

RESULTS FROM THE HL-LHC PROTON RELIABILITY RUN IN THE LHC INJECTORS

S. Sainz Pérez*, M. Albaladejo Rodriguez, F. Asvesta, H. Bartosik, A. Beeckman, M. Coly, H. Damerau, M. Delrieux, G. P. Di Giovanni, J. Flowerdew, A. Huschauer, L. Intelisano, I. Karpov, A. Lasheen, K. Li, I. Mases, G. Papotti, G. Rumolo, M. Schenk, C. Zannini, European Organization for Nuclear Research, Geneva, Switzerland

Abstract

In preparation for High Luminosity (HL) LHC operation from 2030, a staged injector reliability run has been performed in 2025 and continues in 2026 in the LHC injectors to evaluate the beam performance, stability and reproducibility following the LHC Injectors Upgrade (LIU) during the Long Shutdown 2. The objective of this campaign is to demonstrate the capability of the LHC injector chain to deliver beams for the HL-LHC in a stable and reproducible manner with minimal downtime and specialist intervention, while defining clear performance metrics, verifying the performance of the available automatic beam optimisers, and identifying any issues arising during routine high-brightness operation.

Extensive preparation was required across the injectors, including the deployment of new monitoring tools and coordinated operational procedures. This contribution presents an overview of the reliability run objectives and schedule, the required preparation work carried out in the LHC injectors, and the results obtained in each accelerator.

The lessons learned and operational improvements identified provide valuable input for future high-brightness operation and pave the way to ensure the readiness of the LHC injector complex for the HL-LHC era.

RECAP OF THE LIU PROJECT

The LHC Injectors Upgrade (LIU) project was implemented to meet the High-Luminosity LHC (HL-LHC) requirements of increased beam intensity and brightness while ensuring high availability and reliable operation. HL-LHC operation is planned to start in 2030 and last until 2041, following the massive implementation of the LHC upgrade during the Long Shutdown (LS) 3 from 2026 to 2030. These intensity and brightness requirements could be achieved in the injectors through extensive hardware upgrades, such as the replacement of Linac2 with Linac4, the increase of the injection and extraction energies in the Proton Synchrotron Booster (PSB) to 160 MeV and 2 GeV, respectively, the upgrade of the Proton Synchrotron (PS) injection energy to 2 GeV and the upgrade of the main radio-frequency (RF) system in the Super Proton Synchrotron (SPS) [1]. All those upgrades were accompanied by dedicated beam dynamics studies and improved understanding of the performance limitations across the accelerators [2]. The majority of the

hardware upgrades were carried out during the CERN LS2 in 2019-2020 [3].

The HL-LHC baseline filling pattern consists of trains of 4×72 bunches per SPS-to-LHC injection, separated by 25 ns, obtained through successive longitudinal splittings in the PS. Table 1 summarises the main target parameters for protons at injection into the different accelerators [1], where N is the bunch intensity, $\varepsilon_{x,y}$ the transverse normalized emittances, and E the kinetic energy.

The LIU target bunch intensity using the standard 4×72 -bunch scheme was reached in the SPS for the first time in early 2024. The LIU target brightness was subsequently reached in 2025, primarily through increased injector beam brightness and SPS tune optimisation [4].

Table 1: 4×72 -Bunch HL-LHC Target Beam Parameters at Injection into the Accelerators

Parameter	PSB	PS	SPS	LHC
N [10^{11} p]	34.2	32.5	2.6	2.3
$\varepsilon_{x,y}$ [μm , rms]	1.7	1.8	1.9	2.1
E [GeV]	0.16	2.0	26	450

RELIABILITY RUN

Once the required brightness had been achieved, thus fully demonstrating HL-LHC beam performance in the SPS, the focus shifted towards operational reproducibility. HL operation will require excellent beam quality for every LHC fill. To address this, a dedicated HL-LHC Reliability Run (RR) was conducted in 2025 in the PSB and the PS and has been extended to the SPS in 2026, where it is currently ongoing.

