

# PERFORMANCE AND OPERATIONAL OVERVIEW OF THE 2025 LEAD ION RUN IN THE LHC INJECTORS

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## Abstract

In 2025, lead-ion (Pb-ion) physics was performed at multiple CERN experimental facilities, including the East and North Experimental Areas and the Large Hadron Collider (LHC) experiments. The success of this extensive program depended on the reliable operation of the full Pb-ion injector chain, comprising Linac3, the Low Energy Ion Ring (LEIR), the Proton Synchrotron (PS), and the Super Proton Synchrotron (SPS). Throughout the 2025 run, the injector complex demonstrated operational stability and delivered beams with high intensity and reproducibility. The excellent beam quality achieved in the injectors was a key factor in the achievements of the Large Hadron Collider (LHC) Pb-ion program. This contribution provides an overview of the key operational results, performance metrics, and improvements implemented across the injector chain during the 2025 Pb-ion run.

## INTRODUCTION

Following completion of the LHC Injectors Upgrade (LIU) project [1, 2], the ion injector complex is now operating in its final configuration for the High Luminosity LHC (HL-LHC) era. Nevertheless, performance improvements continue to be achieved through the ongoing optimization of machine settings, beam dynamics aspects, and operational procedures across the injector chain.

In 2025, the LHC ion injector chain demonstrated stable and reliable performance, building on several years of continuous improvements. The beam parameters defined within the LIU were successfully reached, and in some cases exceeded. This paper presents an overview of the performance of the injector complex during the 2025 lead-ion run, highlighting the main operational challenges and the improvements implemented.

## THE LHC-ION BEAM PRODUCTION

The CERN ion injector complex is illustrated in Fig. 1. Ion production begins with the generation of lead ions through evaporation of a solid sample, followed by ionization in an Electron Cyclotron Resonance (ECR) source [3]. The charge state  $Pb^{29+}$  is selected and transported through Linac3, where the beam is accelerated to a kinetic energy of 4.2 MeV/nucleon and subsequently stripped to  $Pb^{54+}$ .

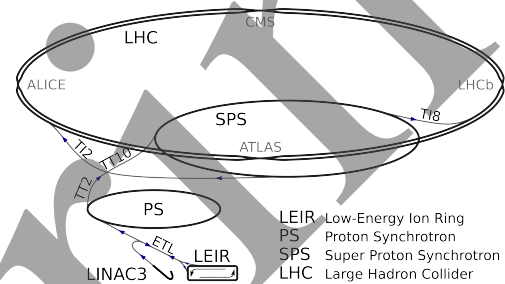


Figure 1: Layout of accelerators and transfer-lines used for ion beam production for the LHC.

Linac3 delivers pulses of 200  $\mu$ s duration at a repetition rate of 200 ms. Up to eight pulses (design value is seven) are injected into the Low Energy Ion Ring (LEIR), where various methods, such as multi-turn injection and electron cooling, are used to accumulate the charge. The resulting coasting beam is then formed into two bunches, accelerated to 72 MeV/nucleon, and extracted towards the Proton Synchrotron (PS). Here each bunch is split into two, producing a total of four bunches, and accelerated to 26 Z GeV. At the final stage the bunches are spaced by 100 ns and are rotated to fit into radio-frequency (RF) buckets of the Super Proton Synchrotron (SPS). In the TT2 transfer-line between PS and SPS (see Fig. 1) the ions are fully stripped to  $Pb^{82+}$ . Up to 14 injections from the PS are accumulated in the SPS at injection energy, which gives a maximum of 56 bunches with a spacing of 100 ns. The beam is accelerated to an intermediate plateau of 300 Z GeV where the RF slip-stacking takes place. Slip-stacking is a technique that permits two particle beams of different momenta (and therefore different RF frequencies) to slip longitudinally relative to each other, in the same beam pipe [4], resulting in the reduction of the bunch spacing to 50 ns. Finally, the produced batch of 56 bunches, spaced by 50 ns, is further accelerated to its final energy of 450 Z GeV and extracted to the LHC. The LHC takes on the order of 40 injections from the SPS, which corresponds to about 1200 bunches in each of the two LHC rings. The bunch scheme evolution is sketched in Fig. 2

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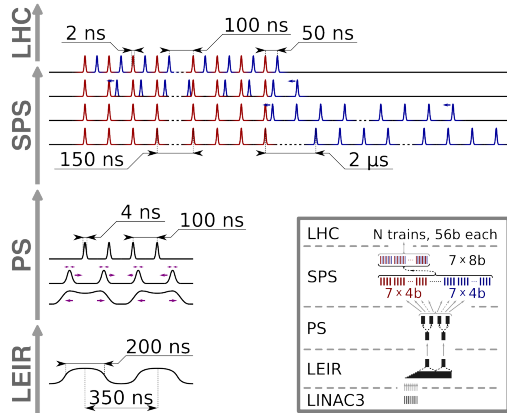


Figure 2: Evolution of longitudinal beam structure along the ion injector chain.

