STUDIES OF TRANSVERSE EMITTANCE GROWTH OF LHC-TYPE BEAMS ON THE LONG INJECTION PLATEAU OF THE CERN SPS

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Abstract

Transverse emittance growth was observed during the long injection plateau for high-intensity multi-bunch LHC-type beams in the CERN SPS, showing a clear dependence on the working point. The working point was adjusted to reduce emittance growth usually observed when the transverse tunes were too close to the integer resonances; however, a residual increase in emittance persists. To characterize this behavior and investigate its possible causes, transverse profile measurements were performed with the SPS wire scanners at several points along the injection plateau. These measurements are used to quantify the evolution of the transverse emittances and to assess the presence and possible generation of overpopulated tails.

INTRODUCTION

Following the implementation of the LHC Injector Upgrade (LIU) project [1] from 2019 to 2021, the intensity of LHC-type beams in the CERN SPS has been progressively increased from 1.3×10^{11} p/b to 2.6×10^{11} p/b. These high-intensity, multi-bunch beams are subject to significant collective effects during the long SPS injection plateau, which is needed for accommodating several batches from the pre-injectors, typically from three to five depending on the LHC filling pattern.

The beams experience transverse tune shifts originating from the SPS beam coupling impedance. These impedance-driven tune shifts accumulate along the bunch trains (the bunches are grouped in a relatively small part of the ring circumference), leading to bunch-to-bunch tune variations [2]. Properly accounting for these variations is essential when setting the machine working point during the injection plateau.

The dependence of the achievable beam brightness on the working point was studied in 2024 and 2025 [3]. For intensities prior to the LIU upgrade (up to 1.3×10^{11} p/b), the operational tune correction approach for LHC beams in the SPS consisted in correcting the coherent tunes of each newly injected batch to $Q_x^{\mathrm{coh}}/Q_y^{\mathrm{coh}} = 20.13/20.18$. This setting provided the best beam transmission and beam quality, consistent with working point studies performed with single bunches in the early days of LHC beam commissioning in the SPS [4]. Since 2021, the intensity per bunch has been gradually increased and the transverse emittances reduced, thanks to improvements in the CERN pre-injectors (PSB and PS) that came with the LIU project. As a result, the LHC-type beams have become significantly brighter and space-charge effects induce very large incoherent tune spreads that depend on the beam variant used. For the so-called Standard beam the maximum incoherent tune shift is approximately $\delta Q_x^{\mathrm{SC}}/\delta Q_y^{\mathrm{SC}} \approx -0.11/-0.18$, while for the BCMS beam (Bunch Compression Merging and Splitting) [5] it can reach values like $\delta Q_x^{\mathrm{SC}}/\delta Q_y^{\mathrm{SC}} \approx -0.14/-0.24$.

Achieving the LIU target beam parameters [6] with the tight budgets on losses and emittance blow-up (in both cases 10% from injection to extraction) has proven to be challenging. In particular, the beam suffers from losses on the injection plateau as well as transverse emittance degradation.

The transverse tunes had to be increased with respect to $Q_x^{\mathrm{coh}}/Q_y^{\mathrm{coh}} = 20.13/20.18$ to avoid emittance blow-up, especially for the BCMS beam [3]. Additionally, the coherent tunes at injection of each train were adjusted such that the incoherent tune shift induced by the quadrupolar impedance is approximately compensated along the cycle. Like that, the tune footprint remains roughly in the same area of the tune diagram and does not approach higher-order resonances such as $Q_x + 3Q_y = 81$ [7], resulting in a reduction of losses and improvement of brightness [3].

After all these optimizations, a residual emittance increase of the order of 8–10% (on average) still persists during the long injection plateau with the Standard LIU beam. This paper presents a series of measurements performed with the Standard LIU beam in October 2025, aimed at characterizing the transverse emittance growth in the SPS, as well as the development of non-Gaussian overpopulated tails.

BEAM PARAMETERS

For the Standard beam, each injection from the Proton Synchrotron (PS) consists of 72 bunches spaced by 25 ns. On the long injection plateau of the SPS, 4 batches from the PS are injected, with 3.6 s between consecutive injections, and 200 ns separation between batches. This results in a train of 4×72 bunches accumulated in the SPS. Table 1 summarizes the main LIU target beam parameters for the Standard beam at SPS injection and extraction. These parameters correspond to the requirements that the SPS needs to achieve for the HL-LHC [8].

The beam parameters used for the measurements were as follows: an intensity per bunch of $N = 2.65 \times 10^{11}$ p/b, and transverse emittances of $\epsilon_x/\epsilon_y = 1.77/1.82\,\mu\mathrm{m}$ at PS extraction. In 2024 and 2025, some emittance blow-up from

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Table 1: Target Parameters at SPS Injection and Extraction

	Injection	Extraction
N (10^{11} p/b)	2.57	2.32
$\epsilon_{x,y}$ (µm)	1.89	2.08
p (GeV/c)	26	450
B_l (ns)	3.0*	1.65

the PS to the SPS was observed for LIU beams, of the order of 5–10%, and is the subject of ongoing studies.

