

INSIGHTS FROM LHC BUNCH-BY-BUNCH PERFORMANCE ANALYSIS

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Abstract

In the Large Hadron Collider (LHC) the multi-bunch proton beams collide at the four main interaction points along its 26.7 km circumference. While global beam parameters provide a macroscopic view of machine performance, a detailed bunch-by-bunch analysis offers a unique “radiograph” of the underlying beam dynamics and collective effects. In this work, we present a study of bunch-by-bunch performance indicators, including luminosity, emittance evolution, and beam intensity decay, using data acquired during Run 3 operation. The analysis combines information from high-resolution beam instrumentation, such as the Fast Beam Current Transformer (FBCT), the Beam Synchrotron Radiation Telescope (BSRT), and luminosity monitors from the LHC experiments.

Clear and reproducible patterns are observed across bunch trains, revealing the impact of long-range beam-beam interactions, electron-cloud effects, and bunch-dependent variations. The results demonstrate the potential of bunch-by-bunch data analysis in disentangling complex interdependent effects and contribute to a deeper understanding of the LHC beam dynamics, paving the way for improved modeling for performance optimization in preparation for the High-Luminosity LHC era.

INTRODUCTION

The LHC operates with proton beams composed of thousands of discrete bunches arranged in complex filling patterns around its 26.7 km circumference. Collisions occur at the four interaction points where the experiments are located; however, not all bunches experience identical conditions: each one follows a distinct dynamical history depending on its position within a train, the number of beam-beam and collision encounters it undergoes, and the surrounding bunch train gap structure. This intrinsic complexity leads to significant bunch-by-bunch variations in luminosity, making the beam behavior far from uniform. Optimizing the integrated luminosity delivered to the experiments therefore requires not only maximizing peak performance but also ensuring uniformity across the colliding bunches. A more homogeneous luminosity distribution results in a more balanced burn-off of beam intensity, a steadier pile-up for the detectors, and a more efficient use of beam time.

Previous studies during Run 2 [1, 2] showed that luminosity variations already could grow up to about $\sim 25\%$ over several hours, with clear patterns linked to the filling scheme and bunch position. These effects are largely driven by long-range beam-beam interactions and electron-cloud

build-up, both of which depend strongly on the local bunch environment. In this work, we extend this bunch-by-bunch study to recent Run 3 data from the 2025 run. We analyze luminosity, intensity, and emittance evolution, introducing a classification based on train position and collision pattern.

Bunch Classification

The LHC ring is filled through multiple injections from the SPS, each comprising batches of 25 ns-spaced bunches (“bunch trains”) defined in the injectors. Gaps between batches accommodate SPS and LHC injection kicker rise times. Batch placement is optimized to maximize collisions at ATLAS (IP1) and CMS (IP5), while still providing collisions at ALICE (IP2) and LHCb (IP8).

Effects along the LHC ring contribute to the distinct dynamical behaviour between bunches, depending on their position. These include collisions at one or several interaction points (IPs), with the associated head-on beam-beam interactions and intensity loss; the number of beam-beam long-range (BBLR) encounters in the common vacuum chamber around the IPs; and the electron cloud (e-cloud) that builds up along the bunch trains [3]. Other effects, such as noise or coupling, primarily affect the entire beam but, when combined with the aforementioned mechanisms, can also contribute to differences between individual bunches.

Figure 1 shows the number of long-range encounters experienced by the 144 bunches injected from the SPS, arranged in 4×36 bunch trains. For this study, we define five bunch groups, as indicated in the figure, to explore characteristic bunch behaviours within the beam.

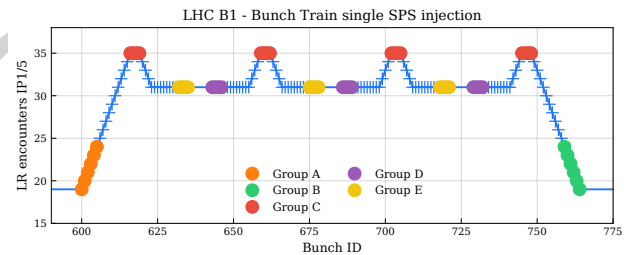


Figure 1: Long-range encounters at IP1/IP5 as a function of bunch slot for a single SPS injection batch. Coloured markers highlight the eight representative family classes.

Groups A and B refer to the first and last bunches in each injection from the SPS, featuring the lowest number of long-range beam-beam interactions (BBLR) and either negligible or maximal electron-cloud effects, respectively. Group C refers to bunches with the highest number of BBLR encounters and increased electron-cloud build-up. Groups D and E comprise bunches with the same number of BBLR

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encounters, positioned at the start or end of the train, at the threshold or maximum electron-cloud formation. The number of bunches in each family is kept similar to allow the same statistical error, while the collision pattern between groups varies, as summarized in Table 1.

Table 1: Distribution across IP combinations for the defined bunch groups and two LHC beams.