## OPERATIONAL IMPROVEMENTS AND PERFORMANCE

In 2025 significant improvements were implemented at every stage of the ion injector chain to further enhance performance and reliability.

For Linac3 beam commissioning, highlights included the deployment of the source automatic restart task, along with further validation and tuning of the automatic source optimizer. A new automatic optimizer based on scanning the transmission between the RF quadrupole (RFQ) and the first cavity tank improved the overall beam transport efficiency. Linac3 resumed operation on 4th August, and throughout the run, the average delivered beam intensity was  $32 \pm 2.7 \mu\text{A}$ , compatible with the LIU target of  $30 \mu\text{A}$ .

Building on the successful experience gained in 2024, the Linac3 pulse length was extended from  $200 \mu\text{s}$  to  $300 \mu\text{s}$ , and up to eight pulses (instead of seven), spaced by 200 ms, were accumulated in LEIR. This resulted in an increased injected intensity, providing a comfortable margin above the LIU intensity target of  $\sim 9 \times 10^{10}$  charges at LEIR extraction. Beam lifetime was improved through careful energy matching between Linac3 and LEIR, and optimization of the RF frequency program and the beam orbit throughout the cycle. An important component of the successful LEIR operation was the extensive use of a high-dimensional Bayesian optimization approach [5], used to optimize both the transfer from Linac3 to LEIR and a large number of machine parameters at LEIR injection (including ramp and debunching cavity phases, injection and e-cooler bumps, gun voltage, and RF frequency), maximizing the accumulated beam in the ring. The newly deployed Longitudinal Beam Observation (LBO) system [6] enhanced online monitoring of longitudinal beam properties throughout the cycle. Key observables, such as longitudinal emittance and bunch length, are continuously recorded in a database for both online and post-mortem analysis, enabling rapid identification and response to operational issues.

The first beam was injected into LEIR on 16th September. Following beam commissioning and the implementation of

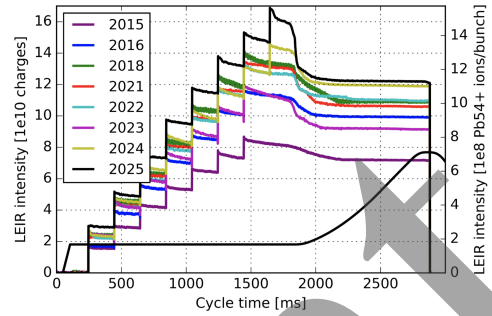


Figure 3: Evolution of the intensity along the LEIR cycle for the best performance achieved over the years. The black curve shows the best 2025 curve, with intensities exceeding  $12 \times 10^{10}$  charges at extraction.

the operational improvements, an excellent performance was achieved, exceeding for the first time  $12 \times 10^{10}$  charges at LEIR extraction (see Fig. 3). This excellent beam intensity was maintained for several months, and at the start of the LHC ion physics run, high beam intensities well above the LIU target were systematically extracted from LEIR. In mid-November, a power glitch in the electrical network occurred, and recovering the LEIR performance proved to be challenging. A short re-commissioning phase was required to restore beam operation, reaching intensities slightly above the LIU target, however, the previous level of performance could not be fully restored. During this period, beam delivery to the LHC continued, and the decision was taken to operate in a degraded mode. Following a second power glitch in early December, the LEIR performance was partially restored after a full re-optimization of the injection, including a change of the Linac3 stripper foil type and the replacement of a power amplifier of the ramp cavity in Linac3. Although the underlying cause of the strong performance degradation after the electrical glitches is not yet fully understood, these actions allowed the LEIR performance to be reestablished to approximately 20 % above the LIU target, as shown in the final period of Fig. 4.

The Pb-ion beams do not suffer from strong intensity limitations in the PS. For high bunch intensities the beam becomes unstable just after transition crossing, but the instability is suppressed by controlled longitudinal blow-up with a beam quality still sufficient for injection into the SPS. Nevertheless, a careful adjustment of the longitudinal phase jump at transition and transverse settings of the gamma jump scheme was performed which resulted in increased beam stability, while minimizing unwanted satellite bunches at extraction.

On 19th September, the first beam was injected into the PS. A beam transmission above 95% was achieved from LEIR to the PS, and  $\sim 90\%$  throughout the PS cycle, in line with the performance observed in 2024. However, the beam intensity in the PS was affected by the degraded LEIR performance, leading to intensities below the LIU target during that period.

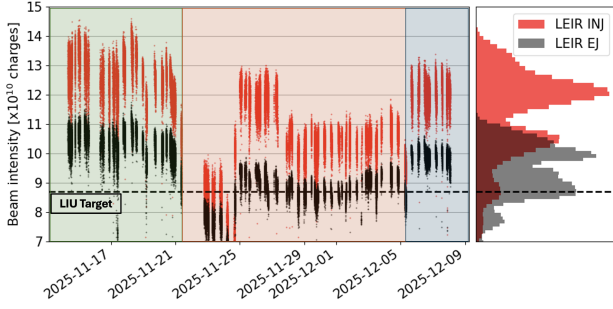


Figure 4: LEIR intensity performance history during the 2025 LHC physics run. The colored background highlights three performance periods: green for excellent performance following beam commissioning, red for degraded performance after a first electrical power glitch, and blue for recovered performance after a second power glitch. The dashed horizontal line marks the LIU target intensity.

