OXYGEN AND NEON ION BEAM PERFORMANCE IN THE CERN ION INJECTOR COMPLEX

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Abstract

In 2025 CERN's ion injector complex delivered both oxygen and neon ion beams to the Large Hadron Collider (LHC) for the first time, with oxygen ion beams only previously having been accelerated in the late 1980s for Super Proton Synchrotron (SPS) fixed-target experiments at CERN. In addition to the initially planned oxygen run, a run with a neon isotope with the same charge to mass ratio as oxygen was also scheduled, following a fruitful workshop between theoretical, experimental and accelerator physicists, underscoring the value of such cross disciplinary exchanges. Given that neon and oxygen have very different nuclear structures, comparing the data from both types of collisions provides a unique opportunity to investigate nuclear geometry driven hydrodynamic flow in light ion collisions at the LHC. The accelerator complex achieved three objectives during this running period: (1) oxygen-oxygen, proton-oxygen and neon-neon collisions in the LHC, (2) primary oxygen beams for the SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) fixed-target experiment in the SPS North Area, and (3) beam studies for the High Energy Accelerators for Radiation Testing and Shielding (HEARTS) ion irradiation to electronics proposal in the PS East Area. We report on the performance of the ion injector chain, highlighting key limitations and the operational mitigations deployed. These results guide the selection of ion species to maximize nucleon–nucleon luminosity for LHC ion runs, thereby laying the groundwork for the future ion programme at CERN.

INTRODUCTION

In 2025, the CERN ion accelerator complex delivered the beams required for four different ion collision modes in the Large Hadron Collider (LHC): proton–oxygen (p–O), oxygen–oxygen (O–O), neon–neon (Ne–Ne), and lead–lead [1] (Pb–Pb). The O–O and p–O collisions, first requested by the LHC experiments in 2019, were prepared in the scope of the OXY4LHC project [2]. Initial physics goals and beam requirements were presented at the 2021 workshop [3] and at the conference [4], respectively. The Ne–Ne collisions were a late addition, emerging from a cross disciplinary workshop in November 2024 [5] involving theoretical, experimental, and accelerator physicists highlighting the value of such exchanges. Only eight days were assigned for p–O and O–O, with one extra day for Ne–Ne. Further time was allocated for crystal collimation studies [6] using O and Ne beams [7] to profit from the unique availability of those ion species at the LHC energies. In addition, oxygen beams were delivered to the Super Proton Synchrotron (SPS) North Area Heavy Ion and Neutrino Experiment (NA61/SHINE) and to the Proton Synchrotron (PS) East Area facility for radiation-to-electronics for HEARTS [8] (High-Energy Accelerators for Radiation Testing and Shielding). LHC performance with p-O, O-O and Ne-Ne collisions is detailed in [9]. This article focuses on the performance of the ion injector complex during preparation and delivery of the O and Ne beams.

SOURCE AND LINAC 3 BEAM COMMISSIONING

The first oxygen beam preparation took place in 2023 with the beam reaching up to PS extraction. In 2025 the beam commissioning began on 9 April, following safety approval and permit issuance. Source commissioning started immediately, and by 11 April, the source delivered 300 eμA, with 110 eμA of $^{16}O^{4+}$ beam transported through the Radio Frequency Quadrupole (RFQ). Beam intensity at the end of Linac 3 at 4.2 MeV/u was measured at 70 eμA on 15 April, and after RF phase optimization, it reached 90 eμA.

Beam commissioning continued through the start of the following week. During the beam commissioning in Linac 3, the source was switched from oxygen to neon for two days to assess contamination levels and species switching times, in preparation for the upcoming 24 hours neon run. After that, Linac 3 commissioning concluded successfully, achieving 91.5 eμA of $^{16}O^{4+}$ beam—a 30 % improvement over the 70 eμA recorded in 2023. The beam was transferred to the Low Energy Ion Ring (LEIR) on 8 May. Figure 1 shows the intensity evolution out of the source and after Linac 3 acceleration for the LHC run period.

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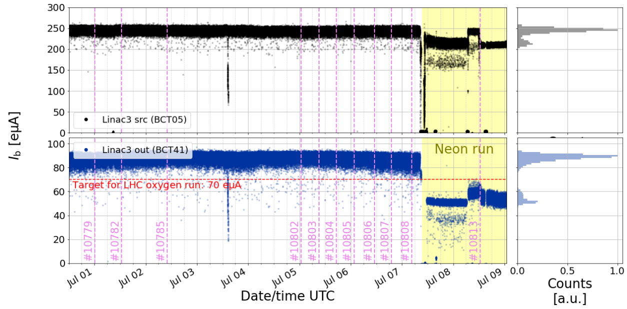

Figure 1: Intensity evolution of the oxygen beam after the source (top) and after Linac 3 (bottom). The magenta numbers correspond to the LHC fill numbers.

