LHC OPERATION WITH OXYGEN AND NEON IONS

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Abstract

During the summer of 2025, the CERN Large Hadron Collider operated for the first time with oxygen and neon ion beams. Three different machine configurations—with collisions of p-O, O-O, and Ne-Ne and with varying beam energies and optics—were commissioned and exploited for physics operation during the eight days allocated. This short run was challenging because of its very tight schedule, the novel modes of operation, and new beam-physics effects such as transmutation of oxygen and neon nuclei into other nuclei with the similar magnetic rigidity. In spite of these challenges, the run was very successful with the luminosity targets set by the LHC experiments fully met and, in most cases, even exceeded by large factors. In addition, time was allocated for machine studies that provided the first LHC data on crystal channeling with O and Ne ions. In this article, we give a general overview of the LHC machine configuration, operational challenges, and experience during the run, as well as the achieved performance and the key contributors to the successful outcome. The results demonstrate the LHC's flexibility for mixed-species operation and give valuable input for future ion operation.

INTRODUCTION

The heavy-ion programme at the CERN Large Hadron Collider (LHC) [1] consists mainly of yearly one-month runs with collisions of fully stripped Pb ions with beam energies up to 6.8 Z TeV [1–5], but includes also asymmetric p-Pb collisions [6–8] and a short 2-day pilot run with Xe–Xe collisions in 2017 [9]. Following the success of the Xe–Xe run, the ion physics community requested a short LHC run with lighter nuclei [10]. Physics motivations included quark-gluon plasma studies and the emergence of collective phenomena in systems with lower mass, and the interactions of cosmic rays with Earth's atmosphere. The run was scheduled in summer 2025, relying on proton and fully stripped $^{16}\mathrm{O}^{8+}$ and $^{20}\mathrm{Ne}^{10+}$ beams from the CERN injector complex to provide proton–oxygen (p-O), oxygen–oxygen (O-O), and neon–neon (Ne-Ne) collision modes. Besides changing beams between these modes, the LHC optics and beam energy were changed to meet specific requirements from the experiments. A mere 8 days were assigned for p–O and O–O, with one additional day for Ne–Ne. Additional machine development time was allocated for studies of crystal collimation [11] with O and Ne beams [12].

This article presents first the constraints and requirements from the experiments for which the LHC machine configurations for each mode were devised. The commissioning, operational experience, and performance achieved in each mode are then reviewed. The production of the O and Ne beams in the CERN injector complex is described in [13].

CONSTRAINTS AND MACHINE CONFIGURATIONS

Ambitious luminosity targets for O–O and p–O were presented in the 2021 physics workshop [10] by the large LHC experiments (ATLAS at interaction point 1, called IP1, ALICE at IP2, CMS at IP5, and LHCb at IP8), and the LHCf experiment, which intercepts forward collision products from IP1. Early feasibility studies were based on the so-called "setup beam" limit at 3×10^{11} charges per ring (where interlocks can be masked to relax machine-protection requirements), and the re-use of an existing Pb–Pb configuration to shorten setup procedures. These indicated that the targets could be reached in about one week [14]. Subsequently, the experiments updated the final luminosity targets as summarised in Table 1, and also introduced further requirements.

For p–O, LHCf, as one of the main requestors together with LHCb, demanded the highest possible beam energy of 6.8 Z TeV, a −145 µrad IP1 half crossing angle and a very low pileup at IP1 of μ=0.01 for the first 8 h followed by μ=0.03, as well as a large β^*. The other experiments favoured smaller β^* and β^*=1 m was adopted as a compromise. LHCb, LHCf, and ALICE asked for p in the clockwise Beam 1 (B1) and O in the counter-clockwise Beam 2 (B2), while a beam reversal was not requested. Roman pot detectors for forward physics around IP1 (ATLAS Forward Proton Project—AFP) and IP5 (Precision Proton Spectrometer—PPS) were to be inserted in p-O, while only AFP was to be inserted for O-O. ALICE asked for $\mu \leq 0.2$ in all modes.

In addition to p–O and O–O operation, Ne–Ne collisions were also requested to study the effect of the different nuclear shapes between O and Ne. This was technically possible

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Table 1: Target and Delivered Integrated Luminosity in nb^{-1} at the LHC Experiments for the Three Modes of Operation.

	p–O			**O–O**			**Ne–Ne**		
	target	**delivered**	**ratio**	**target**	**delivered**	**ratio**	**target**	**delivered**	**ratio**
ATLAS	N/A	6.9	N/A	0.8	8.2	10.3	0.1	1.0	10
ALICE	5	7.85	1.6	0.5	5.15	10.3	0.1	0.91	9.1
CMS	3	48.4	16	0.8	9.4	11.8	0.1	0.91	9.1
LHCb	2	33.1	16.6	0.5	5.75	11.5	0.1	0.61	6.1
LHCf	1.5	1.8	1.2	N/A	N/A	N/A	N/A	N/A	N/A

thanks to their very similar charge-to-mass ratio (Z/m). This allowed a record-fast switching of particle species both in the source (possible only with certain ion species), as well as in the rest of the injector complex and LHC where the O settings could be reused for Ne in each machine.

