HIGH-INTENSITY LHC TESTS IN 2025 FOR TRANSVERSE BEAM DYNAMICS STUDIES

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Abstract

During dedicated machine development periods in 2025, the LHC operated with High-Luminosity LHC (HL-LHC) beam parameters to study transverse beam dynamics in a high-intensity and high pile-up regime. For the first time, collisions with trains of 2.3×10^{11} ppb were achieved, reaching a pile-up of 150 and reproducing operational conditions close to those foreseen for the HL-LHC. These experimental tests allowed for detailed measurements of emittance growth and proton losses. In particular, a fill with bunches having different transverse distributions was performed to assess the impact of non-Gaussian tails on beam lifetime and losses beyond the burn-off limit when the two beams are brought into collisions. Furthermore, the evolution of the beam quality throughout the cycle was studied for different HL-LHC beam types. These results represent a key milestone towards the demonstration of the HL-LHC operational conditions.

INTRODUCTION

The High-Luminosity LHC (HL-LHC) performance relies on operation with high bunch intensity, low transverse emittances, long trains for fast filling and a high number of bunches, high pile-up and very small β^* at the two high-luminosity experiments, ATLAS and CMS [1, 2]. Reaching these conditions will push the machine into a beam-beam regime that is significantly more demanding than what is routinely explored in the LHC today. Although the present LHC already operates in a highly optimized configuration, several observations of beam degradation, such as emittance growth and intensity losses, are still not fully understood and are only partially captured by existing models. A series of Machine Development (MD) studies was therefore carried out in 2025 to investigate how these effects scale under HL-LHC beam conditions and study the beam-beam effects of the HL-LHC era, marking important milestones such as the first collisions with HL-LHC beams at high pile-up.

Reproducing the fully nominal HL-LHC conditions is, however, not possible in the present LHC configuration [3], as several systems will only be upgraded during Long Shutdown 3 (LS3) and additional mitigation measures are required to enable operation with nominal HL-LHC beams [4, 5]. The HL-LHC MD program therefore relied on a range of baseline and alternative beam configurations to probe HL-LHC regimes while remaining within present machine constraints. The studies followed a progressive approach, starting with HL-LHC individual bunches, then HL-LHC baseline beams at injection and finally 8b4e beams or short 25 ns trains with reduced bunch intensity compared to the HL-LHC target at top energy. The information collected will help refine and strengthen confidence in the HL-LHC operational scenario.

LOSSES AT THE START OF COLLISIONS AND TRANSVERSE TAILS

When the beams are brought into collision during nominal LHC operation, a significant increase in losses is systematically observed, well above what is expected from luminosity burn-off alone. Luminosity simulations indicate that, in the most critical cases, this effect can lead to a reduction in integrated luminosity of up to 4%. Improvements in beam preparation in the injectors led to a reduced tail population in the transverse bunch distributions and the LHC consequently started receiving bunches with transverse profiles closer to a Gaussian distribution [6–8]. No significant tail re-population was observed in the LHC cycle and the losses at the start of collisions were reduced, already pointing to a direct link between tail population and losses [9].

To demonstrate this correlation more clearly, dedicated MD studies were performed with bunches having similar emittances but different transverse tail populations, prepared already in the injectors. Two classes of bunches were compared, with q-values from q-Gaussian fits [10] equal to 1 (Gaussian) and 1.4 (heavy tails), respectively. The test configurations consisted of six bunches with 2.3×10^{11} ppb and one bunch at 1.5×10^{11} ppb.

Figure 1 shows the evolution of the effective cross section, defined as the loss rate normalized by the luminosity, for Gaussian bunches (green) and for bunches with a q-value of 1.4 as obtained by a q-Gaussian fit (heavily populated tails) at HL-LHC bunch intensity (red) or at lower bunch intensity (black). The inelastic cross section, around 81 mb, is indicated by the horizontal black line. The graph clearly shows that bunches with enhanced transverse tails suffer systematically larger losses beyond burn-off at the start of collisions compared to the Gaussian bunches. The measured loss of performance for the non-Gaussian bunches corresponds to about 3% in integrated luminosity, in very good agreement with simulated predictions. These additional losses beyond burn-off are therefore strongly mitigated for Gaussian bunches.

The underlying mechanism is consistent with a reduction of Dynamic Aperture (DA) when entering the head-on beam-

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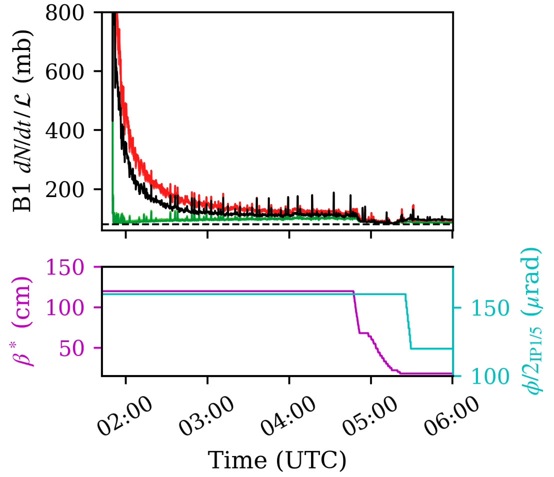

Figure 1: Evolution of effective cross section for Gaussian (green) and non-Gaussian bunches with large transverse tails (black and red)

beam-dominated regime at the start of collisions. During this process, the larger the tail population, the larger the fraction of particles driven beyond the available stable phase space and therefore the larger the observed losses.

