spread (Gaussian fit) [10^{-4}]	3.7 (0.45 TeV) to 1.3 (7 TeV)	
FWHM energy spread [10^{-4}]	8.7 (0.45 TeV) to 3.0 (7 TeV)	
β* [m] in IP1/2/5/8	6/10/6/10 – 0.64[8]/10/0.64[8]/3	
Optics	HL-LHCV1.3 injection (0.45 TeV) - HL-LHCV1.3 end of ramp (7 TeV)	
Tunes (H/V)	62.27/60.295 to 62.31/60.32	
Transition gamma (B1/B2)	53.8/53.9 to 53.8/53.8	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	+250 (H)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±0.55[9] (V)	
Half external crossing angle at IP for ALICE (IP2) [μrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2) [μrad]	±1089 (V) ±170 (V) to ±70 (V) ±170 (V) scaling with p	
Half parallel separation at the IP for ALICE (IP2) [mm]	±1.4[9] (H)	
Half crossing angle at the IP for CMS (IP5) [μrad]	±250 (V)	
Half parallel separation at the IP for CMS (IP5) [mm]	±0.55[9] (H)	
Half external crossing angle at the IP for LHCb (IP8) [μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8) [μrad]	±2100 (H) -170 (H) to ±135 (H) -250 (H) scaling with p	
Parallel angle at the IP for LHCb (IP8) [μrad]	±30 (0.45 TeV) to 0 (7 TeV) (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±3.5 to ±1.0[9] (V)	
Transverse damper damping time [turns]	50	
Transverse damper bandwidth	Fully bunch-by-bunch	
IBS growth-times (x,y,z) [h]	β* = 6m: 5.3, 107.2, 4.3 β* = 0.64 m: 15.3, inf, 22.2	4.0, 77.7, 3.8 10.9, inf, 18.4
Damping times from synchrotron radiation (x,y,z) [10^3 h]	β* = 6m: 194.7, 194.7, 973.6 β* = 0.64 m: 0.052, 0.052, 0.026	
Power loss due to synchrotron radiation (W/m/beam)	~ 0 (0.45 TeV) to ~ 0.32 (7 TeV)	
Chromaticity Q' (dQ/(dp/p))	+20	

[8] The limitation on β* at flat-top came from the sextupoles dI/dt in the 2017 Run, the exercise has to be redone with the final squeeze sequence and circuit performance to establish the minimum β*.

[9] As currently used in the LHC. A further optimization for HL-LHC could be done if needed.

Landau octupole Current (LOF) [A]	-40 (0.45 TeV) to < -420[10] (7 TeV) scaling with ~ p^2
Collimators: TCP IR7 [σ]	6.7
Collimators: TCSG IR7 [σ]	7.9 to 9.1
Collimators: TCLA IR7 [σ]	11.8 to 12.7[11]
Collimators: TCLD IR7 [σ]	20 to 16.6
Collimators: TCP IR3 [σ]	9.5 to 17.7
Collimators: TCSG IR3 [σ]	11.0 to 21.3
Collimators: TCLA IR3 [σ]	11.8 to 23.7
Collimators: TCSG IR6 (B1/B2) [σ]	8.3 to 12.3 / 9.6
Collimators: TCDQ IR6 (B1/B2) [σ]	8.3 to 12.3 / 9.6[12]
Collimators: TCT IR1/5 [σ]	15.4 to 43.8
Collimators: Protected Aperture 1/5 [σ]	12.6 to 19.3
Collimators: TCT IR2 [σ]	15.4 to 43.8
Collimators: TCT IR8 [σ]	15.4 to 43.8
TDIS [in mm]	+/- 55
Crab Cavities: frequency [MHz]	400.788-400.789
Crab Cavities: voltage per cavity [MV]	0.25
Crab Cavities: phase between the 2 cavities [deg]	±90
Crab Cavities: total voltage [MV]	0 (as the 2 CCs are counter-phased)
Crab Cavities: crabbing angle [μrad]	0
Crab Cavities: max. transverse emittance blow-up [μm/h]	Should be small wrt blow-up from IBS (which is ~ 0.4 μm/h in H-plane at injection) => < ~ 0.04

[10] 420 A (out of a maximum of 570 A) is the required current in the Landau octupoles to reach beam stability taking into account only the impedance model and without any margin (as seen in the picture of page 4).

[11] End point is under study for compatibility with TCDQ setting – see note below. This applies to the TCLA setting in all later tables.

[12] This assumes that the TCDQ must stay constant in mm during the squeeze, with the mm point taken from the end of the squeeze at 15 cm, and the V1.3 optics as of 4/9/2017. It should be noted that the setting in mm is not compatible with the 5.2 mm TCDQ setting demanded by the ABT group, which means that the ABT requirements will have to be reviewed in the future or the optics redone. This note applies to the TCDQ setting in later configurations as well.