For the O–O and Ne–Ne runs, the LHCf detector had to be removed as ATLAS needed to install its zero-degree calorimeters (ZDCs) in the same slot, and ATLAS, CMS, and ALICE required a lower beam energy of 5.36 Z TeV to match the energy per nucleon in the previous Pb–Pb [5] and p-p reference runs. On the other hand, there were no constraints on $\beta^*$from the experiments, and the smallest possible β^*compatible with machine aperture [15, 16] could therefore be implemented for maximal luminosity reach.

Because only 9 days were available, it was crucial to choose a machine scenario that required minimal commissioning. Although the same LHC setup could be used for O–O and Ne–Ne, a different cycle with higher beam energy was needed for p–O, which lengthened the commissioning. A 1 μs bunch-spacing requirement imposed the use of single bunches rather than bunch trains—the latter would raise total intensity but also increase commissioning time. Luminosity simulations [17, 18] across configurations and commissioning schedule optimisations, partly reusing existing optics and settings from Pb–Pb operation, identified a solution fitting within the 9-day window, including also contingency for an estimated 75% machine availability. The plan allocated 3.9 days to commissioning and 2.7 days to physics. For O–O and Ne–Ne, β^*=0.5 m was proposed, using Pb–Pb optics and with a small crossing angle to avoid parasitic collisions. The total intensity was increased beyond the setup beam limit by up to a factor 5, while still staying much below the intensities used when operating with bunch trains, and hence requiring a shorter machine-protection validation. Key parameters in the final chosen configurations for the three modes are shown in Table 2.

p-O OPERATION

The intensity and nucleon-nucleon luminosity during the full light-ion period are shown in Fig. 1. Only the last optics commissioning [19] is shown—this started earlier using low-intensity proton beams. The p–O commissioning, interleaved with commissioning for proton operation, included a non-standard RF setup as in previous p-Pb runs [7, 8]. Because of the 2-in-1 magnet design, implying the same magnetic field for the two beams, the p and O beams have different revolution frequencies due to their different Z/m. Therefore, injection and acceleration are done with different RF frequencies in the two beams. At top energy, both beams are brought off-momentum in opposite directions ($\delta \approx \pm 4 \times 10^{-5}$) to lock the RF frequencies together and equalise the revolution frequencies. Other commissioning activities included alignment of tertiary collimators and roman pots, beam background studies, and loss maps, where beam losses are provoked on a low-intensity beam to validate the machine safety before high intensity is allowed.

Shortly after the start of the first p–O physics fill, more commissioning had to be added to correct the position of the LHCb collision point, after which the two main physics fills followed. Offset levelling was used at IP1 and IP2 to keep a constant luminosity satisfying the LHCf and ALICE pileup targets, except during emittance scans that resulted in rapid luminosity variations. The un-levelled experiments could very rapidly accumulate data, and hence exceeded their targets by factors 16–17. At the end of the second fill, when the LHCf target had been reached, the levelling was removed at IP1, allowing also ATLAS to record a larger set of p–O collisions. The total integrated luminosities are shown in Table 1, together with the factors by which the targets were exceeded, and the achieved intensities and peak luminosities are shown in Table 2. Further analysis of key parameters is shown in [20].

O–O OPERATION

Once the p–O targets had been reached, the LHCf detector was removed and the ZDCs were installed, before a rapid switch to the O–O configuration, comprising a final optics measurement, collimator alignment, background checks and loss maps. Following a very successful machine development study [12], crystal collimation was implemented in all O–O physics fills. One problem was encountered when the initial O bunch intensities delivered by the injectors were on the limit between the pre-programmed high and low gain of the LHC beam position monitors (BPMs), making several BPMs unusable for the orbit feedback. Furthermore, the transverse damper (ADT) would require additional setup for optimal performance with this intensity. Therefore, the injector chain quickly commissioned a second O beam variant for the remainder of the O–O run, extracting 2 bunches from the Low-Energy Ion Ring (LEIR) but keeping only one in the Proton Synchrotron (PS), reducing intensity, emittance and satellite population [13].