Dedicated MD studies were performed at injection with 4×72 bunch trains at 2.3×10^{11} ppb, which is the HL-LHC baseline. In present nominal operation with trains of 4×36 at 1.8×10^{11} ppb, the transverse tails tend to gaussianize ($q \to 1$) and no significant tail re-population is observed. As a result, when the injectors deliver bunches with reduced tail population, this beam quality can in general be preserved in the LHC. The picture changes, however, for long HL-LHC-type trains. Figure 2 shows the evolution of the q-value in the horizontal (top) and vertical (bottom) plane along the train. Bunches at the start of the train, shown in blue, tend to become more Gaussian, consistently with the behavior observed in nominal operation. In contrast, tail generation is measured for bunches towards the end of the train, indicated in orange and red. This behavior suggests a mechanism generating increased tails along the train, consistent with incoherent electron-cloud effects.

These observations suggest that tail generation with HL-LHC long trains, combined with the DA reduction when entering collisions, may lead to enhanced losses for HL-LHC beams, although mitigation measures are planned for e-cloud effects in LS3 [11, 12]. A direct demonstration of this effect is not yet possible, since the present machine configuration does not allow HL-LHC baseline beams to be brought to top energy and will be further studied during dedicated high-intensity tests planned at the end of the 2026 operational run.

LOSSES DURING COLLISIONS

A first exploration of a more aggressive beam-beam regime at very high pile-up was carried out. For this study, short 24-bunch trains with 25 ns spacing were used, with an initial bunch intensity limited to 2.1×10^{11} ppb due to present machine constraints. Figure 3 shows the effective cross section for Beam 1 (top) and Beam 2 (bottom) while levelling to a pile-up of 150. These conditions were reached through a combination of high bunch intensity, fast β^* levelling and low crossing-angle. The bunch intensity evolution is shown in blue for Beam 1 and red for Beam 2, while the magenta and cyan curves indicate the evolution of β^* and crossing

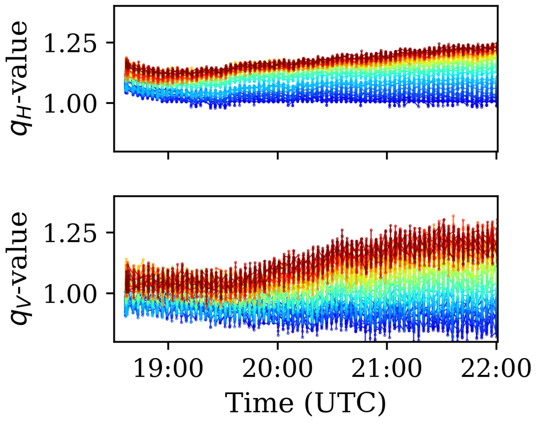

Figure 2: q-factor evolution at injection with HL-LHC trains for bunches at the start (blue) and end (red) of the train.

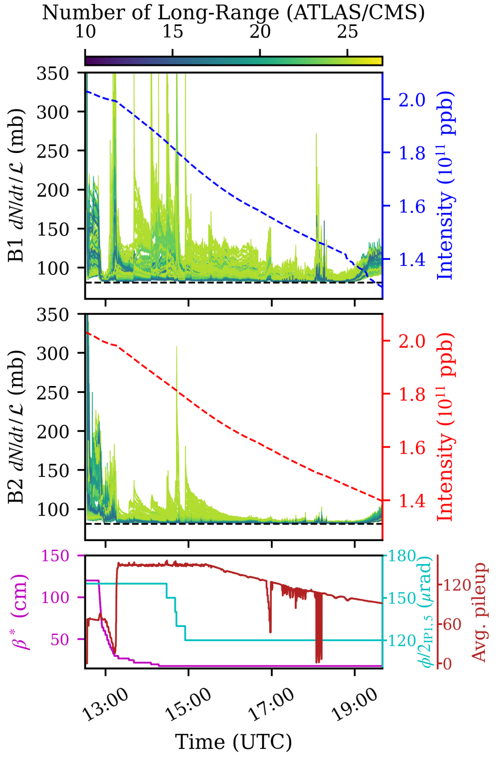

Figure 3: Effective cross section for B1 (top) and B2 (middle), color-coded with the number of long-range interactions. The evolution of the average bunch intensity is also shown in blue and red. Pile-up (dark red), β^* (magenta) and half crossing angle (cyan) are also given (bottom plot).

angle, respectively. No dedicated time was available for tune optimization at the different stages of the process.