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

Nominal Scenario (levelling at a luminosity of 5×10^{34} $cm^{-2}s^{-1}$**)**

Table 5: 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	2760	2748
Number of colliding pairs in IP1/2/5/8 (at the end of the collision process)	2748/2494/2748/2572	2736/2258/2736/2374
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	132/132/5.7	133/133/6.2
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8	5.0/0.001/5.0/0.2	5.0/0.001/5.0/0.2
ε_n [µm]	2.5	
Total RF voltage [MV]	16	
Longitudinal beam loading compensation	Full detuning (with phase modulation)	
Peak-to-peak RF phase modulation due to full detuning scheme [40] for the considered filling pattern and maximum bunch population [ps]	111	
ε_L [eVs]	3.03	
RMS bunch length (q-Gaussian) [cm]	7.6	
RMS bunch length (Gaussian fit) [cm]	9.0	
FWHM bunch length [cm]	21.2	
RMS energy spread (q-Gaussian) [10^{-4}]	1.1	
RMS energy spread (Gaussian fit) [10^{-4}]	1.3	
FWHM energy spread [10^{-4}]	3.0	
β^* [m] in IP1/2/5/8	0.64/10/0.64/3.0	
Optics	HL-LHCV1.3 pre-squeeze (0.64 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.80	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	+250 (H)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±0.55 to 0 (V)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2) [µrad]	±70 (V) ±170 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±1.4 to ±Xip2=0.138 (H) (see Appendix C)	
Half crossing angle at the IP for CMS (IP5) [µrad]	±250 (V)	
Half parallel separation at the IP for CMS (IP5) [mm]	±0.55 to 0 (H)	
Half external crossing angle at the IP for LHCb (IP8) [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8) [µrad]	±135 (H) -250 (H)	
parallel angle at the IP for LHCb (IP8) [µrad]	0 (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±1 to ±Yip8=0.043 (V) (see Appendix C)	
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	< 3 [5, p.45]	
Transverse damper damping time [turns]	50	
Transverse damper bandwidth	Fully bunch-by-bunch	
IBS growth-times (x,y,z) [h]	25.8, inf, 30.3	
Damping times from synchrotron radiation (x,y,z) [h]	51.7, 51.7, 25.9	
Power loss due to synchrotron radiation (W/m/beam)	~ 0.32	
Chromaticity Q' (dQ/(dp/p))	+15	
Landau octupole Current (LOF) [A]	< -420	
Collimators: TCP IR7 [σ]	6.7	
Collimators: TCSG IR7 [σ]	9.1	
Collimators: TCLA IR7 [σ]	12.7	
Collimators: TCLD IR7 [σ]	16.6	
Collimators: TCP IR3 [σ]	17.7	

Collimators: TCSG IR3 [σ]	21.3
Collimators: TCLA IR3 [σ]	23.7
Collimators: TCSG IR6 (B1 / B2) [σ]	12.3 / 9.6
Collimators: TCDQ IR6 (B1 / B2) [σ]	12.3 / 9.6
Collimators: TCT IR1/5 [σ]	18.0
Collimators: Protected Aperture 1/5 [σ]	19.4
Collimators: TCT IR2 [σ]	43.8
Collimators: TCT IR8 [σ]	17.7
TDIS [in mm]	+/- 55
Crab Cavities: frequency [MHz]	400.789
Crab Cavities: voltage per cavity [MV]	0.25
Crab Cavities: phase between the 2 cavities [deg]	0
Crab Cavities: total voltage [MV]	0.5 (as the 2 CCs are in phase)
Crab Cavities: crabbing angle [μrad]	± 180
Crab Cavities: max. transverse emittance blow-up [μm/h]	0.04

