OPERATIONAL β^* LEVELLING AT THE LHC IN 2022 AND BEYOND

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Abstract

During the third run period of the CERN Large Hadron Collider (LHC), as well as for the future High-Luminosity LHC era, luminosity levelling by β^* is a key technique to control the pile-up in the high-luminosity experiments ATLAS and CMS while maintaining Landau damping through the head-on beam-beam interaction. This implies changing the machine optics in the interaction regions while keeping high-intensity beams in collision and the experimental detectors in their data taking configuration. This paper summarizes the implementation and operational experience obtained during the first year of operation with beta levelling at the LHC and provides an outlook for the following years, when the β^* levelling range will be further extended.

INTRODUCTION

For the Run 3 of the CERN Large Hadron Collider (LHC) [1], the improved beam brightness provided by the LHC Injector Upgrade (LIU) [2] has allowed the luminosity to be pushed beyond twice the design value of $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the high-luminosity Interaction Points (IP) 1 and 5, where the ATLAS and CMS experiments are located.

However, the instantaneous luminosity must be limited for two main reasons: first, the capacity of the cryogenic system for the superconducting final-focusing triplets in the interaction regions limits the total instantaneous luminosity; second, the experiment data taking capabilities limit the number of collisions per bunch crossing (pile-up).

The total instantaneous luminosity of two bunched Gaussian beams colliding head-on is given by [3]

$$\mathcal{L} = \frac{k N_1 N_2 f_\mathrm{rev} \gamma}{2\pi \varepsilon \beta^*} \tag{1}$$

where k is the number of colliding bunch pairs, $N_{1,2}$ are the bunch intensities, f_rev is the revolution frequency, γ is the relativistic factor, ε is the normalized beam emittance, and β^* is the β function at the collision point.

The number of collisions per bunch crossing (pile-up) is

$$\mu = \mathcal{L}\frac{\sigma_\mathrm{inel}}{k f_\mathrm{rev}} \tag{2}$$

where σ_inel is the inelastic cross-section.

In the past different techniques for levelling the luminosity have been proposed [4], including introducing a beam separation, changing the beam crossing angle, and varying β^* by squeezing the beams in collisions.

Out of these options, levelling by β^* has the advantage of maintaining the full amplitude detuning and Landau damping from the head-on beam-beam interaction, which is crucial to stabilize high-intensity beams in the LHC [4]. However, changing β^* requires a change of machine optics, which is a delicate operation with high intensity beams colliding and the detectors fully powered in data taking configuration.

On the other hand, levelling by beam separation allows for maximum flexibility to level the luminosity at an IP over a wide range using local closed-orbit bumps of limited amplitude, without affecting the global machine configuration.

Therefore, a combination of levelling by separation and levelling by β^* is used at the LHC: The two high-luminosity IPs 1 and 5 (ATLAS and CMS experiments) are levelled by β^* to a common target luminosity to ensure beam stability, while the two low-luminsity IPs 2 and 8 (ALICE and LHCb experiments) are levelled to their individual luminosity targets by beam separation.

β^* LEVELLING AT THE LHC

Optics Management

The low-β^* LHC collision optics used in Run 3 employ the Achromatic Telescoptic Squeeze (ATS) technique [5, 6]. Thus, the strength of the final focusing triplets in IP 1 and 5 remains constant throughout the β^* squeeze.