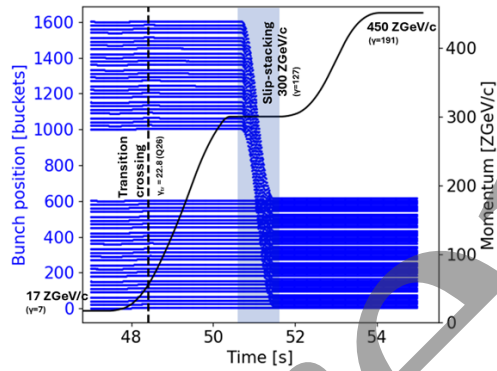


Figure 5: Bunch position evolution, measured by the newly deployed LBO system in the SPS, during the slip-stacking manipulation at the intermediate energy plateau of 300 ZGeV/c. Two bunch trains of 28 bunches, with bunches spaced by 100 ns, are interleaved to a single 56 bunch train with 50 ns bunch spacing.

Over the full duration of the run, the average beam intensity remained slightly above the LIU target value.

All the SPS upgrades required to reach the LIU performance for ion beams have been in place since the start of Run 3 (2023), including the slip-stacking RF manipulations (Fig. 5 shows the process of SPS slip-stacking as measured with the newly deployed LBO system) and the use of the 800 MHz RF system to enhance the longitudinal stability along the cycle. However, the beam degradation during the very long flat-bottom (50 s) mainly arises from transverse space charge effects and intra-beam scattering, and it strongly depends on the bunch intensity. Studies were carried out to optimize the working point while preserving the transverse emittance [7]; however, the most significant improvement was achieved through the compensation of 50 Hz and 100 Hz noise on the current ripples of the main quadrupoles, operational since 2024. This resulted in a significant increase of the beam lifetime along the flat-bottom (>15%), as shown

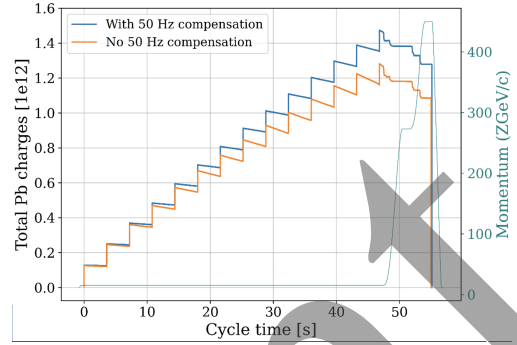


Figure 6: SPS intensity along the cycle with (blue) and without (orange) the 50 Hz noise compensation of the main quadrupoles.

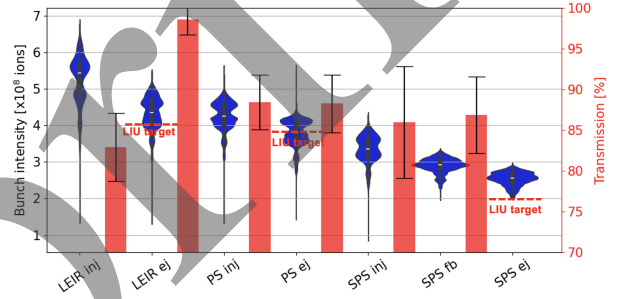


Figure 7: Performance summary along the LHC ion injector chain during the 2025 run. Average bunch intensities from LEIR injection to SPS extraction are shown in blue, together with the corresponding transmission along the chain (red bars).

in Fig. 6. As a result, the extracted intensities from the SPS remained above the LIU target of  $2 \times 10^8$  ions per bunch, even during periods of degraded LEIR performance.

This is illustrated in Fig. 7, which summarizes the beam performance along the LHC injector chain during the 2025 physics run. The bunch intensities (shown in blue) remain high across all accelerators, combined with excellent transmission (red bars) both between machines and within each accelerator. The impact of the power glitches is visible in LEIR and at PS extraction, where the intensities temporarily fall below the LIU target (red dashed line). In contrast, SPS intensities remain above target due to the implemented noise compensation, with an average of  $\sim 2.5 \times 10^8$  ions per bunch.

## SUMMARY

The 2025 lead-ion run demonstrated excellent injector chain performance, with an average intensity of  $2.5 \times 10^8$  ions per bunch achieved at SPS extraction, surpassing LHC physics requirements. Overall, performance was comparable to 2024, confirming the maturity of the injector complex and the impact of recent improvements. Key factors include high beam quality, operational flexibility, and improved machine availability. Further work is required to better understand

and mitigate remaining limitations, in particular the intensity degradation observed in LEIR after the power glitches.

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