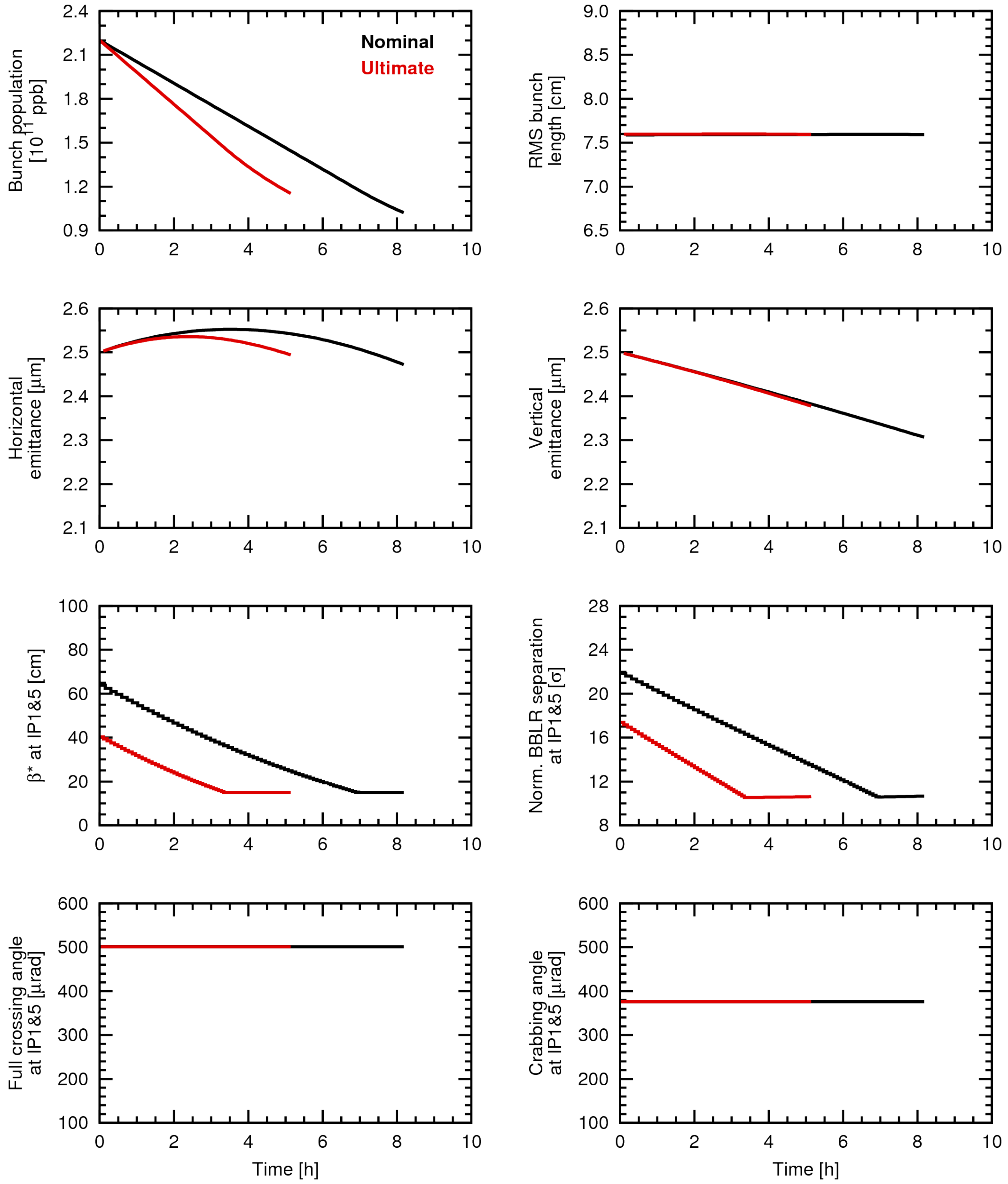
Table 6: Parameters in stable beams (nominal)	HL-LHC (standard)	HL-LHC (BCMS)
Beam total energy [TeV]	7	
Particles per bunch, N [10^{11}]	2.2 (start of fill)	
ε_n [µm]	2.5 (start of fill)	
Maximum number of bunches per beam	2760	2748
Number of colliding pairs in IP1/2/5/8	2748/2494/2748/2572	2736/2258/2736/2374
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	131/131/5.6	132/132/6.1
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8	5.0/0.001/5.0/0.2	5.0/0.001/5.0/0.2
Levelling method in IP1/2/5/8	β*/separation/β*/separation	
Total RF voltage [MV]	16	
Longitudinal beam loading compensation	Full detuning (with phase modulation)	
Peak-to-peak RF phase modulation due to full detuning scheme [40] for the considered filling pattern and maximum bunch population [ps]	111	
ε_L [eVs]	3.03 (start of fill)	
RMS bunch length (q-Gaussian) [cm]	7.6 (start of fill)	
RMS bunch length (Gaussian fit) [cm]	9.0 (start of fill)	
FWHM bunch length [cm]	21.2 (start of fill)	
RMS energy spread (q-Gaussian) [10^{-4}]	1.1 (start of fill)	
RMS energy spread (Gaussian fit) [10^{-4}]	1.3 (start of fill)	
FWHM energy spread (Gaussian fit) [10^{-4}]	3.0 (start of fill)	
β* [m] in IP1/2/5/8	0.64 to 0.15/10/0.64 to 0.15/3.0	
Optics	HL-LHCV1.3 pre-squeeze (0.64 m) to HL-LHCV1.3 pre-squeeze (0.46 m) to HL-LHCV1.3 collision round (0.15 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.80 to 53.58	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	+250 (H) (norm. BBLR sep. from 21.8 σ to 10.6 σ)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	0 (V)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2) [µrad]	±70 (V) ±170 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±Xip2=0.138 to 0 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	±250 (V) (norm. BBLR sep. from 21.8 σ to 10.6 σ)	
Half parallel separation at the IP for CMS (IP5) [mm]	0 (H)	
Half external crossing angle at the IP for LHCb (IP8) [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8) [µrad]	±135 (H) -250 (H)	
Parallel angle at the IP for LHCb (IP8) [µrad]	0 (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±Yip8=0.043 to 0 (V)	
Transverse damper damping time [turns]	50	
Transverse damper bandwidth	Standard (to reduce the associated noise)	
IBS growth-times (x,y,z) [h]	β* = 0.64 m: 25.8, inf, 30.3 β* = 0.15 m: 21.4, inf, 33.7	
Damping times from synchrotron radiation (x,y,z) [h]	β* = 0.64 m: 51.7, 51.7, 25.9 β* = 0.15 m: 51.7, 51.7, 25.9	
Power loss due to synchrotron radiation (W/m/beam)	~ 0.32 (at start of fill) and then decreases	
Chromaticity Q' (dQ/(dp/p)) for colliding bunches	+5	
Landau octupole Current (LOF) [A] for colliding bunches	-100	
Chromaticity Q' (dQ/(dp/p)) for non-colliding bunches	+15	
Landau octupole Current (LOF) [A] for non-colliding bunches	< -420	
Collimators: TCP IR7 [σ]	6.7	
Collimators: TCSG IR7 [σ]	9.1	
Collimators: TCLA IR7 [σ]	12.7	

