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# EMITTANCE AND LUMINOSITY MONITORING AND MODELLING FOR LHC RUN 3

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## *Abstract*

A comprehensive model accurately depicts and tracks emittance and luminosity evolution in the Large Hadron Collider (LHC), considering known effects like IBS, synchrotron radiation damping, coupling and incorporating data-driven factors on emittance growth and intensity losses. Used extensively in LHC Run 2, the model is updated for compatibility with new optics and operational schemes in Run 3, featuring luminosity levelling. This paper discusses the analysis of 2022 and 2023 LHC data, exploring emittance evolution and identifying extra blow-up at injection and collision energies compared to model predictions. Examining the model's agreement with collision data provides insights into the impact of degradation mechanisms, configuration options, filling schemes, and beam types on delivered luminosity. These studies offer valuable insights into potential gains in integrated luminosity for subsequent Run 3 years.

## INTRODUCTION

The Large Hadron Collider (LHC) resumed operation for Run 3 in 2022, after a long three-year shutdown (LS2), aimed to improve the beam brightness in the injectors and reach the required bunch intensity for the HL-LHC operation [1]. In 2022, priority was given to restarting the LHC and qualifying beams from the upgraded injectors, with a brief 16-week period allocated for physics luminosity production with protons, followed by few weeks with Pb-ion beams. Despite encountering technical challenges, particularly in 2023, valuable studies were conducted during these runs, characterized by incrementally brighter beams, optimized cycle schemes utilizing varied production paths in the injectors, and novel filling and luminosity leveling strategies. These efforts pushed the limits of the machine, probing cryogenic systems' resilience, and of pile-up effects in the high-intensity experiments, thereby paving the way for maximal luminosity production in subsequent years of Run 3 and the eventual transition to HL-LHC operations.

The tools used to monitor the LHC performance in Run 2 had to be modified to the new configuration including accessing data from the new NXCALS [2] LHC logging database. The luminosity model [3, 4] developed in Run 2 to assist in the understanding of what goes beyond known phenomena in the machine, had to be consolidated to describe the beam and bunch emittance evolution in the cycle and during collisions in the presence of leveling. This paper aims to discuss key observations and performance insights gleaned during the early stages of LHC operation in Run 3.

## EMITTANCE EVOLUTION

**Injection:** In 2022, high-brightness 25 ns beams, produced using the Batch Compression Bunch Merging and Splitting (BCMS) scheme [5], were employed, maintaining the approach from the latter years of Run 2, with an average intensity of $1.4 \times 10^{11}$ ppb. However, in 2023, to streamline beam preparation in the injectors and mitigate issues like blow-up due to space charge at higher intensities, the standard LHC-type beam production [6] was adopted, allowing for intensities up to $1.6 \times 10^{11}$ ppb. Due to constraints in the LHC cryogenic system, hybrid filling schemes were utilized, combining nominal 36 b trains with those having 33% empty slots, known as 8b4e. Additionally, in 2023, up to 10% scraping was implemented in the Super Proton Synchrotron (SPS) to counteract beam losses at LHC injection.

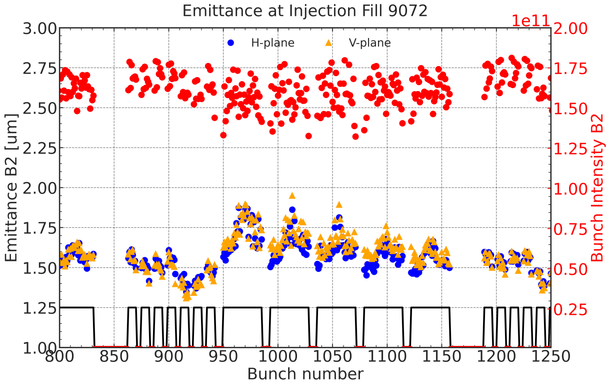

Figure 1: The BSRT emittance and intensity at injection for a fill of 2023 for B1. The bunches correspond to a full SPS injection to LHC in the hybrid scheme with $7 \times 8\text{b4e} + 5 \times 36\text{b}$ trains.