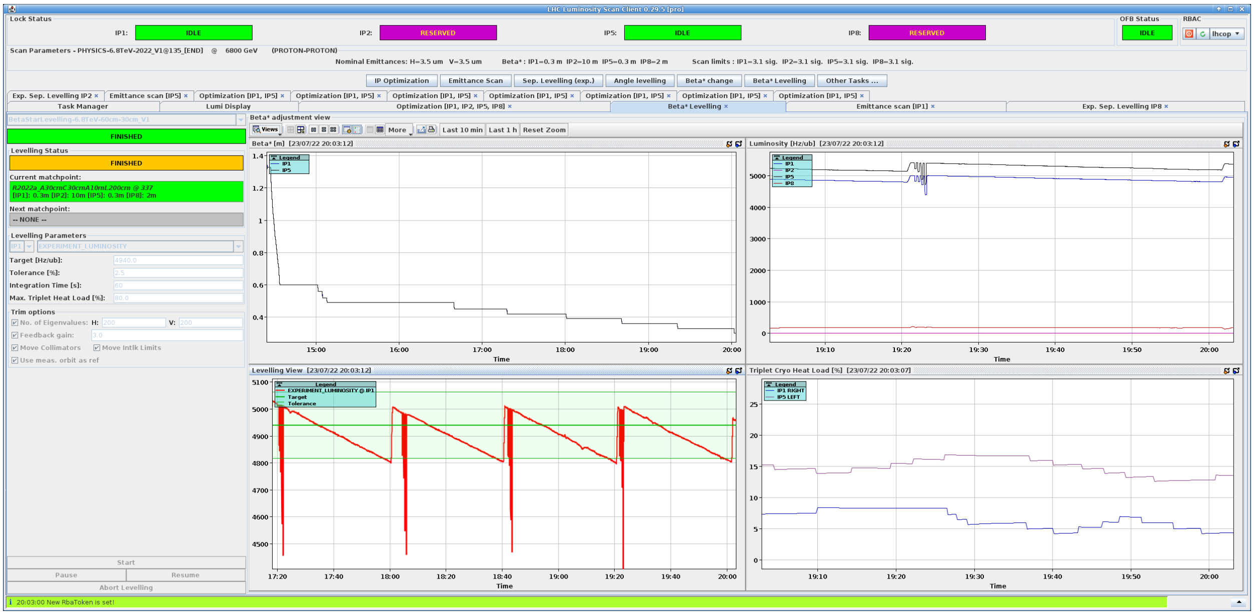
β^* levelling at the LHC is done in discrete steps. A set of optics covering the desired range of β^* in steps of ~5 % luminosity equivalent is pre-matched using the MAD-X program [7]. The required magnet strengths are then uploaded to the LHC settings database (LHC Software Architecture, LSA [8]), complemented by any optics corrections established during the commissioning phase [9].

In nominal physics operation, all prepared β^* steps are played in sequence. During machine development, the system also allows for transitions between any two β^* levelling optics, including de-squeezing the beams by running optics transitions backwards.

Orbit Control

When changing the optics for β^* levelling, closed orbit bumps in the interaction regions (e.g. crossing angles) change their shape. Also, additional orbit perturbations can be introduced on the orbit due to quadruple misalignments. To keep the beams colliding head-on in IP 1 and 5, and to avoid luminosity excursions to IP 2 and 8 which are levelled by beam separation, the orbit at the IPs must be controlled at a level better than 5 µm during the entire process.

To achieve this level of orbit control, a combination of feed-forward corrections and a real-time orbit feedback system (OFB) system [10] is used. During the commissioning of the β^* levelling process, for every optics used, both the global orbit and the local beam separation in the IPs are measured and corrected; these corrections are stored in the settings database and re-played during β^* levelling. To correct for residual orbit perturbations, for each β^* levelling



LHC Luminosity Scan Client 0.29.5 [pro]

Lock Status — IP1: IDLE; IP2: RESERVED; IP5: IDLE; IP8: RESERVED

OFB Status: IDLE

Scan Parameters - PHYSICS-6.8TeV-2022_V1@135_[END] @ 6800 GeV (PROTON-PROTON)

Nominal Emittances: H=3.5 um V=3.5 um Beta* : IP1=0.3 m IP2=10 m IP5=0.3 m IP8=2 m Scan limits : IP1=3.1 sig. IP2=3.1 sig. IP5=3.1 sig. IP8=3.1 sig.

BetaStarLevelling-6.8TeV-60cm-30cm_V1

FINISHED

Levelling Status: FINISHED

Current matchpoint:
R2022a_A30cmC30cmA10mL200cm @ 337
[IP1]: 0.3m [IP2]: 10m [IP5]: 0.3m [IP8]: 2m

Next matchpoint: -- NONE --

Levelling Parameters: IP1 EXPERIMENT_LUMINOSITY

Target [Hz/ub]: 4940.0
Tolerance [%]: 2.5
Integration Time [s]: 60
Max. Triplet Heat Load [%]: 80.0

Trim options
☑ No. of Eigenvalues: H: 200 V: 200
☑ Feedback gain: 3.0
☑ Move Collimators ☑ Move Intlk Limits
☑ Use meas. orbit as ref

20:03:00 New RbaToken is set!