Collimators: TCLD IR7 [σ]	16.6
Collimators: TCP IR3 [σ]	17.7
Collimators: TCSG IR3 [σ]	21.3
Collimators: TCLA IR3 [σ]	23.7
Collimators: TCSG IR6 (B1 / B2) [σ]	12.3 / 9.6 to 10.1
Collimators: TCDQ IR6 (B1 / B2) [σ]	12.3 / 9.6 to 10.1
Collimators: TCT IR1/5 [σ]	18.0 to 12.9[13] / 10.1[14]
Collimators: Protected Aperture 1/5 [σ]	19.4 to 14.6[13] / 11.9[14]
Collimators: TCT IR2 [σ]	43.8
Collimators: TCT IR8 [σ]	17.7
TDIS [in mm]	+/- 55
Crab Cavities: frequency [MHz]	400.789
Crab Cavities: voltage per cavity [MV]	3.4
Crab Cavities: phase between the 2 cavities [deg]	0
Crab Cavities: total voltage [MV]	6.8 (as the 2 CCs are in phase)
Crab Cavities: crabbing angle [μrad]	±180 to ±190
Crab Cavities: max. transverse emittance blow-up [μm/h]	0.04

The main plots for the baseline nominal (and ultimate) fill evolutions can be found in Fig. 3, assuming a constant crossing angle. For the nominal scenario, this would lead to a yearly-integrated luminosity of ~ 260 fb^{-1} for both standard and BCMS beams, assuming 160 days of operation, a turn-around time of 145 min (see Table 1) and an efficiency of 50%.

[13] Old setting without MKD-TCT phase assumption.

[14] Relies on MKD-TCT phase advance being below 30 deg.



Nominal
Ultimate
Bunch population [10^11 ppb]
RMS bunch length [cm]
Horizontal emittance [µm]
Vertical emittance [µm]
β* at IP1&5 [cm]
Norm. BBLR separation at IP1&5 [σ]
Full crossing angle at IP1&5 [µrad]
Crabbing angle at IP1&5 [µrad]
Time [h]
Time [h]

