LHC MACHINE CONFIGURATION EVOLUTION OVER RUN 3 FOR MAXIMISED PERFORMANCE AND INNER TRIPLET LIFETIME

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Abstract

Initially planned to start in 2021 and to end up in 2024, the third exploitation period of the LHC (Run 3) started in 2022 and was extended by two years to fit the adjusted schedule of the High Luminosity LHC (HL-LHC) project. Run 3 was not only marked by the exceptional performance of the machine (with 125 fb^{-1} delivered to the two high luminosity experiments ATLAS and CMS, both in 2024 and 2025). Run 3 was also used as a unique opportunity for the transition between the LHC and the HL-LHC, both in terms of optics and beam parameters, in particular with the smallest β^* of 15 cm put in operation so far, and the highest bunch charge of 1.8×10^{11} protons/bunch now routinely used for proton physics fills. In order to make this transition as adiabatic as possible, the machine configuration was modified year by year, not only to profit as much as possible from the incremental increase of the bunch charge available at the exit of the injector chain, but also to mitigate as much as possible the radiation dose deposited in the inner triplets of the ATLAS and CMS experiments. This paper describes the main changes applied to the machine configuration over this period, together with the motivations.

PERFORMANCE OVERVIEW IN RUN 3

The LHC machine was designed to deliver an instantaneous luminosity of 10^{34} $cm^{-2}s^{-1}$ in proton operation to the two multi-purpose ATLAS and CMS detectors [1]. The target integrated performance was set to 300 fb^{-1}, basically limited by the tolerance to radiation estimated at that time for the existing inner triplets (IT) equipping the experimental insertions (IR) of the ring. This performance target was based on a certain number of key beam and optics parameters which are recalled in Table 1 for the LHC, and compared to HL-LHC [2]. These parameters were then revisited before the start of Run 3 [3] in order to profit as much as possible from the beam quality improvement and intensity ramp up which was planned to be gradually offered by the upgrade project of the LHC injector chain (LIU [4]) during Run 3, pending the long shutdown 3 (LS3) for the complete installation of the HL-LHC and the full exploitation of the LIU beam. As shown in Table 1, the transverse beam emittances were basically twice smaller than initially targeted [6–8], essentially thanks to post-LHC-design RF beam manipulations in the injector chain (so-called BCMS beam [9]) and their preservation through the injector chain and LHC. These sensibly smaller emittance values could still be essentially maintained at higher bunch population, up to 1.8×10^{11} p/b, as targeted for Run 3 (due to limitations from existing LHC equipment [3]), to be compared with 2.2×10^{11} p/b for the HL-LHC operation planned after LS3. The maximum possible number of bunches colliding at IP1 and IP5 was however lower than initially planned (~ 2450 corresponding to the worst prediction in [3]), limited by heat-load from the electron cloud, and imposing shorter bunch trains (36 b or 48 b per train vs. 72 b per train for standard LHC beam production with 25 ns bunch spacing), or even hybrid beam production scheme (see [10] for more details). This limitation is planned to be lifted in LS3 thanks to an in-situ carbon-coating of the beam-screen surface, at least for a certain fraction of the LHC arc cells [11, 12]. The maximum possible instantaneous luminosity is about 2×10^{34} $cm^{-2}s^{-1}$ for the LHC, being limited by the cryo-cooling capacity of the existing ITs [13] (and, just in the shadow, by a maximum allowed average pile-up of $\mu \sim 60$ events per bunch crossing). In order to mitigate the impact on machine performance, additional levels of complexity were introduced for operating the LHC in Run 3, namely: (i) luminosity leveling with β^* [14] (discrete steps in β^*), (ii) later on (as of 2024), moving as well the beam separation at the IP for smoothing as much as possible the luminosity profile in stable beam and cope with slightly different requests from ATLAS and CMS, and (iii) finally reducing as well the crossing angle towards the end of leveling (in 2025 and 2026), when the bunch population is significantly smaller, in order to maximize the machine performance per fill. As of the beginning of Run 3, a 30 cm collision optics was targeted at the end of luminosity leveling, starting from a β^* calibrated to 1.2 m at the beginning of stable beams (only 60 cm in 2022) in order to avoid a luminosity excess at the start of the collisions, and then leveling the optics in purely telescopic mode [15] in order to gain experience for the HL-LHC but also to accommodate the requirements of forward physics experiment data taking (see detailed motivations in [3]). A deep change of configuration was however introduced in 2025/2026, passing from round to flat optics after rotation of the crossing plane in ATLAS and CMS (see below), with a final β^* of 15 cm achieved in 2026 in the plane perpendicular to the crossing plane.