Figure 1 illustrates the BSRT[1]-measured bunch emittances and intensities at injection for a fill in 2023, corresponding to a full SPS injection to LHC for the hybrid scheme. At LHC injection, traces of the electron cloud as well as emittance blow-up due to time spent in the SPS machine are clearly observable in the BSRT data. The 8b4e trains, unaffected by the electron cloud, exhibit up to 14% lower emittance in both planes compared to the 36b trains, where a structure correlated to the bunch location in the train, typical of an electron cloud signature, is pronounced.

The preservation of beam brightness from SPS to LHC injection is illustrated in Fig. 2. A comparison with measurements at SPS injection energy reveals a 15% blow-up attributed to SPS acceleration, beam transmission, and injection into the LHC for the standard-type beams of 2023.

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[1] Beam Synchrotron Radiation Telescope [7, 8])

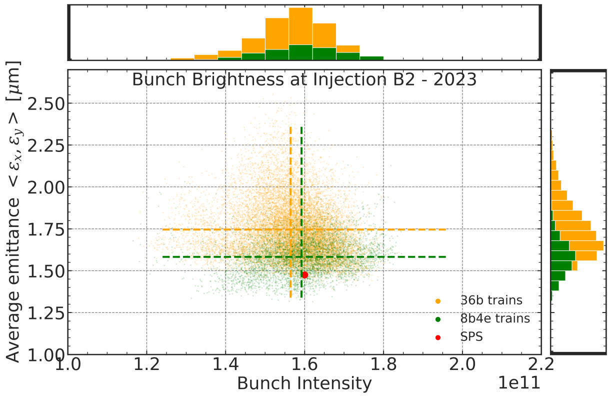

Figure 2: Bunch brightness distributions for fills in 2023. The lines correspond to the average values for each bunch train type. The red dot corresponds to the measured brightness at SPS injection energy.

Table 1: Measured (BSRT) Emittance along the LHC Cycle

| | **B1H** | **B1V** | **B2H** | **B2V** |
|---|---|---|---|---|
| | | **2022 - BCMS** | | |
| **Injection** | 1.52 | 1.62 | 1.42 | 1.25 |
| **Start of acceleration** | 1.79 | 1.94 | 1.77 | 1.55 |
| **Start of collisions** | 1.67 | 1.89 | 1.63 | 1.70 |
| | | **2023 - STANDARD** | | |
| **Injection** | 2.02 | 1.60 | 1.78 | 1.63 |
| **Start of acceleration** | 2.14 | 1.84 | 1.84 | 1.87 |
| **Start of collisions** | 2.37 | 2.15 | 2.40 | 2.14 |

Similarly, for the 2022 BCMS-type beams, the blow-up was somewhat smaller at 10%, albeit with a lower bunch intensity.