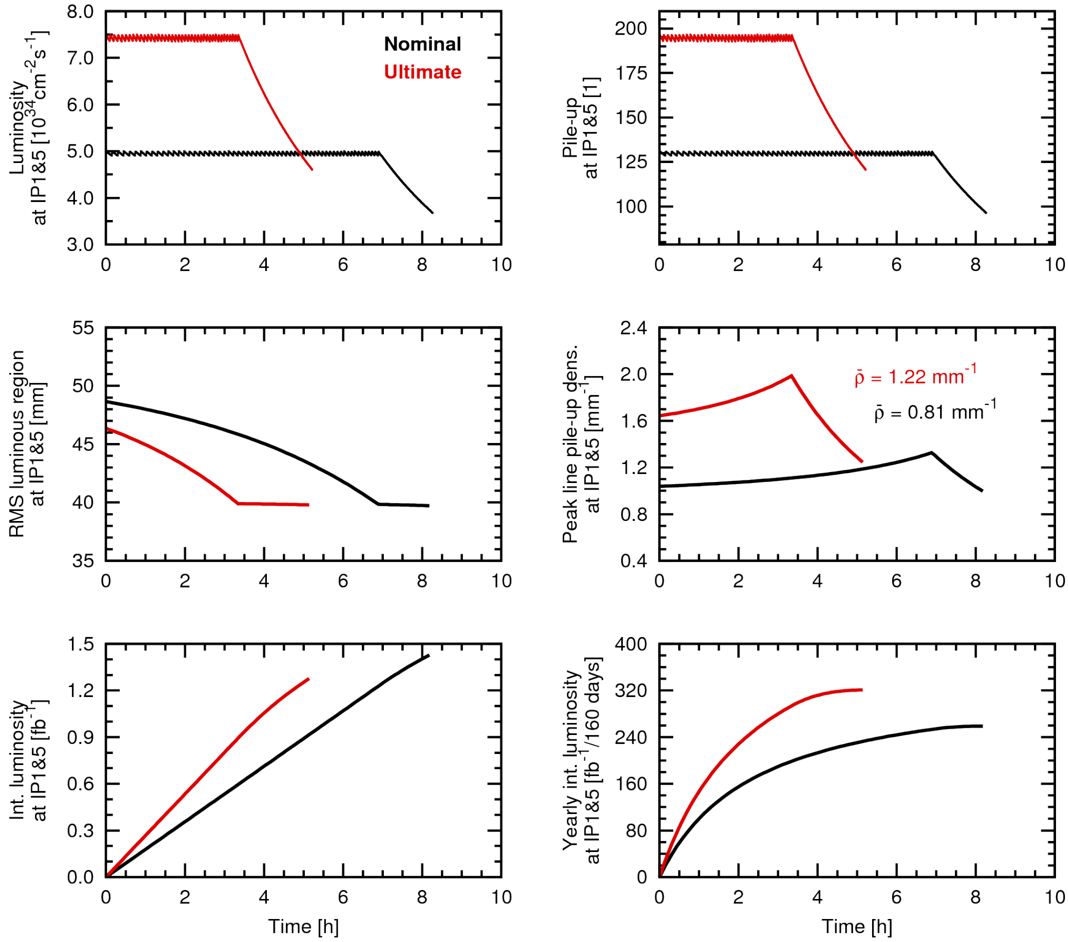


Figure 3: Main plots for the baseline nominal (and ultimate) fill evolutions assuming a constant crossing angle.

Ultimate Scenario (levelling at a luminosity of 7.5×10^{34} $cm^{-2}s^{-1}$**)**

Table 7: 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	2760	2748
Filling pattern	standard	BCMS
ε_n [µm]	2.0	1.7
Total RF voltage [MV]	16	
Longitudinal beam loading compensation	Full detuning (with phase modulation)	
Peak-to-peak RF phase modulation due to full detuning scheme [40] for the considered filling pattern and maximum bunch population [ps]	111	
ε_L [eVs]	3.03	
RMS bunch length (q-Gaussian) [cm]	7.6	
RMS bunch length (Gaussian fit) [cm]	9.0	
FWHM bunch length [cm]	21.2	
RMS energy spread (q-Gaussian) [10^{-4}]	1.1	
RMS energy spread (Gaussian fit) [10^{-4}]	1.3	
FWHM energy spread [10^{-4}]	3.0	
β* [m] in IP1/2/5/8	0.64/10/0.64/3.0 to 0.40/10/0.40/3.0	
Optics	HL-LHCV1.3 end of ramp to pre-squeeze (0.46 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.86 to 53.80	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	+250 (H)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±0.55 (V)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2) [µrad]	±70 (V) ±170 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±1.4 (H)	
Parallel angle at the IP for Alice (IP2) [µrad]	0 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	±250 (V)	
Half parallel separation at the IP for CMS (IP5) [mm]	±0.55 (H)	
Half external crossing angle at the IP for LHCb (IP8) [µrad]	-250 (H)	
Half crossing angle at the IP for LHCb (IP8) [µrad]	±135 (H) -250 (H)	
Parallel angle at the IP for LHCb (IP8) [µrad]	0 (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±1.0 (V)	
Transverse damper damping time [turns]	50	
Transverse damper bandwidth	Fully bunch-by-bunch	
IBS growth-times (x,y,z) [h]	β* = 0.64 m: 15.3, inf, 22.2 β* = 0.40 m: 15.2, inf, 22.3	10.9, inf, 18.4 10.8, inf, 18.4
Damping times from synchrotron radiation (x,y,z) [h]	β* = 0.64 m: 51.7, 51.7, 25.9 β* = 0.40 m: 51.7, 51.7, 25.9	
Power loss due to synchrotron radiation (W/m/beam)	~ 0.32	
Chromaticity Q' (dQ/(dp/p))	+15	
Landau octupole Current (LOF) [A]	< -420	
Collimators: TCP IR7 [σ]	6.7	
Collimators: TCSG IR7 [σ]	9.1	
Collimators: TCLA IR7 [σ]	12.7	
Collimators: TCLD IR7 [σ]	16.6	
Collimators: TCP IR3 [σ]	17.7	
Collimators: TCSG IR3 [σ]	21.3	
Collimators: TCLA IR3 [σ]	23.7	
Collimators: TCSG IR6 (B1 / B2) [σ]	12.3 / 9.6 to 11.7 / 9.6	
Collimators: TCDQ IR6 (B1 / B2) [σ]	12.3 / 9.6 to 11.7 / 9.6	
Collimators: TCT IR1/5 [σ]	43.8 to 17.5	