Pushing the beam and optics parameters, and adapting consequently the machine configuration/operation clearly contributed to the outstanding performance of the LHC in Run 3, with an integrated luminosity of 41 fb^{-1} delivered in 2022 (recommissioning year) and about 125 fb^{-1} in both 2024 and 2025 [5], albeit only 32 fb^{-1} in 2023 due to an incident which severely truncated the proton run for this specific year [16]. A target of 30 fb^{-1} has been given for 2026, which will be a very short proton run (with in addition 50 % of the time allocated to a so-called low-μ run, i.e. at low luminosity). Together, the LHC should have delivered nearly 550 fb^{-1} to the ATLAS and CMS experiments, i.e. almost

Table 1: LHC Performance [5] and Beam and Optics Parameters Evolution in Run 3 [6–8], Compared to LHC Initial Targets [1], Run 3 Targets [3], and HL-LHC [2]

Parameters and Performance	**LHC** (Design)	**Run 3** (Target)	**2022**	**2023**	**2024**	**2025**	**2026**[e]	**HL-LHC** (Design)
Collision energy (c.m.) [TeV]	7.0	6.8	6.8	6.8	6.8	6.8	6.8	7.0
Number of colliding bunches at IP1-5	2808	2484-2736	2450	2452	2340	2448	2448	2748
Bunch population[a] [10^{11} p/b]	1.15	1.80	1.45	1.60	1.60	1.75	1.80	2.20
Normalized transverse emittance[a] [µm]	3.75	1.80	1.7	2.2	1.8	1.6	1.6	2.50
Optics type	Round	Round		Round		Flat		Round
Crossing plane at IP1/5	V/H	V/H		V/H		H/V		H/V
β^* [cm] at IP1& IP5 in ×/|| planes	55/55	30/30[b]	30/30[b]	30/30[b]	30/30[b]	60/18[b]	50/15[b]	15/15[b]
Crossing angle [µrad] at IP1& IP5	285	320[b]	320[b]	320[b]	300[b]	240[b]	240[b]	500[b]
Triplet polarity in IR1/5	F/F	F/F	F/F	F/F	D/F	F/D	F/D	F/F
Peak Luminosity [$\mathrm{cm^{-2}s^{-1}}$]	1.00	2.00	1.95	2.00	2.20	2.20	2.20	5.00
Integrated performance [$\mathrm{fb^{-1}}$]	300	395[c]	231[d]	263[d]	387[d]	512[d]	542[d]	3000

[a] At the start of collisions (averaged between Beam 1 and Beam 2). [b] At the end of luminosity leveling (not considered at the time of the LHC design). [c] For a running period of only 3 years (2022, 2023 and 2024), before the first decision of Run 3 extension taken in 2023. [d] Cumulated performance since the start of the LHC till the end of the current year (projection for 2026), including 190 $\mathrm{fb^{-1}}$ integrated in Run 1 & 2 [5].[e] 2026 is a projection.

twice more than the assumed threshold above which the ITs were meant to be exchanged. Because of the very specific azimuthal and longitudinal distribution of the radiation dose deposited in the magnet coils (see [17] for more details), it was in fact realized, already in Run 2, that the IT luminosity lifetime is actually strongly dependent on the machine configuration itself, in particular the crossing angle plane and polarity (changed nearly year by year in ATLAS since 2015 [18]), and, more recently, the polarity of the inner triplet. LHC injection and collision optics with reversed IT polarity (and nominal polarity recovered as of Q5), so-called RP optics [19], were then developed and implemented in the LHC in 2024 (ATLAS only), and 2025/2026 (CMS only). In 2025, the crossing plane, nominally V/H in ATLAS/CMS, was also rotated to appropriately redistribute the radiation dose deposited in the IT of IR1 and IR5, and minimize its peak value integrated so far. As a result, in order to preserve the machine performance, while coping with the race-track geometry of the LHC triplet beam-screen, the optics was flattened during the β^*-leveling process (as of $\beta^*_\times$ = 60 cm) to reach in 2026 a HL-LHC-like β^* as small as $\beta^*_{||}$ = 15 cm in the plane perpendicular to the crossing plane (see [20] for more details). All these efforts helped in nearly doubling the IT luminosity lifetime, making possible an extension of Run 3 by 2 years, without the need of slowing down the LHC luminosity production rate, on the contrary.