Figure 1: The operational control room application for β^* levelling at the LHC, after levelling from $\beta^* = 60\,\mathrm{cm}$ to $\beta^* = 30\,\mathrm{cm}$ in IP 1 and 5 during 2022 physics operation. The target luminosity band is shown in the bottom left panel.

step the OFB is programmed with a reference orbit function reflecting the expected orbit change, and used to perform a real-time SVD based orbit correction at 25 Hz.

Collimation System

Changing the optics around the IPs during β^* levelling changes the beam size at the tertiary collimators (TCTs) upstream of the IPs. For the limited β^* levelling ranges used up to 2022, this change can be tolerated without breaking the collimation hierarchy, but for the extended levelling ranges used as of 2023, the gaps of the TCTs have to be adjusted during the levelling process [11].

Furthermore, due to the change of closed orbit bumps around the IPs (e.g. the crossing angles) during the β^* levelling squeeze, the beam position at the TCTs changes. Thus, to avoid an asymmetric beam passage trough the TCTs, the centres must be adjusted according to the expected orbit changes.

Both the TCT jaw positions and gaps are protected by hardware interlocks with a tolerance of 400 µm around the nominal position. The changes applied during β^* are larger than this tolerance, hence the interlock limits have to be moved as the jaws move. As settings critical for machine protection (MCS, [12]), the interlock limit functions are pre-generated and digitally signed settings stored in the LHC settings database and validated during machine commissioning. To allow loading these functions in steps into the hardware during β^* levelling, the functions have to be segmented according to the β^* levelling steps, and each segment has to be digitally signed and stored [11, 13].

Equipment Orchestration

To ensure the smooth transition between optics during the execution of a β^* levelling step, the aforementioned systems (magnet power converters, orbit feedback, collimation system) are orchestrated to perform the transition in sync [14, 15].

When executing a β^* levelling step, the orchestration logic loads the magnet strength functions for optics transition, as well as any established feed-forward corrections, from the LHC settings datebase into the magnet power converters. It then calculates the expected orbit change due to the change of optics, uploads it as a new reference to the orbit feedback system, and prepares the OFB for correcting the orbit with increased strength (gain and SVD eigenvalues) during the transition. Finally it prepares the TCTs to follow the change of orbit (centres) and beam sizes (gaps), in both jaw positions and interlock limits.

Once all systems are successfully prepared and armed for the transition, a start event is sent on the LHC timing system to launch the transition synchronously on all involved systems. In case any involved system refuses the transition, the others are reset to their initial state, the transition is not executed, and the failure is reported to the LHC operator.

Levelling Logic

The β^* levelling process at the LHC is fully automated. On top of the low-level logic to perform single β^* levelling steps while in collisions, a high-level levelling logic governs the execution of steps when needed, based on the luminosity signals from the experiments.

From the control room application, shown in Fig. 1, a target (in luminosity or pile-up) and a tolerance band is set. As soon as the luminosity in IP 1 and 5 reaches the lower tolerance limit, a β^* levelling step is automatically taken to increase it. During the β^* transition, the levelling by separation in IP 2 and 8 is automatically paused, and resumed after the step completes.

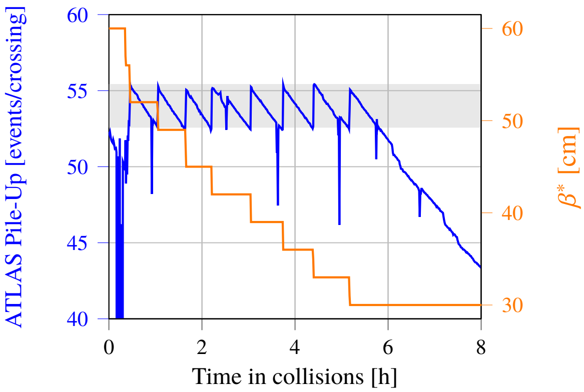


Figure 2: Pile-up and β^* evolution with β^* levelling during LHC fill 8387. The target pile-up was $\mu = 54 \pm 2.5\,\%$. The final $\beta^* = 30\,\mathrm{cm}$ was reached after 5.2 h of levelling.