Collimators: Protected Aperture 1/5 [σ]	19.4 to 19.0
Collimators: TCT IR2 [σ]	43.8
Collimators: TCT IR8 [σ]	17.7
TDIS [in mm]	+/- 55
Crab Cavities: frequency [MHz]	400.789
Crab Cavities: voltage per cavity [MV]	0.25
Crab Cavities: phase between the 2 cavities [deg]	± 90
Crab Cavities: total voltage [MV]	0 (as the 2 CCs are counter-phased)
Crab Cavities: crabbing angle [μrad]	0
Crab Cavities: max. transverse emittance blow-up [μm/h]	0.04

Table 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	2760	2748
Number of colliding pairs in IP1/2/5/8 (at the end of the collision process)[10]	2748/2494/2748/2572	2736/2258/2736/2374
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	197/197/5.7	198/198/6.2
Levelled luminosity [10^{34} cm^{-2}s^{-1}] in IP1/2/5/8[11]	7.5/0.001/7.5/0.2	7.5/0.001/7.5/0.2
ε_n [µm]	3.5	
Total RF voltage [MV]	16	
Longitudinal beam loading compensation	Full detuning (with phase modulation)	
Peak-to-peak RF phase modulation due to full detuning scheme [40] for the considered filling pattern and maximum bunch population [ps]	111	
ε_L [eVs]	3.03	
RMS bunch length (q-Gaussian) [cm]	7.6	
RMS bunch length (Gaussian fit) [cm]	9.0	
FWHM bunch length [cm]	21.2	
RMS energy spread (q-Gaussian) [10^{-4}]	1.1	
RMS energy spread (Gaussian fit) [10^{-4}]	1.3	
FWHM energy spread (Gaussian fit) [10^{-4}]	3.0	
β^* [m] in IP1/2/5/8	0.40/10/0.40/3.0	
Optics	HL-LHCV1.3 pre-squeeze (0.46 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.70	
Half crossing angle at the IP for ATLAS (IP1) [µrad]	+250 (H)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	±0.55 to 0 (V)	
Half external crossing angle at IP for ALICE (IP2) [µrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2) [µrad]	±70 (V) ±170 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±1.4 to ±Xip2=0.138 (H)	
Half crossing angle at the IP for CMS (IP5) [µrad]	±250 (V)	
Half parallel separation at the IP for CMS (IP5) [mm]	±0.55 to 0 (H)	
Half external crossing angle at the IP for LHCb (IP8) [µrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8) [µrad]	±135 (H) -250 (H)	
Parallel angle at the IP for LHCb (IP8) [µrad]	0 (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±1.0 to ±Yip8=0.043 (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	< 3 [5, p.45]	
Transverse damper damping time [turns]	50	
Transverse damper bandwidth	Fully bunch-by-bunch	
IBS growth-times (x,y,z) [h]	53.2, 0, 45.7	
Damping times from synchrotron radiation (x,y,z) [h]	51.7, 51.7, 25.9	
Power loss due to synchrotron radiation (W/m/beam)	~ 0.32	
Chromaticity Q' (dQ/(dp/p))	+15	
Landau octupole Current (LOF) [A]	< -420	
Collimators: TCP IR7 [σ]	6.7	
Collimators: TCSG IR7 [σ]	9.1	
Collimators: TCLA IR7 [σ]	12.7	
Collimators: TCLD IR7 [σ]	16.6	
Collimators: TCP IR3 [σ]	17.7	

Collimators: TCSG IR3 [σ]	21.3
Collimators: TCLA IR3 [σ]	23.7
Collimators: TCSG IR6 (B1 / B2) [σ]	11.7 / 9.6
Collimators: TCDQ IR6 (B1 / B2) [σ]	11.7 / 9.6
Collimators: TCT IR1/5 [σ]	17.5
Collimators: Protected Aperture 1/5 [σ]	19.0
Collimators: TCT IR2 [σ]	43.8
Collimators: TCT IR8 [σ]	17.7
TDIS [in mm]	+/- 55
Crab Cavities: frequency [MHz]	400.789
Crab Cavities: voltage per cavity [MV]	0.25
Crab Cavities: phase between the 2 cavities [deg]	0
Crab Cavities: total voltage [MV]	0.5 (as the 2 CCs are in phase)
Crab Cavities: crabbing angle [μrad]	±180
Crab Cavities: max. transverse emittance blow-up [μm/h]	0.04