The 2025 RR in the PS complex simulated LHC filling conditions using LIU beam parameters following the protocol described in [5]. The 72-bunch LHC beam was accelerated up to PS extraction for approximately 45 minutes after each operational LHC fill, leading to approximately 1 RR every 8 hours. Out of these 45 minutes, about 15 minutes were allocated to beam setup (equalisation of longitudinal bunch splittings, bunch length checks and wire scan measurements), followed by about 30 minutes of simulated stable filling. The beam consisted of a single LHC batch: a 3600 ms cycle in the PS, each needing two 1200 ms cycles in the PSB. Filling the HL-LHC will eventually require several SPS cycles, injecting each time 4 PS batches, a configuration that was only tested during specific SPS machine development (MD) studies to minimise the perturbation to the PS

* sara.sainz.perez@cern.ch

physics programme. The RR took place from 15 September to 3 November 2025, following the demonstration of the target brightness at the SPS injection.

BEAM PRODUCTION AND RESULTS PER ACCELERATOR

Linac4

After generation in the source, Linac4 accelerates H⁻ beam to 160 MeV for subsequent injection into the PSB, where the electrons are stripped by a carbon stripping foil to produce proton beams. During the 2025 campaign, the machine showed stable and reproducible performance with no unexpected behaviour.

PSB

Two batches from the PSB, with a duration of 1200 ms each, are needed for every batch of 72 bunches in the PS. In the first batch, beam is injected into each of the four rings of the PSB, while in the second batch only two rings are filled. Both batches have identical beam parameters, with an extracted intensity of approximately 340×10^{11} p per ring and transverse emittances of about $1.5 \mu\text{m}$. These parameters correspond to operation close to the PSB brightness limit, where performance is primarily constrained by space-charge effects. The LIU upgrades were specifically designed to mitigate these limitations. Optimisations along the cycle were required to provide the target brightness at PSB extraction. Injection perturbations caused by the decay of the injection bump were dynamically corrected to reduce emittance growth and beam losses [6]. The transverse working point in the PSB is changing along the cycle to maintain a high brightness. In particular, the tunes are kept at sufficiently high values at injection to prevent beam blow-up driven by interactions with integer resonances in the space-charge-dominated regime. As the energy increases and the space charge effect weakens, the tunes are reduced to a resonance-free regime to avoid losses and tail generation from higher order resonances. In recent years, in order to maintain brightness and reduce as much as possible the effects of higher order resonances, a triple harmonic capture has been employed in operations. This scheme generates beams with smaller space charge tune spreads at injection energy and thus allows lower tunes, i.e. from $(Q_x = 4.40, Q_y = 4.45)$ to $(Q_x = 4.31, Q_y = 4.43)$. One of the most significant improvements of this scenario is that, due to the reduced tune spread, the beam overlaps fewer resonances, which in turn allows for more effective resonance compensation [7].

PS

The two batches injected from the PSB (6 bunches in total) are accelerated and subsequently longitudinally split through RF manipulations in a 3600 ms cycle. A first triple splitting, followed by two double splittings, results in 72 bunches with the required bunch spacing of 25 ns. The longitudinal beam

structure in the PS is shown in Fig. 1. The longitudinal emittance of the bunches injected from the PSB is approximately 3 eVs, but a small longitudinal blow-up is done in the PS nevertheless to stabilise the beam longitudinally.

Due to the higher beam intensity compared with the operational beam for the LHC, several RF optimisations were required. In particular, the coupled-bunch feedback and the multi-harmonic feedback systems had to be retuned to help reduce oscillations during the longitudinal splittings, that can cause a longitudinal halo. This period also provided an excellent opportunity to test the automated bunch splitting controllers [8].

During the reliability run, 93 fills with HL beam specifications were performed in the PS, with a median duration of 47.5 min. The average extracted bunch intensity was of 2.6×10^{11} p with a standard deviation of 0.1×10^{11} p, corresponding to the HL-LHC target beam parameter. Fills with higher intensity spread were mainly correlated to variations in the injected beam intensity originating from PSB fluctuations or from the Linac4 source, non-optimal bunch splitting parameters when the splitting optimisers were not fully tuned, or erratic RF cavity pulses affecting both the splitting process and the bunch length.

Regarding the transverse emittances, as shown in Fig. 2, the average value is $1.81 \mu\text{m} \pm 0.05 \mu\text{m}$ in horizontal and $1.80 \mu\text{m} \pm 0.05 \mu\text{m}$ in vertical, which is consistent with the HL-LHC beam requirements at PS extraction. The longitudinal beam parameters are well within the stable region with a safe distance from longitudinal instabilities, indicating a comfortable margin for reliable beam operation.