OPERATIONAL EXPERIENCE IN 2022

In 2022 proton physics operation, β^* levelling was used between $\beta^* = 60\,\mathrm{cm}$ and $\beta^* = 30\,\mathrm{cm}$ in IP 1 and 5 in every LHC fill. For the limited levelling range, the TCTs were kept at constant gaps (in mm) [11], though the full process orchestration including moving the collimation system was commissioned to gain operational experience for the next years.

The total luminosity was limited to $2 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ by the cooling capacity of the cryogenic system for the superconducting triplets, while the pile-up was limited to $\mu = 54$ by the ATLAS and CMS experiments. Given the number of colliding bunch pairs ($k = 2450$), the pile-up was the limiting factor.

The levelling process for a typical fill is shown in Fig. 2. A total of 10 β^* levelling steps were used between 60 cm and 30 cm, each corresponding to a 5 % change in luminosity [16]. Following the natural decay of luminosity due to intensity burn-off and transverse emittance growth, a step was taken every ~30 min, keeping the luminosity in IP 1 and 5 in a ±2.5 % band around the desired target. The final $\beta^* = 30\,\mathrm{cm}$ was reached typically $5 - 6\,\mathrm{h}$ after the start of collisions; thereafter, the beams were kept at constant β^*, with the luminosity decaying naturally.

Throughout 2022 operation, β^* levelling proved to be very effective and reliable to control the luminosity in IP 1 and 5 while avoiding possible instabilities arising from separated beams. Optics and orbit corrections were well under control, and luminosity excursions in IPs 2 and 8 levelled by separation were limited to less than 5 %.

PLANNED CONFIGURATION FOR 2023

To allow for controlling the luminosity and pile-up with the increased beam intensity planned for 2023 operation, the β^* levelling will be used in an extended range from $\beta^* = 1.2\,\mathrm{m}$ to $\beta^* = 30\,\mathrm{cm}$ in IP 1 and 5. Also, the crossing angles in IP 1 and 5 will be changed during the levelling process to reduce the irradiation of the superconducting triplets [17].

For this β^* levelling range, the TCTs can no longer remain stationary. Centres and gaps will have to follow the crossing angle and beam size changes [11]. The hardware interlock limits will have to be moved following the expected changes. The full configuration has been successfully tested in 2022 during the machine development program [18].

The limiting factors for the peak luminosity will be improved in 2023, allowing for a higher levelling target. Following upgrades in the experiment data taking, the maximum allowable pile-up will be $\mu = 65$; and following a load test in 2022, the triplet cooling capacity was found to accommodate an instantaneous luminosity of up to $2.2 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ [19].

CONCLUSIONS AND OUTLOOK

Proposed since the beginning of the LHC era, and first demonstrated in a limited operational setting in 2018, β^* levelling has been successfully used throughout 2022 LHC operation to control the luminosity in the high-luminosity experiments, ATLAS (IP 1) and CMS (IP 5).

Changing β^* implies a change of the machine optics, while keeping the high-intensity beams in collision. Currently, β^* levelling is done in discrete steps, transitioning between a set of pre-matched machine optics. To allow for a smooth transition, the LHC luminosity control system needs to drive the power converters powering the magnets, the orbit feedback system, and the collimation system in a well synchronized way.

The β^* levelling range in 2022 was $\beta^* = 60\,\mathrm{cm}$ to $\beta^* = 30\,\mathrm{cm}$, which reduced the complexity as the beam size changes at the collimators around the IPs were limited, and thus the collimators could remain stationary during the levelling. Nevertheless, the mechanics to move the collimation system were implemented and commissioned in 2022.

As of 2023, the levelling range will be significantly extended ($\beta^* = 1.2\,\mathrm{m}$ to $\beta^* = 30\,\mathrm{cm}$), to allow the luminosity to be controlled while increasing the beam intensity. In this setting, the collimation system will need to move during β^* levelling.

Following this experience, β^* levelling is now considered the baseline technique for luminosity control for LHC Run 3 and the following High-Luminosity LHC, as it allows for luminosity control while keeping the full stabilizing effect of Landau damping through the head-on beam-beam interaction.

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