Table 9: 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	2760	2748
Number of colliding pairs in IP1/2/5/8	2748/2494/2748/2572	2736/2258/2736/2374
Filling pattern	standard	BCMS
Levelled pile-up in IP1/5/8	197/197/5.6	197/197/6.1
Levelled luminosity [10^{34} $cm^{-2}s^{-1}$] in IP1/2/5/8	7.5/0.001/7.5/0.2	7.5/0.001/7.5/0.2
Levelling method in IP1/2/5/8	β^*/separation/β^*/separation	
Total RF voltage [MV]	16	
Longitudinal beam loading compensation	Full detuning (with phase modulation)	
Peak-to-peak RF phase modulation due to full detuning scheme [40] for the considered filling pattern and maximum bunch population [ps]	111	
ε_L [eVs]	3.03 (start of fill)	
RMS bunch length (q-Gaussian) [cm]	7.6 (start of fill)	
RMS bunch length (Gaussian fit) [cm]	9.0 (start of fill)	
FWHM bunch length [cm]	21.2 (start of fill)	
RMS energy spread (q-Gaussian) [10^{-4}]	1.1 (start of fill)	
RMS energy spread (Gaussian fit) [10^{-4}]	1.3 (start of fill)	
FWHM energy spread [10^{-4}]	3.0 (start of fill)	
β^* [m] in IP1/2/5/8	0.40 to 0.15/10/0.40 to 0.15/3.0	
Optics	HL-LHCV1.3 pre-squeeze (0.46 m) to HL-LHCV1.3 collision round (0.15 m)	
Tunes (H/V)	62.31/60.32	
Transition gamma (average B1/B2)	53.70 to 53.58	
Half crossing angle at the IP for ATLAS (IP1) [μrad]	+250 (H) (norm. BBLR sep. from 17.3 σ to 10.6 σ)	
Half parallel separation at the IP for ATLAS (IP1) [mm]	0 (V)	
Half external crossing angle at IP for ALICE (IP2) [μrad]	±170 (V)	
Half crossing angle at the IP for ALICE (IP2) [μrad]	±70 (V) ±170 (V)	
Half parallel separation at the IP for ALICE (IP2) [mm]	±Xip2=0.138 to 0 (H)	
Half crossing angle at the IP for CMS (IP5) [μrad]	±250 (V) (norm. BBLR sep. from 17.3 σ to 10.6 σ)	
Half parallel separation at the IP for CMS (IP5) [mm]	0 (H)	
Half external crossing angle at the IP for LHCb (IP8) [μrad]	-250(H)	
Half crossing angle at the IP for LHCb (IP8) [μrad]	±135 (H) -250 (H)	
Parallel angle at the IP for LHCb (IP8) [μrad]	0 (V)	
Half parallel separation at IP for LHCb (IP8) [mm]	±Yip8=0.043 to 0 (V)	
Transverse damper damping time [turns]	50	
Transverse damper bandwidth	Standard (to reduce the associated noise)	
IBS growth-times (x,y,z) [h]	β^* = 0.40 m: 25.6, inf, 30.4 β^* = 0.15 m: 21.4, inf, 33.7	
Damping times from synchrotron radiation (x,y,z) [h]	β^* = 0.40 m: 51.7, 51.7, 25.9 β^* = 0.15 m: 51.7, 51.7, 25.9	
Power loss due to synchrotron radiation (W/m/beam)	~ 0.32 (at start of fill) and then decreases	
Chromaticity Q' (dQ/(dp/p)) for colliding bunches	+5	
Landau octupole Current (LOF) [A] for colliding bunches	-100	
Chromaticity Q' (dQ/(dp/p)) for non-colliding bunches	+15	
Landau octupole Current (LOF) [A] for non-colliding bunches	< -420	
Collimators: TCP IR7 [σ]	6.7	
Collimators: TCSG IR7 [σ]	9.1	
Collimators: TCLA IR7 [σ]	12.7	

Collimators: TCLD IR7 [σ]	16.6
Collimators: TCP IR3 [σ]	17.7
Collimators: TCSG IR3 [σ]	21.3
Collimators: TCLA IR3 [σ]	23.7
Collimators: TCSG IR6 (B1 / B2) [σ]	11.7 / 9.6 to 10.1
Collimators: TCDQ IR6 (B1 / B2) [σ]	11.7 / 9.6 to 10.1
Collimators: TCT IR1/5 [σ]	17.5 to 12.9[13]/ 10.1[14]
Collimators: Protected Aperture 1/5 [σ]	19.0 to 14.6[13]/ 11.9[14]
Collimators: TCT IR2 [σ]	43.8
Collimators: TCT IR8 [σ]	17.7
TDIS [in mm]	+/- 55
Crab Cavities: frequency [MHz]	400.789
Crab Cavities: voltage per cavity [MV]	3.4
Crab Cavities: phase between the 2 cavities [deg]	0
Crab Cavities: total voltage [MV]	6.8 (as the 2 CCs are in phase)
Crab Cavities: crabbing angle [μrad]	±180 to ±190
Crab Cavities: max. transverse emittance blow-up [μm/h]	0.04

The main plots for the baseline nominal and ultimate fill evolutions were already shown before (see Fig. 3). For the ultimate scenario, this would lead to a yearly-integrated luminosity of ~ 320 fb^{-1} for both standard and BCMS beams, assuming 160 days of operation, a turn-around time of 150 min (see Table 1) and an efficiency of 50%. With an efficiency of say 58% (as assumed in the past), ~ 370 fb^{-1}could be achieved per year.