Group	Total	Collision IPs - B1/B2			
		IP1,5	IP1,5,2	IP1,5,8	all IPs
A	114	15/0	15/6	33/30	51/78
B	114	0/18	6/18	36/27	72/51
C	272	0/0	8/12	12/12	252/248
D	196	6/0	2/8	110/30	78/158
E	196	0/3	8/1	26/113	162/79

FILL ANALYSIS

For this contribution, we present results from a representative 2025 fill, in which the machine was operated with 2460 bunches per beam, with the majority of them (2448) brought into collision for more than 10 hours in the two high-luminosity experiments ATLAS and CMS. The luminosity in the experiments was actively levelled to maintain a constant pile-up, corresponding to an instantaneous luminosity in the range of $2.0\text{--}2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. We show qualitative results on luminosity, intensity, and emittance variations reflected by the selected bunch groups.

Luminosity

Figure 2 depicts the luminosity evolution for the full beam and for each bunch group, as measured by CMS. Significant variations between groups are already visible from the start of collisions, reflecting differences established at injection, as well as effects arising in the LHC during injection and acceleration before reaching top energy and stable collisions. During luminosity levelling, the luminosity of the full beam remains approximately constant, while the luminosities of the individual bunch groups tend to converge towards the beam average. The initial spread between groups decreases from about 15% to 10% by the end of the levelling period, after approximately 9 hours in collisions. This effect is clearly

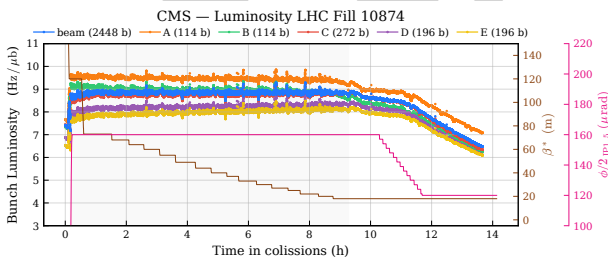


Figure 2: Per-group mean instantaneous bunch luminosity as measured by CMS. The shaded band indicates the luminosity levelling time. The corresponding β^* and crossing angle ϕ are also shown for reference.

visible in Fig. 3, where the group luminosities are normalised to their values at 0.6 hours in collisions.

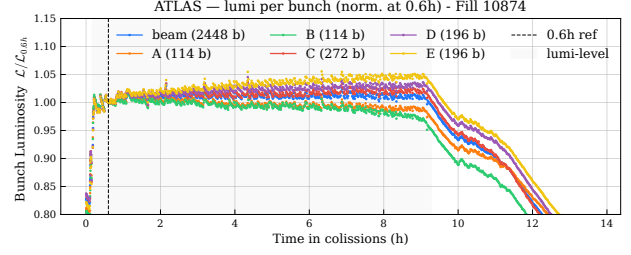


Figure 3: Relative per-group mean instantaneous bunch luminosity, normalised to the values measured at 0.6 h after the start of collisions, as measured by ATLAS. The shaded band indicates the luminosity levelling period.

We observe that the relative luminosity of groups A and B decreases with time, while that of groups D and E increases. This behaviour can be attributed to the luminosity levelling process, which is primarily achieved by adjusting the β^* value and the average beam separation in the non-crossing plane. Since groups A and B initially exhibit higher-than-average luminosity, they experience a faster burn-off of particles in collisions. Conversely, groups D and E, which start with lower luminosity, undergo a smaller burn-off. As the beam separation is adjusted to maintain the average beam luminosity, the relative luminosity of these groups consequently appears to decrease or increase, respectively.

Intensity

In a collider, a key observable for understanding beam-intensity dynamics is the beam-loss rate. In the LHC, this quantity is measured using dedicated instrumentation based on diamond beam-loss monitors (DBLMs), which provide bunch-by-bunch measurements [4]. In an ideal machine, the proton loss rate should be equal to the burn-off rate at the interaction points. Equivalently, the proton loss rate normalised to the total luminosity measured by the experiments should remain constant and correspond to the total proton-proton inelastic cross-section at the collision energy. Figure 4 shows this normalised loss rate, referred to here as the effective cross-section, for the defined bunch groups. No major variations between groups are observed, particularly for Beam 2, although there are indications that the electron-cloud-affected groups (B and E) tend to exhibit higher values, while group A, characterised by minimal electron-cloud and long-range beam-beam effects, shows lower values.

Besides the classification based on electron-cloud and BBLR effects, the bunches can also be regrouped according to their collision pattern across the interaction points (IPs). The effective cross-section for this classification is shown in Fig. 5. In this case, significant variations between the new groups are observed. In particular, beam losses are found to increase when IP8 is included in the collision pattern. We recall that IP8 (LHCb) is operated at a constant levelled luminosity approximately one order of magnitude lower than that of the IP1 and IP5 experiments (and IP2 at two orders of