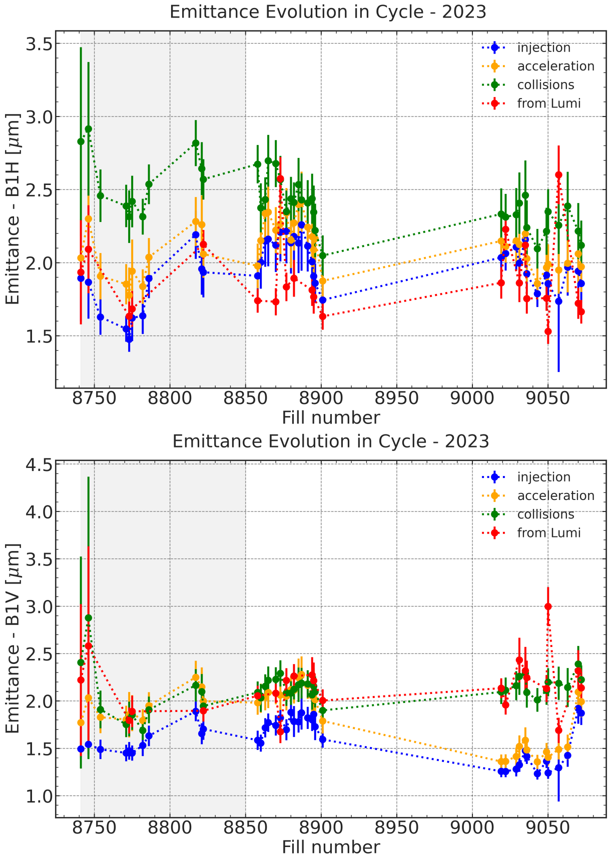

Figure 3: Horizontal (top) and vertical (bottom) convoluted emittances along the LHC energy cycle for the 2023 fills using the BSRT measurements. The red points are extracted using the luminosity from the experiments at the start of collisions.The fills in the grey zone are not considered in the summary values of Table 1.

**Energy Cycle:** Table 1 presents the measured emittances along the LHC energy cycle for both Beam 1 (B1) and Beam 2 (B2), graphically shown for Beam 1 in 2023 in Fig. 3. The average relative emittance growth of beams and planes, primarily attributed to the combined effects of IBS and e-cloud during the approximately 33 min spent at injection, is 21% for 2022 and 9.4% for 2023. When considering the energy ramp to the start of collisions, the measured growth is 18.6% for 2022 and 28.8% for 2023 fills.

Notably, the measured emittances at the start of collisions are smaller for the BCMS beams of 2022 compared to the standard beams of 2023, but the latter having a 15% higher bunch intensity. Assuming linear scaling, the BCMS-type beams appear to have approximately 10% smaller emittance at the start of collisions, which could be advantageous for luminosity production. Additionally, this allows for increased margin for aperture and losses at higher intensities. Considering that the BSRT device has an up to 20% inaccuracy in its measurements [9], a systematic test is planned for 2024 to evaluate both beams under stable and comparable conditions to determine which beam leads to higher luminosity for the experiments. Confirming the BSRT-measured emittance growth along the LHC energy cycle is crucial for understanding the machine's behavior. Figure 3 illustrates a 15% discrepancy between the BSRT-measured emittances and those calculated using the experimental luminosities in the horizontal plane, while the difference is within 5% in the vertical plane. Similar results were obtained for Beam 2. If confirmed, this indicates a much smaller growth in the horizontal plane, whereas the growth in the vertical plane remains consistent. This discrepancy is intriguing and warrants further investigation, highlighting the need for additional studies to fully understand its implications.

## BEAM LOSSES

In the Run 2 analysis [10], extra beam losses were observed during collisions beyond the luminosity burn-off. Figure 4 shows the beam loss rate normalized to the luminosity [11] for both beams. Fast losses occur at the onset of collisions and later during the steps in crossing angle or $\beta^*$, albeit not consistently and at varying levels each time. Of particular interest is that these losses reach the nominal burn-off limit after leveling during the luminosity decay.

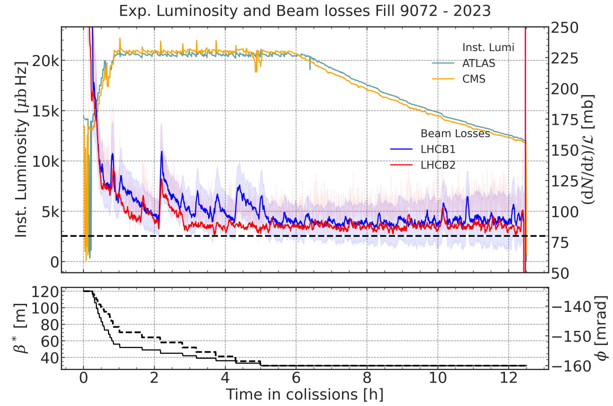

Figure 4: Illustration of the beam collisions for luminosity production for a fill of 2023. Top: the instantaneous luminosity in ATLAS and CMS experiments, and the average bunch beam loss rate normalized to the luminosity for B1 (blue) and B2 (red). Bottom: $\beta^*$ and crossing angle variation during the luminosity leveling process.