The results demonstrate stable and reproducible beam production, confirming the readiness of the PS for routine HL-LHC operation.

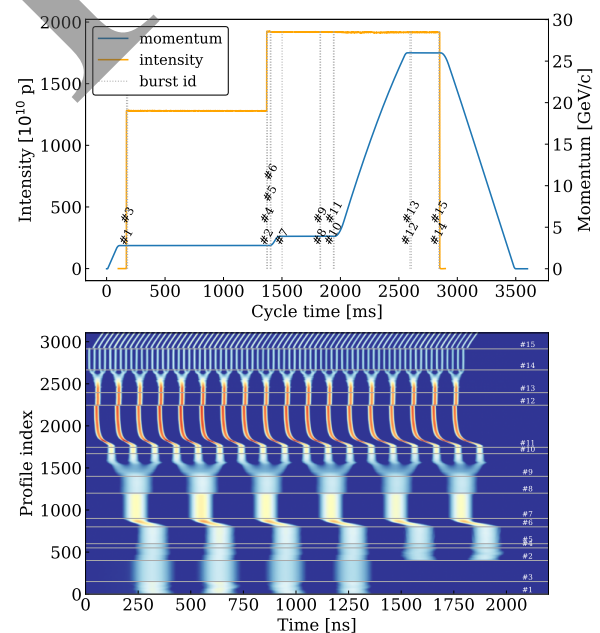


Figure 1: Longitudinal structure and evolution along the cycle of the beam in the PS measured with the Longitudinal Beam Observation (LBO) system.

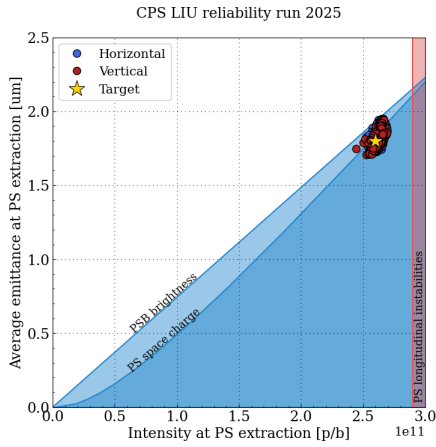


Figure 2: Limitation diagram of the LIU beam in the PS. Markers correspond to RR beam measurements. Shaded areas indicate regions theoretically excluded by space-charge effects and beam instabilities. The target denotes the values listed in Table 1.

Tools for Efficiency Increase Several tools were developed to ensure efficient operation during the reliability run. These tools form the basis for beam optimisation routines and define the achievable beam quality at PS extraction.

- **Longitudinal Beam Observation (LBO):** provides bunch-by-bunch longitudinal parameter measurements along the cycle, including bunch length evolution and tomographic reconstruction of the longitudinal emittance. It is also used by automated bunch-splitting optimisers [8].
- **PS Beam Quality Monitor (BQM):** displays key beam quality observables and their thresholds, enabling fast and reliable monitoring during operation [9].
- **Automated recovery and restarts:** implemented mainly for RF cavities to ensure rapid recovery when LHC beam requests occur.

SPS

During a machine development period in October 2025, the HL-LHC beam was injected into the SPS. With all the experience gained during the RR in the PS complex, the beam quality was reported to be excellent and stable over several hours, consistently reaching SPS extraction energy for approximately four hours.

During the 2025 run, the LIU target intensity per bunch and emittances were achieved. Beam losses remained low, predominantly arising from slow losses during the injection plateau. This performance resulted from optimised PS-to-SPS longitudinal parameters, working point optimisation based on tune scans and model-based Laslett compensation, as well as mitigation of 50 Hz perturbations [4].

Some limitations observed during 2025 are expected to be further investigated during the reliability run currently ongoing in the SPS in 2026. These include RF power limitations

due to ageing cavity components, occasional arcing in cavity transmission lines, high failure rates of solid state amplifier modules in RF towers, and possible heating limitations in the kicker system [4].

The results shown in this paper were obtained from the SPS reliability run carried out between March 17 and 23 2026, corresponding to the latest available data at the time of writing.