LEIR BEAM COMMISSIONING

LEIR commissioning began with the 2.4 s single injection cycle, the so called Early cycle. Transfer line setup was completed on 9 May, two days ahead of schedule, enabling first beam accumulation that evening following a main dipole field scan. Commissioning resumed on 12 May, achieving 4×10^{10} charges of $^{16}O^{4+}$ at injection after optimising the transfer line trajectory and injection elements. Further optimisation of beam parameters enabled stable storage from injection to acceleration.

Consistently with simulations, lighter ions require longer electron cooling times. In the Early cycle, the cooling time is limited to ≤400 ms, yielding a transverse emittance 80 % larger than for lead beams. The larger momentum spread also increases capture losses compared lead. To mitigate this, injection was optimised to prioritise emittance reduction over efficiency, enabling the 2.4 s beam to barely meet the ejected intensity target of 3.5×10^{10} charges of $^{16}O^{4+}$. For the Early cycle, the longitudinal emittance of oxygen at extraction was 60 % higher than for lead, a difference that resulted in poor transmission in the PS due to the larger beam size.

To address this, the 3.6 s cycle - called Nominal - was commissioned with a single injection. This provided an extra 1.2 s cooling time. To minimize the loss of ions that change charge state by capturing electrons during cooling, the electron current was reduced to 176 mA (versus 210 mA-340 mA for lead). The beam was captured in a single bunch, unlike the typical two bunch capture scheme used for the Nominal cycle of lead. By optimizing the tune for capture and setting very small vertical chromaticity (confirmed via chromaticity scans), higher intensity was delivered from LEIR, compensating for downstream losses. Nonetheless, the longitudinal emittance at extraction remained 40 % larger when all the intensity was captured in a single bunch than for the two bunch Nominal lead cycle. This operational configuration was used for the p-O collisions at LHC.

PS BEAM COMMISSIONING

Beam commissioning in PS started 27 Jun. The initial setup with the Nominal cycle (single injection from Linac 3 and capture in a single bunch) revealed several key challenges. Fast injection losses from excessive bunch length from LEIR were mitigated by optimizing LEIR extraction to deliver shorter bunches. The high bunch intensity, combined with the absence of bunch splitting (the lead Nominal cycle undergoes double splitting, extracting four bunches), caused longitudinal instabilities and significant transition crossing losses. A controlled longitudinal blow up provided partial mitigation at the expenses of larger longitudinal emittance, which degraded re-bucketing and produced satellite bunches containing 5 %-10 % of the intensity. As this approached LHC experiment satellite limits, blow up was abandoned despite resulting instabilities. Dedicated studies confirmed that although these instabilities were present, overall transmission to SPS extraction remained good, and satellite population dropped to 1 %–2 %.

However, PS transition timing was intensity dependent and unstable, varying per cycle. Incorrect timing caused large oscillations at transition, contributing to satellite formation. To overcome those limitations, the Anominal cycle was setup in LEIR, which extracted two bunches but discarded one before PS injection to meet the 1 μs bunch separation requirement of LHC. Transition crossing was stable, and while the bunch length at extraction remained 4.4 ns (10 % larger than required by SPS), no satellites were observed. This cycle was used for O-O collisions at LHC. In addition, the Anominal cycle was required to keep the bunch intensity within the range necessary for the proper operation of the LHC beam position monitor and transverse damper systems.

As expected from simulations [10], continuous losses from residual gas scattering were very significant, leading to 50 % oxygen transmission in the PS compared to 90 % for lead. Increasing the vacuum sublimation to every three hours during the LHC runs allowed to keep an average transmission efficiency of 80 %. The oxygen beam was sent to the East Area irradiation facility for HEARTS to test the beam performance in view of the future upgrade.

SPS BEAM COMMISSIONING

Despite losing two days for unrelated long repairs that could be recovered later, PS to SPS transfer line steering began 13 June. After one day of tuning—optimising the energy matching, injection kicker, vertical steering, and orbit—the beam circulated in the SPS.

Initial LHC cycle commissioning in the SPS delivered an ejection intensity below the initial target, but this was deemed acceptable for LHC operations. Simulations indicated that projected luminosity targets remained reachable within the eight day schedule, which included oxygen beam commissioning in the LHC. The SPS working point and bunch length at extraction for the LHC cycle was Q_H=26.31, Q_V=26.25 and 1.4 ns–1.6 ns, respectively.