MACHINE CONFIGURATION IN RUN 3

Injection, Ramp and Squeeze

The evolution of the optics parameters, and different manipulations put in place in Run 3 are detailed in Table 2. With the exception of localised optics modifications in 2024-2026 for reversing the IT polarity in IR1 or IR5, the injection optics was basically kept unchanged in Run 3, being the same as the one used since the implementation in 2017 of ATS optics [21]. On the other hand, deep modifications were introduced for the energy ramp from 450 GeV to 6.8 TeV. More precisely, the combined ramp and squeeze [22] was kept basically unchanged in 2022, albeit with a relaxed end of ramp (EoR) β^* of 1.33 m for that recommissioning year (vs. 1 m EoR at the end of Run 2). Then, from 2023 onward, the ramp was also combined with an anti-telescopic squeeze, as tested earlier in a machine development program over Run 2 [23]. The motivation was two-fold, namely: (i) in view of the increased beam brightness, and thanks to the β-beating wave induced in the LHC arcs for (anti-)telescopic optics, improve the Landau damping efficiency at constant octupole current towards the end of the ramp, where the machine impedance makes the beam stability most critical [24], and (ii) enable a rather large β^* dynamic range in purely telescopic mode, e.g. a factor of 4 from β^* = 1.2 m down to 30 cm for the round optics used in 2023 and 2024, at still moderate β-beating in the arcs[1]. As for Run 2, the completion of the optics squeeze was operated at flat top energy before putting the beams into collision. The cycle was however fully optimized in 2026, with the entire squeeze embedded in the ramp, and other crossing angle manipulations (see below), for a net gain of 10 min. in the turn around time [25].

Crossing Angle Manipulations and β^*-leveling

The LHCb experiment requested a vertical external crossing angle in Run 3 to withdraw statistical bias when taking physics data with either polarity of its horizontal spectrometer. The so-called LHCb rotation was implemented in 2023, first operated at flat top energy and separated from the optics squeeze beam process, then combined with it in 2024 and 2025, and finally accommodated towards the end of the

[1] e.g. only 100 % peak β-beating, when mowing from an anti-telescopic optics (e.g. with r_{Tele}=0.5 for β^* = 1.2 m) towards a telescopic optics (e.g. with r_{Tele}=2 for β^* = 30 cm) at constant IR1/5 quadrupole settings corresponding to a pre-squeezed β^* of β^*_{Pre} = 60 cm ($\beta^* \equiv r_{\mathrm{Tele}} \times \beta^*_{\mathrm{Pre}}$).

Table 2: Evolution of the Main Optics Parameters for the LHC Proton Cycle in Run 3