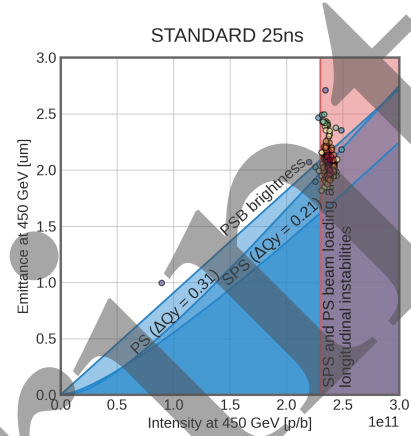


Figure 3: Limitation diagram of the LIU beam in the SPS. Markers correspond to RR beam measurements (as in the PS). Shaded areas indicate regions excluded by space-charge effects and beam instabilities.

The achieved average bunch intensity, as shown in Fig. 3, is $2.39 \times 10^{11} \text{ p} \pm 0.04 \times 10^{11} \text{ p}$, with transverse emittances of $2.16 \mu\text{m} \pm 0.24 \mu\text{m}$ (horizontal) and $2.10 \mu\text{m} \pm 0.12 \mu\text{m}$ (vertical), all of which are close to the LIU target values. The main limitation lies in the RF cavities, for which consolidation is planned during LS3.

CONCLUSION AND FUTURE STEPS

The reliability run in 2025 in the PS complex successfully demonstrated stable and reproducible HL-LHC-type beam production up to PS extraction, with beam parameters consistently meeting the required specifications. These results confirm that HL-LHC beam production up to PS extraction is operationally robust and ready for routine operation with high reproducibility and limited operational overhead.

The campaign allowed quantification of the PS performance, validation of beam production tools, and definition of key performance indicators for beam stability monitoring. Operation required less expert intervention than initially anticipated, and a stable RF operational regime was achieved. New monitoring tools, such as the LBO and PS BQM, significantly improved beam quality diagnostics and optimisation capabilities. SPS RR studies are ongoing, with preliminary results showing that the beam parameters are in agreement with HL-LHC requirements and identifying limitations still to be addressed.

REFERENCES

- [1] K. Hanke *et al.*, “The LHC Injectors Upgrade (LIU) Project at CERN: Proton Injector Chain”, in *Proc. IPAC’17*, Copenhagen, Denmark, May 2017, pp. 3335–3338. doi:10.18429/JACoW-IPAC2017-WEPVA036
- [2] V. Kain *et al.*, “Achievements and Performance Prospects of the Upgraded LHC Injectors”, in *Proc. IPAC’22*, Bangkok, Thailand, Jun. 2022, pp. 1610–1615. doi:10.18429/JACoW-IPAC2022-WEIYGD1
- [3] G. Rumolo *et al.*, “Proton Throughput in the LHC Injectors Upgrade (LIU) Era”, presented at the *Physics Beyond Colliders Kickoff Workshop*, CERN, Geneva, Switzerland, Sep. 6, 2016.
- [4] C. Zannini *et al.*, “Beam Performance and Preparation in the Injectors”, presented at the *Chamonix Workshop 2026*, Chamonix, France, Feb. 2026.
- [5] H. Damerau *et al.*, “Outcome of JAP24: Reach of the Injectors and Priorities until LS3”, presented at the *Chamonix Workshop 2025*, Chamonix, France, Feb. 2025.
- [6] T. Prebibaj *et al.*, “Injection Chicane Beta-Beating Correction for Enhancing the Brightness of the CERN PSB Beams”, in *Proc. 64th Adv. Beam Dyn. Workshop High-Intensity High-Brightness Hadron Beams (HB’21)*, Batavia, IL, USA, Oct. 2021, pp. 112–117. doi:10.18429/JACoW-HB2021-MOP18
- [7] F. Asvesta *et al.*, “Pushing High Intensity and High Brightness Limits in the CERN PSB after the LIU Upgrades”, in *Proc. HB’23*, Geneva, Switzerland, Oct. 2023, pp. 458–461. doi:10.18429/JACoW-HB2023-THBP09
- [8] A. Beeckman *et al.* “Real-time Monitoring of Longitudinal Beam Quality across the CERN Accelerator Complex”, in *Nucl. Instrum. Methods Phys. Res. A*, vol. 1086, p. 171244, Jun. 2026. doi:10.1016/j.nima.2025.171244
- [9] M. Coly *et al.*, “Advancing beam quality control in the CERN Proton Synchrotron”, presented at the *IPAC’26*, Deauville, France, May 2026, paper WEP6081, this conference.

Preprint