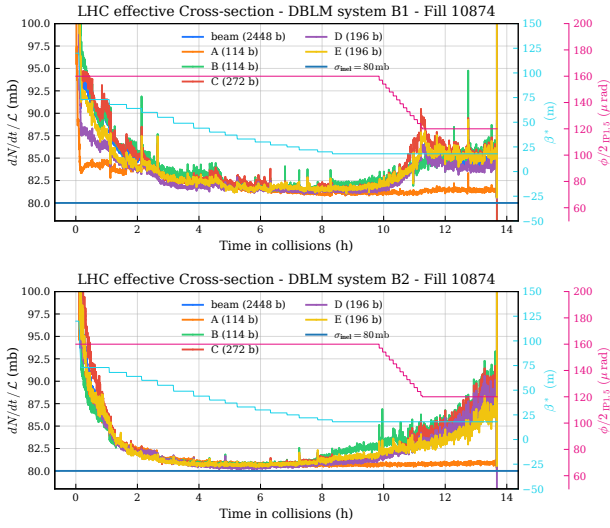


Figure 4: Effective cross-section measured using DBLM data for the bunch groups defined in Fig. 1.

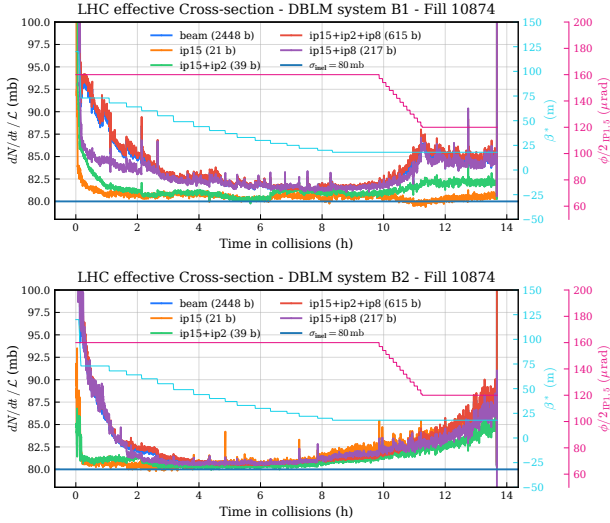


Figure 5: Effective cross-section for bunches grouped according to their collision pattern across the IPs.

magnitude lower than IP8). These observations suggest that the inclusion of this collision point modifies the non-linear beam-beam effects, resulting in increased losses for the chosen working point. Further studies are ongoing, motivated in particular by HL-LHC operation, where LHCb is expected to operate at approximately four times higher instantaneous luminosity.

Emittance

The emittance evolution during collisions was also studied for the defined bunch groups. In the LHC, the BSRT system provides bunch-by-bunch emittance measurements with reasonable precision [5–7]. As an example, Fig. 6 shows the evolution of the average bunch emittance for the defined groups in Beam 1. No significant variations are observed within the measurement precision, although there are indications that groups A and E reach collisions with

respectively lower and higher emittance values, while the remaining groups lie in between. These differences appear to be preserved throughout the luminosity levelling period.

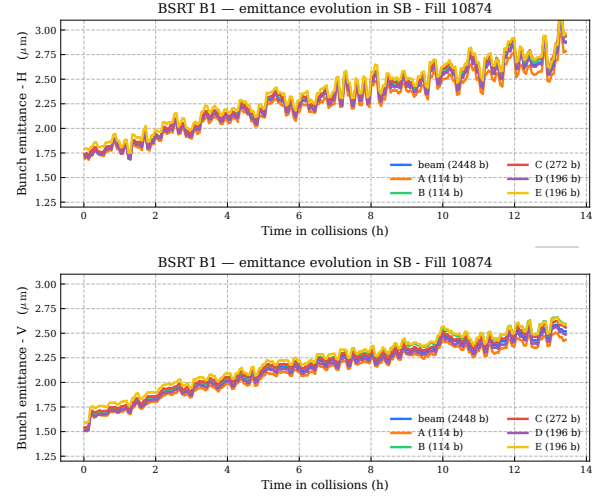


Figure 6: Average bunch emittance evolution for the defined groups of Fig. 1, as measured by the BSRT system.

SUMMARY AND CONCLUSIONS

A bunch-by-bunch analysis of representative LHC fills from 2025 has been presented, focusing on luminosity, intensity, and emittance evolution during stable collisions. Bunches were classified according to their position within the bunch train, probing different electron-cloud and long-range beam-beam interaction conditions, as well as according to their collision pattern across the interaction points. Clear and reproducible luminosity differences between bunch groups are observed throughout the fill, with the spread partially reduced during luminosity levelling due to the interplay between burn-off and beam-separation adjustments. The intensity analysis reveals moderate variations between the train-position groups, while a stronger dependence is observed for bunches colliding in IP8, which exhibit systematically increased effective cross-sections. This can be explained by the non-linearities induced by the additional beam-beam effects: the optimal working point conditions cannot be achieved for all bunch groups simultaneously, and the operational optimization targeted bunches colliding only in IP1 and IP5, which represent the majority of bunches. Emittance measurements show smaller variations, although systematic offsets between groups are visible. These results demonstrate the sensitivity of bunch-by-bunch observables to collective effects and collision configuration, providing essential input for bunch-level performance modelling and luminosity optimisation in the HL-LHC era.

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