Optics parameters	**2022**	**2023**	**2024**	**2025**	**2026**
Injection (450 GeV)					
β^* [m] at IP1-2-5-8 (round optics)	11.0-10.0-11.0-10.0				
Crossing angle [µrad] in IR1-2-5-8	340(V)-340(V)-340(H)-340(H)				
End of energy ramp (6.8 TeV)					
β^* [m] at IP1-5 (round optics)	1.33-1.33	2.00-2.00	2.00-2.00	2.00-2.00	1.20-1.20
Telescopic index	1.00	0.50	0.50	0.50	0.50
Pre-squeezed β^* [m]	1.33	1.00	1.00	1.00	0.60
β^* [m] at IP2-8 (round optics)	10.0-2.0				
Crossing angle [µrad] in IR1-5	320(V)-320(H)	320(V)-320(H)	320(V)-320(H)	320(V)-320(H)	320(**H**)-320(**V**)
Crossing angle [µrad] in IR2-8	400(V)-400(H)	400(V)-400(H)	400(V)-400(H)	400(V)-400(H)	400(V)-400(**V**)
End of squeeze (=start of collision)					
β^* [m] at IP1-5 (round optics)	0.60-0.60	1.20-1.20	1.20-1.20	1.20-1.20	1.20-1.20
Telescopic index	1.00	0.50	0.50	0.50	0.50
Pre-squeezed β^* [m]	0.60	0.60	0.60	0.60	0.60
β^* [m] at IP2-8 (round optics)	10.0-2.0				
Crossing angle [µrad] in IR1-5	320(V)-320(H)	270(V)-270(H)	320(V)-320(H)	320(**H**)-320(**V**)	320(**H**)-320(**V**)
Crossing angle [µrad] in IR2-8	400(V)-400(H)	400(V)-400(**V**)	400(V)-400(**V**)	400(V)-400(**V**)	400(V)-400(**V**)
End of luminosity leveling (no further change for IR2-8)					
$\beta^*_{X/\|\|}$ [m] at IP1-5	0.30/0.30	0.30/0.30	0.30/0.30	0.60/0.18	0.50/0.15
Telescopic index ($X/\|\|$ planes)	2.00/2.00	2.00/2.00	2.00/2.00	1.00/3.33	1.00/3.33
Pre-squeezed β^* [m]	0.60	0.60	0.60	0.60	0.50
Crossing angle [µrad] in IR1-5	320(V)-320(H)	320(V)-320(H)	300(V)-300(H)	240(**H**)-240(**V**)	240(**H**)-240(**V**)

ramp in 2026. The nominal crossing planes, V in ATLAS and H in CMS, were kept till 2024, with collisions which took place at constant crossing angle in 2022 (320 µrad) and 2024 (300 µrad), and concomitant variations with β^* in 2023 [270 ($\beta^* = 1.2$ m) $\longrightarrow$ 320 µrad ($\beta^* = 30$ cm)] as a first step to mitigate the radiation in the ITs of IR1 and IR5. In 2024, RP optics were implemented in IR1 to displace to the exit of Q2b the peak radiation dose integrated until then at the entrance of Q2a [19]. In 2025 and 2026, the only remaining degree of freedom to preserve the IT longevity in IR5 was the crossing plane, which was then decided to be rotated in IR5 and subsequently in IR1[2]. Due to the ~5 mm beam-stay-clear reduction in the V (resp. H) plane of the triplets of IR5 (resp. IR1) to accommodate the beam-screen helium capillaries, the ATLAS and CMS crossing rotation implied a flattening of the optics, keeping a "large" 60-50 cm β^* in the (rotated) crossing plane, while offering enough aperture to strongly push β^* down to 18-15 cm in the other plane. In 2025, the ATLAS/CMS rotation was run as a separated beam process at flat top, then fully embedded in the ramp in 2026. Most of the collisions took place at constant crossing angle (320 µrad) in 2025 and 2026, from $\beta^* = 1.2$ m down to $\beta^*_{\times/\|\|} = 60/18$ cm, but the crossing angle was systematically anti-leveled down to 240 µrad at the end of each physics fills (lower intensity), at constant β^* in 2025, and in parallel with an extension of β^*-leveling in 2026 ($60/18 \longrightarrow 50/15$ cm), in order to maximize the machine performance.

[2] to preserve an alternated, H/V or V/H, crossing scheme in IR1/5, for the partial compensation of the long-range beam-beam effects in the LHC.

CONCLUSIONS

The machine configuration considerably evolved in Run 3 in order to extract the maximum possible performance from the LIU beam [4] intensity ramp up, while preserving as much as possible the existing LHC equipment, in particular the triplets, liable to suffer from radiation damage. The outstanding LHC performance in Run 3, which should almost triple the data quantity produced in Run 1+2, and nearly double the 300 fb^{-1} longevity initially assumed for the IT, has been made possible by new optics techniques and manipulations, such as (anti-)telescopic and flat optics, but also thanks to state of the art machine control, operation (e.g. β^*-leveling, fully combined ramp and squeeze) and optics corrections [26], and a battery of simulations regularly launched to decide year by year all details of machine configuration and cope with possible limitations from beam instabilities, beam-beam effects, radiation, etc.

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