As predicted by simulations [10], strong space-charge losses occurred at injection. Combined with a non-optimal working point, beam lifetime degraded significantly after each bunch injection. Contrary to lead ions, the compensation of the 50 Hz noise from the main quadrupole magnets, had minimal effect for oxygen. Losses at flat bottom and at

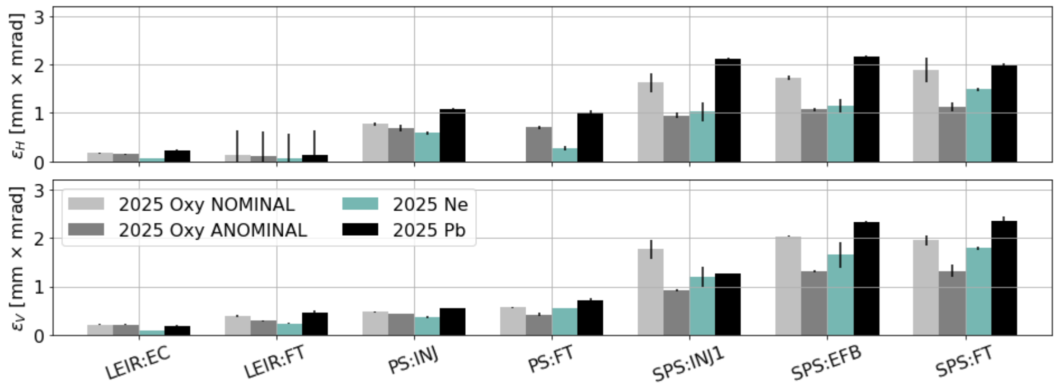

Figure 2: Transverse emittance comparison: oxygen and neon vs. lead in 2025.

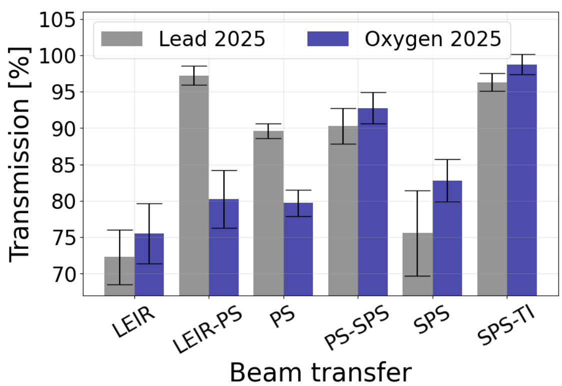

Figure 3: Transmission efficiency across the complex measured in 2025 for the oxygen Anominal cycle compared to lead Nominal cycle.

transition were mitigated with working point and with transition crossing optimisation, respectively. Figures 2 and 3 show the emittance and transmission efficiencies of the oxygen beam through the injector complex.

Commissioning of the SFTION oxygen cycle (constituted of four Early cycles from LEIR) for NA61/SHINE [11, 12] began 17 June, the same day as first LHC extractions. On 26 June, the safety test for primary ion beam extraction to the North Area was completed successfully, allowing oxygen extracted to NA61/SHINE at 150 GeV/c/u. In parallel, extraction setup for the LHC beam to the two transfer lines towards LHC resumed. The beam delivered to NA61/SHINE featured large transverse emittance (ϵ_H = 3 µmrad, ϵ_V = 2.5 µmrad) but with a beam intensity larger than required by the end user.

NEON BEAM COMMISSIONING

Neon beam commissioning occurred in three phases. An initial test in April demonstrated rapid source switching: first beam was available 15 minutes after switching from oxygen, using similar settings with minimal tuning. Over two days, charge-state distribution and RFQ transmission scans were performed, and beam was transmitted through Linac 3. Using natural neon (90 % ^{20}Ne, 10 % ^{22}Ne), the test confirmed low neon contamination within three hours of switching back to oxygen and no long term stability issues, enabling a second test that started on 27 May. The neon beam reached LEIR within 3.5 hours of source switching. Using identical settings to oxygen thanks to the equal mass to charge ratio, injection and acceleration were achieved almost immediately. After 1.5 days of optimisation, 2.2×10^{10} charges of $^{20}Ne_5^+$ per bunch were obtained at LEIR extraction. The longitudinal emittance was significant but smaller than for oxygen. The beam reached PS flat top two hours after first LEIR injection, and the test concluded on 28 May.

For the LHC physics run, the source switched to neon on 7 July, with first beam in LEIR five hours later. Intensity out of the source was 220 eµA and 65 eµA out of Linac 3. A roughly 5 % contamination in the neon beam was confirmed by measurements. The LHC used the LEIR Nominal one bunch cycle, delivering bunch intensities within the beam position monitor high sensitivity range. Despite using oxygen optimised source settings, intensity was still double the initial projections. The neon beam reached the LHC within 8 hours, but LHC commissioning was delayed 16 hours by cryogenics and power converter issues. Nevertheless, a single 10 hour physics fill surpassed initial luminosity targets by nearly an order of magnitude [9].

CONCLUSIONS

In 2025, the CERN injector complex set several records, delivering beams for five different collision modes to the LHC, p–p, p–O, O–O, Ne–Ne, and Pb–Pb, offering unprecedented physics diversity. Two new ion species, oxygen and neon, were commissioned in the record time of just three months. Beyond the LHC, oxygen beams were also delivered to the NA61/SHINE fixed target experiment in the SPS North Area and to the HEARTS radiation to electronics setup in the PS East Area.

Numerous challenges arose during the oxygen beam commissioning, but all were successfully overcome thanks to the dedication of expert teams across the accelerators. This run provided invaluable experience for potential future operations with new particle types, both in the LHC and its injector complex.

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