MEASUREMENTS ALONG THE CYCLE

In the SPS, the beam transverse profiles are measured with wire scanners. Currently, only one measurement per cycle is possible. Thus obtaining information on the emittance evolution along the cycle with a high sampling rate requires multiple cycles and is very time consuming. Due to the limited machine development time, emittance measurements were performed at the following points in the cycle: 35 ms, 3635 ms, 7235 ms, and 10 835 ms, corresponding to 35 ms after each injection. These points are on the injection plateau at 26 GeV. Acceleration starts at 11 100 ms, and at 14 100 ms (corresponding to 79 GeV), transverse scraping is applied to remove particles with large transverse amplitudes [9]. Therefore, emittance measurements were also performed before scraping, at 13 900 ms, and after scraping, at 14 500 ms. Measurements at the highest energy, 450 GeV, with the full beam are not possible, as this is beyond the wire breakage limit [10, 11]. Ten measurements were carried out at each of the selected times in the cycle to provide sufficient statistics. In the following sections, the emittances and q-values are studied along the cycle for each batch individually. The q-value is used to characterize the non-Gaussian tails and is obtained from a q-Gaussian fit [12] to the beam transverse profiles.

Transverse Emittances Batch-by-Batch

Figure 1 shows the horizontal and vertical average emittances for each batch individually along the cycle. For all batches, the emittance increases along the cycle up to the measurement before scraping, at 13 900 ms. After scraping, both the horizontal and vertical emittances decrease, but their values remain larger than those measured at injection, at 35 ms. A detailed study of the impact of scraping on the transverse profile shape is beyond the scope of this paper.

The smallest emittance values are observed for the first batch at the first injection. At the subsequent injections, the injected batches have larger emittances than those measured at the first injection.

Figure 2 shows the bunch-by-bunch relative emittance growth of the four batches in both the horizontal and vertical planes. The different colors indicate the cumulative emittance growth from the injection time of each batch up to different times in the cycle. The first batch, corresponding to bunches 0–71, remains longest in the ring and shows

* Bunch length after filamentation.

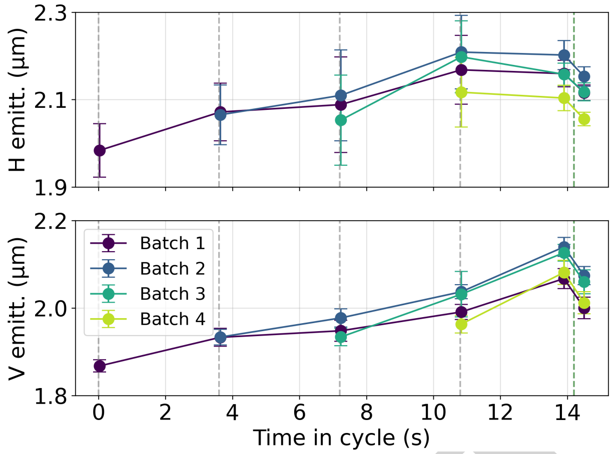

Figure 1: Horizontal (top) and vertical (bottom) average emittances per batch along the cycle. The four colors correspond to the four batches. The gray dashed lines indicate the injection times, and the green dashed line indicates the time of transverse scraping.

the largest emittance growth, while the emittance growth is smaller for the following batches, which are injected later and have a larger emittance already when injected. Within each batch, the last bunches are those experiencing the largest emittance growth. Between batches, which are separated by 8 empty 25 ns slots, the trailing bunches of a batch show large emittance growth, whereas the leading bunches of the following batch show less growth after the empty gap. This behavior points to a possible contribution from electron cloud effects [13], as it is consistent with the generation and accumulation of electrons during the passage of a train of 72 bunches, as well as with a reduction of the electron density in the gaps between batches.

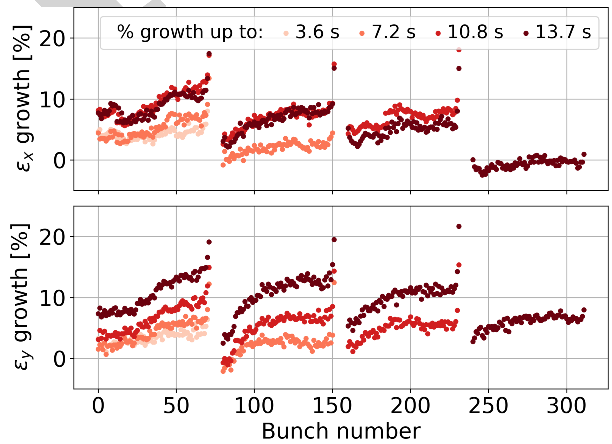

Figure 2: Relative bunch-by-bunch emittance growth (top: horizontal, bottom: vertical) from the injection time of each batch up to different times in the cycle. Batch 1: bunches 0–71; Batch 2: bunches 80–151; Batch 3: bunches 160–231; Batch 4: bunches 240–311.

Tails Batch-by-Batch

Regarding the overpopulated non-Gaussian tails, Fig. 3 shows the horizontal and vertical average q-values for each

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batch individually along the cycle. In both planes, the q-values increase during the injection plateau. In the vertical plane, the q-values at the injection of later batches is clearly increased.