## LUMINOSITY MODELING

Developed during Run 2, the luminosity model [10, 12] tracks the transverse emittance evolution, primarily during collisions, accounting for phenomena such as Intrabeam Scattering (IBS), Synchrotron Radiation (SR), elastic scattering, coupling, and noise effects. Bunch length calculations are based on the combined influence of IBS and SR effects, and luminosity burn-off, resulting in bunch intensity decay due to collisions and to transverse emittance blow-up, are being considered.

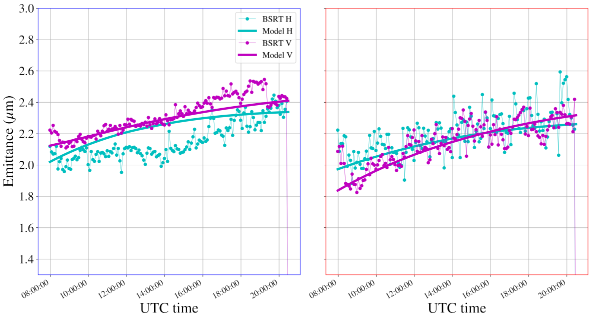

Figure 5: BSRT measured and predicted by the model during collisions in a 2023 fill, for beam 1 (B1) (left) and beam 2 (B2) (right). The model includes an extra growth of 0.05 μm/h in the horizontal and 0.1 μm/h in the vertical plane as found in Run 2 analysis [13].

For Run 3, the model was updated to accommodate new optics and luminosity leveling configurations. At injection energy, it was found that an extra blow up is present (i.e. beyond the known effects as described above), similar to that of Run 2 [12] namely at 0.4 μm/h in the horizontal and 0.5 μm in the vertical planes. During collisions, as shown in Fig. 5, the model predicts well the values at the end of the fill when considering all effects along with the extra emittance growth as found in Run 2 of 0.05 μm/h in the horizontal and 0.1 μm/h in the vertical planes.

Figure 6 illustrates the luminosity evolution for an example Fill of 2023. The model utilizes beam current data, accounting for any extra losses, and includes coupling and additional emittance growth as measured in Run 2 and discussed above. A significant challenge in Run 3 is accurately modeling the complex process of luminosity leveling, which involves dynamic adjustments such as beam separation, $\beta^*$, and crossing angle steps to meet the requested pile-up target set by the experiments.

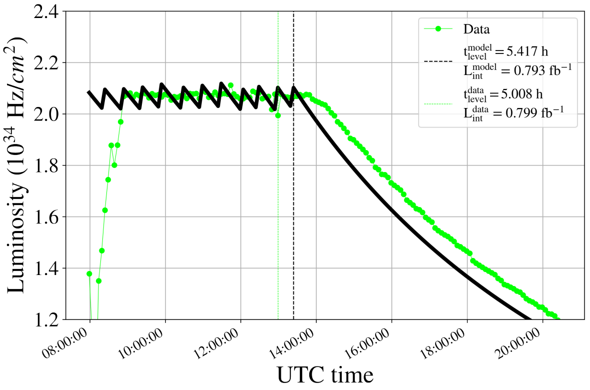

Figure 6: Luminosity evolution in a representative fill of 2023 as measured by the experiments and predicted by the model.

In this example, the luminosity leveling target is maintained in the model by adjusting the $\beta^*$ and crossing angle steps to within ±2.5%. While the steps may not precisely match the fine tuning done in the data, the overall integrated luminosity for the Fill closely aligns.

## SUMMARY

Results from the initial analysis of LHC Run 3 data on beam emittance evolution along the energy cycle of the machine are presented. A notable 30% emittance increase from injection to the onset of collisions is observed, particularly at the higher intensities utilized, reaching up to $1.6 \times 10^{11}$ ppb, with half of this increase occurring at injection energy. A comparison between BCMS-type and standard-type beams indicates slightly higher brightness for the former. A final validation test is planned for 2024 to determine the optimal operation strategy for the remaining years. For both injection and top energies, utilizing the updated luminosity model reveals additional emittance growth beyond the model's predictions, similar to observations in Run 2. Ongoing efforts are focused on further refining and adjusting the model to accurately reflect operational conditions, ensuring its continued effectiveness as a valuable tool for monitoring machine performance and identifying degradation mechanisms.

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