Despite these particularly aggressive conditions, the measured beam lifetime remained good throughout collisions. At the end of levelling, the bunch intensity was still around 1.8×10^{11} ppb, with a crossing angle of 120 µrad and β^*=60/18 cm, corresponding to a long-range interaction regime even more aggressive than that foreseen for the HL-LHC. Although simulations indicate a DA below the 6 σ target, no strong lifetime degradation was observed. This suggests that, once tails are cleaned at the start of collisions and do not repopulate, good lifetime can be maintained even in a regime with reduced DA.

EMITTANCE GROWTH

Emittance growth was also investigated, since it remains only partially reproduced by existing models and not all contributions are fully understood yet. A key question is how the excess emittance growth observed today scales under HL-LHC beam conditions. Figure 4 shows the bunch-by-bunch emittance growth measured during the injection plateau with HL-LHC baseline beams, for the horizontal plane (cyan) and the vertical plane (magenta). According to Intrabeam Scattering (IBS) models, the expected emittance growth is around 0.5 µm/h in the horizontal plane, while no significant emittance growth is expected in the vertical plane because of the absence of dispersion. The measured emittance growth beyond these model expectations is about 0.2 to 0.25 µm/h on top of other effects such as e-cloud, which is compatible with what is observed in nominal operation. Although the exact underlying mechanism is not yet fully understood, the effect appears to be largely independent of brightness and does not seem to be more severe for HL-LHC beams.

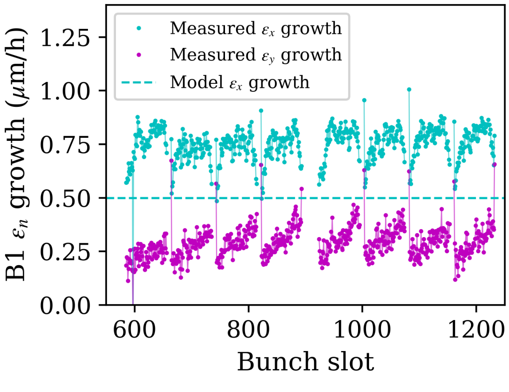

Figure 4: Measured bunch-by-bunch emittance growth at injection for the horizontal (cyan) and vertical (magenta) plane. The expected emittance growth from IBS is illustrated with the cyan dashed line.

At top energy, the vertical emittance is expected to decrease because of synchrotron radiation damping, while there is still some contribution from IBS in the horizontal plane. Figure 5 compares the emittance evolution predicted by the models (light cyan and magenta) with the measurements (dark cyan and magenta) during collisions. While the horizontal emittance evolution is in good agreement with the IBS expectations, a clear discrepancy is observed in the vertical plane. The measured vertical behaviour therefore points to an additional contribution not captured by the present model, currently being studied [13]. Nevertheless, the excess emittance growth is similar to the one observed with nominal beams in operation and does not appear to be more severe for HL-LHC beams. It should be noted that these studies mark the first collisions with HL-LHC trains and bunch intensities but were performed with 8b4e beams. Confirmation with nominal HL-LHC beams remains open.

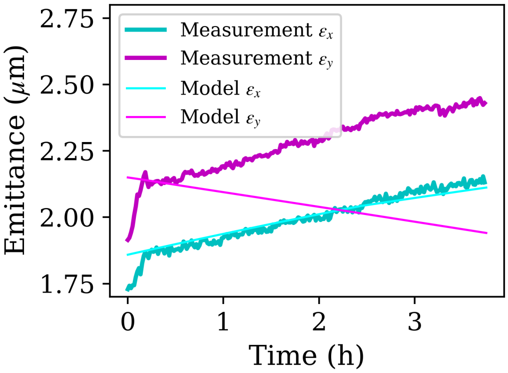

Figure 5: Emittance evolution in the horizontal (cyan) and vertical (magenta) plane during collisions. The expected evolution from the models is also illustrated (light cyan and magenta, respectively.)

CONCLUSIONS

A series of HL-LHC MD studies were carried out in 2025 as a first systematic exploration of several key effects under HL-LHC-like conditions, representing an important milestone in the preparation of HL-LHC operation. HL-LHC baseline beams were studied at injection, where transverse tail generation was observed with long trains. First collisions with HL-LHC trains and bunch intensities at high HL-LHC pile-up were achieved. These studies demonstrated a clear correlation between transverse tails and losses beyond burn-off at the start of collisions, with a measured performance gain for more Gaussian bunches. The results indicate that losses beyond burn-off at the start of collisions are particularly critical in case of over-populated tails combined with a low DA, whereas operation in a very aggressive long-range beam-beam regime with high pile-up and short trains still showed good lifetime once transverse tails had been cleaned. The impact of tail generation in long HL-LHC trains still needs to be assessed at top energy and remains one of the open points to be addressed before LS3. Finally, the additional emittance growth observed beyond current models, both at injection and in collision, does not appear to be more severe for HL-LHC beams than for nominal operation today, although its underlying mechanism remains to be fully understood.

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