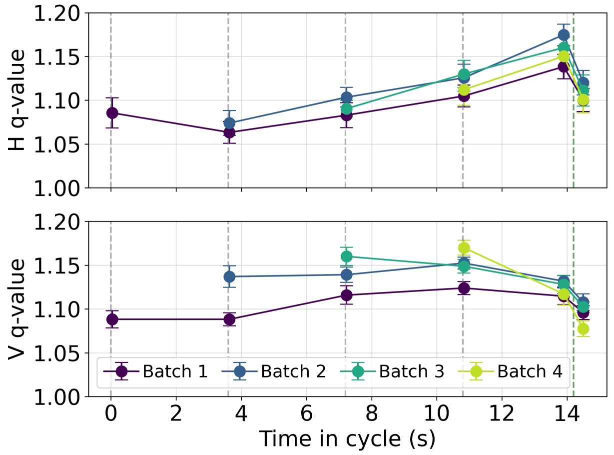

Figure 3: Horizontal (top) and vertical (bottom) average q-values per batch along the cycle. The four colors correspond to the four batches.

This behavior, with the tails increasing with batch number, has also been observed in the 2026 BCMS operational beam for the LHC, consisting of 4 × 36 bunches with $N = 1.8 \times 10^{11}$ p/b. A measurement campaign started in April 2026 to study this phenomenon with the operational beam. The first observations show that injection oscillations play an important role in the generation of overpopulated tails at the injection of each batch. So far, in the SPS, the injection steering is corrected based only on the first injection, with the same settings used for the subsequent injections. The injection oscillations were measured after each of the four injections using the LHC BPMs in the SPS, which can acquire bunch-by-bunch and turn-by-turn data. These measurements revealed that the injection oscillation amplitudes at the second, third, and fourth injections are about a factor of two larger than at the first injection.

Figure 4 shows the results of a test in which the amplitude of the injection oscillations of the first injected batch was deliberately increased in the horizontal plane by a factor of two. As a result, the tails increased in both transverse planes, with the q-value reaching levels similar to those measured for the second injected batch. The average transverse emittance of the first batch also increased with the larger injection oscillation amplitude. Therefore, large injection oscillation amplitudes may also contribute to the emittance growth observed at each injection in Fig. 1.

The intentional increase in the steering error was applied only in the horizontal plane, but the increase in emittance and tails is also observed in the vertical plane, most likely because of coupling between the transverse planes, as the working point is close to the coupling resonance ($Q_x^{coh}/Q_y^{coh} = 20.17/20.21$ for the operational beam) and the incoherent tune spread from space charge is very large

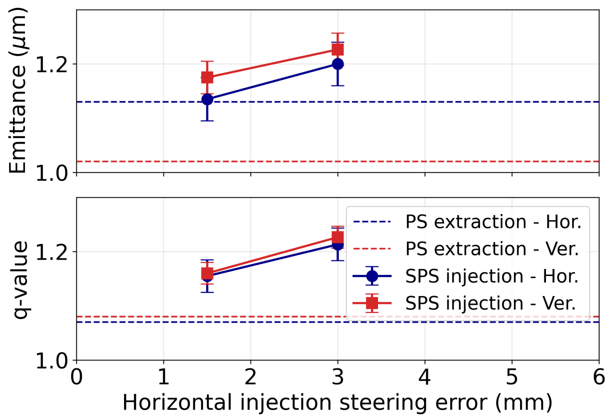

Figure 4: Emittance (top) and q-value (bottom) in the horizontal and vertical planes for two different horizontal injection steering errors. They correspond to the maximum oscillation amplitude within the first few turns after injection and were measured with LHCBPM 51999, where the horizontal beta function is $\beta_x = 95$ m.

($\delta Q_x^{SC}/\delta Q_y^{SC} \approx -0.12/-0.22$). Larger tunes separation will be tested in future measurements.

In future machine development studies, the injection oscillations will be corrected individually for each injection using new tools currently under development. This will make it possible to assess whether minimizing the injection oscillations at all injections mitigates the increase of the tails with batch number. Furthermore, in order to study other possible sources of emittance growth and tail generation, it is essential to correct the injection oscillations accurately so that they can be excluded as a dominant cause.

CONCLUSION

Transverse profile measurements with high-intensity Standard LIU beam show a progressive increase in transverse emittances and non-Gaussian tails during the long SPS injection plateau. The largest relative emittance growth is observed for the first batch, while the trailing bunches of each batch are more affected than the leading ones, suggesting a possible contribution from electron cloud. The q-Gaussian analysis also shows a build-up of overpopulated tails, with larger q-values for later injected batches, particularly in the vertical plane. Dedicated observations indicate that larger injection oscillations at the later injections can enhance tail formation and contribute to the emittance increase. These results suggest that the residual emittance growth observed after working-point optimization is therefore likely driven by a combination of electron cloud effects and injection mismatch or steering errors. Further studies will focus on minimizing the injection oscillations at each injection to assess whether the q-values and emittances can be reduced for all batches. This is also required for disentangling the impact of injection oscillations from other possible sources of tail generation and emittance growth.

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