APPENDIX A: q-Gaussian longitudinal bunch profile

The longitudinal bunch profile in the LHC is well described (and it is also justified for HL-LHC) by

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

This function is a particular case of the Tsallis q-Gaussian distribution [9]

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

with mean $\mu = 0$, deformation parameter $q = 3/5$, and scale parameter $\beta = 10/S^2$. The normalization factor C_q and the q-exponential function in the equation above are given by

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

and

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

Such a description is valid at the beginning of the fill, as the profile tends to Gaussian at the end of it. The RMS value of the q-Gaussian distribution $\lambda(s)$ is

$$\sigma_\lambda = \frac{S}{4\sqrt{2}}.$$

The q-Gaussian distribution is compared to the usual Gaussian description of the longitudinal bunch profile (characterized by the RMS bunch length σ) in Table 10. The relation between their corresponding RMS values is

$$\sigma_\lambda = \frac{\sigma}{2}\sqrt{\frac{\ln 2}{1-2^{-2/5}}} \approx 0.846\sigma\,.$$

For the Gaussian RMS bunch length of $\sigma = 9$ cm, $\sigma_\lambda = 7.6$ cm. With this, both distributions share an identical FWHM (21.2 cm), which is the parameter of interest for the threshold of the longitudinal beam stability.

Table 10: Comparison between the q-Gaussian distribution and the usual Gaussian description of the longitudinal bunch profile (with RMS bunch length σ).

	Gaussian	q-Gaussian
Distribution	$\rho(s) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{s^2}{2\sigma^2}\right)$	$\lambda(s) = \frac{4\sqrt{2}}{5\pi\sigma_\lambda}\left(1-\frac{s^2}{8\sigma_\lambda^2}\right)$, $\lvert s\rvert \leq 2\sqrt{2}\sigma_\lambda$
RMS	σ	σ_λ
FWHM	$\mathrm{FWHM}(\rho) = 2\sqrt{2\ln 2}\,\sigma$	$\mathrm{FWHM}(\lambda) = 4\sqrt{2}\sqrt{1-2^{-2/5}}\,\sigma_\lambda$

APPENDIX B: Transverse emittance growth from CCs

Without sophisticated feedback on the CC, but including the ADT damping effect, the currently estimated transverse emittance blow-up from the CCs is ~ 4.6%/h (at β^* = 15 cm and 3.4 MV/CC), i.e. ~ 0.12 μm/h [41]. The absolute transverse emittance growth depends on both beam parameters and power spectral density of the RF noise on the betatron bands. Assuming constant betatron tune, RF noise spectrum and bunch length, the absolute growth rate is i) proportional to the betatron function at the CC (inversely proportional to β^*), ii) proportional to the square of the CC voltage and iii) inversely proportional to the square of the beam energy [42]. Some mitigation measures are currently under study (feedback on the CC voltage amplitude and phase from a measurement of the bunch transverse and head-tail motion) [43] and a factor 10 reduction of the growth rate is contemplated.

APPENDIX C: Levelling by transverse offset

IP2&8 will be levelled by parallel separation: Xip2 = 138 μm, which corresponds to 2.38 σ, and Yip8 = 43 μm, which corresponds to 1.36 σ. The luminosity reduction factor is plotted vs. the (full) transverse offset in Fig. 4.

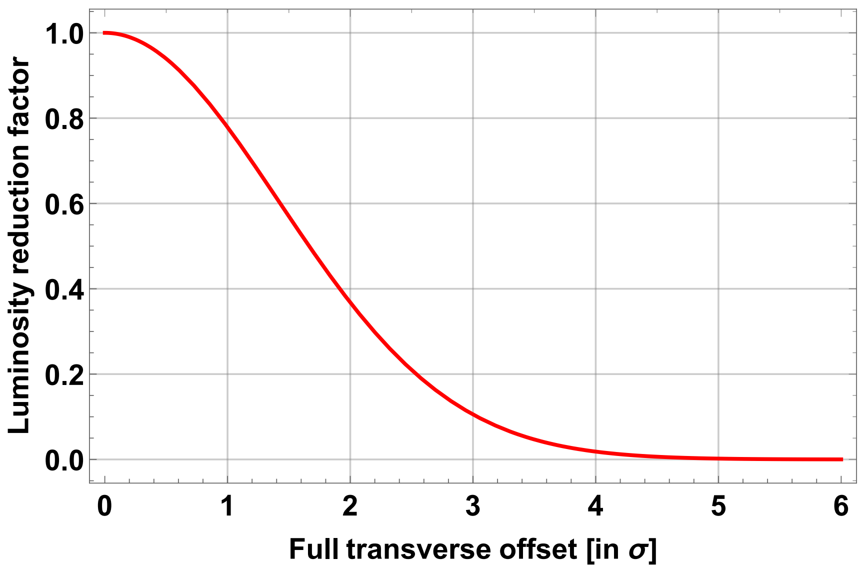


Figure 4: Luminosity reduction factor vs. the (full) transverse offset.

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