Table 2: LHC Parameters for the Three Modes of Operation.

	p–O	**O–O**	**Ne–Ne**
Energy (Z TeV)	6.8	5.36	5.36
β^*(m) IP1,2,5,8	1, 1, 1, 1.5	0.5, 0.5, 0.5, 1	0.5, 0.5, 0.5, 1
Net half crossing angle (μrad)	-145, 40, 60, -40	100, 60, 100, -50	100, 60, 100, -50
Average bunch intensity B1, B2 (10^{10} charges at start of physics)	3.0, 2.3	2.2, 2.2	2.0, 2.0
Total number of bunches per beam	52	62	62
Colliding bunches per IP	32	40	40
Peak luminosity (10^{29} cm^{-2}s^{-1}) IP1,2,5,8	5.6, 6.5, 6.6, 4.8	0.82, 0.66, 0.91, 0.50	0.45, 0.27, 0.36, 0.19

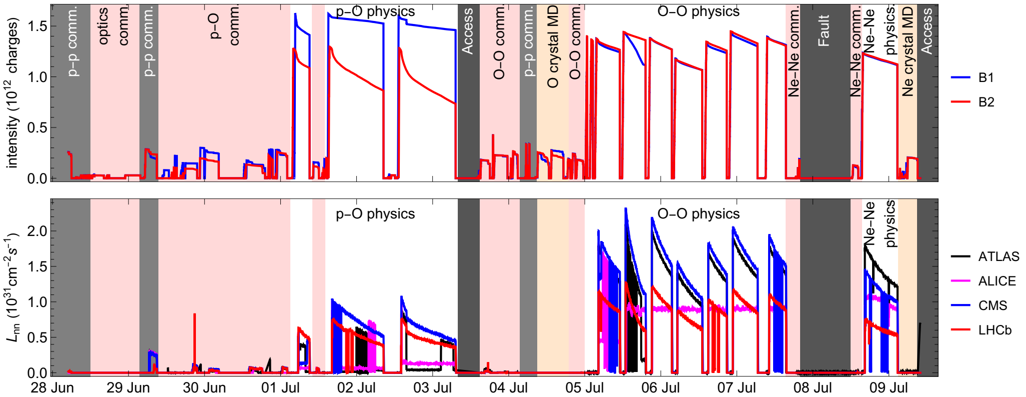

Figure 1: The intensity in B1 and B2 (top) and the instantaneous nucleon-nucleon luminosity (bottom) over the full duration of the 2025 light-ion run. The background colours indicate different phases of the run, e.g. commissioning (comm.), physics operation, and machine development (MD). Rapid variations of luminosity occur during Van der Meer scans.

Initially, only one fill of O–O was scheduled, which was sufficient to reach the targets, and a total machine availability of 75% was assumed in the full period. However, almost no faults were encountered, and the LHC reached close to 100% availability in both the p–O and O–O periods. Therefore, the O–O physics programme could continue for a total of seven fills, using the initial contingency time allocation. The luminosity targets were hence surpassed by more than a factor 10 (see Table 1). The beams were kept in collision for about 6 h before refilling, in order to minimise the transmutation effect [21], where lighter nuclei with similar Z/m produced in collisions could continue to circulate.

Ne-Ne OPERATION

To save time, the ion source started the switch to Ne ions in parallel to the last O–O fill, shortly after LHC injection—this switching had been tried twice previously in dedicated tests. About 3 h after the source switch, the first Ne ions could be sent from the source to the injector chain [13], and about 8 h after the switch, the first Ne ions could be injected in the LHC. Shortly after this, an LHC cryogenics fault occurred, which delayed the schedule as it took about 16 h to recover. Once back in operation, a short commissioning fill for loss maps was done, followed by Ne–Ne physics operation. Because of the delay, there was time for only one physics fill, keeping the beams colliding for about 10 h. The initial production scheme with one bunch from LEIR [13] could be used, since the intensity was not high enough to cause problematic BPM readings. The achieved intensity per bunch was anyway significantly higher than predicted (see Table 2), which, together with the larger number of bunches than initially foreseen, allowed the experiments to exceed their targets by factors 6–9 (see Table 1).

CONCLUSIONS

The LHC operated for the first time with O and Ne beams during a special run in 2025. Three new configurations with collisions of p–O, O–O, and Ne–Ne had to be commissioned and used for physics operation in only 9 days. This schedule was very challenging, involving different beam energies and optics and put unprecedented demands on both the LHC, the injectors, and the expert teams involved in the commissioning. The outcome was nevertheless very successful, demonstrating a record-fast switching of particle species in the CERN accelerator complex. The targets for integrated luminosity set by the experiments were exceeded by large factors (1.2–16.6 for p–O, 10.3–11.8 for O–O, and 6.1–10 for Ne–Ne). This success can be attributed to the excellent machine availability and beam quality from the injectors, the optimised machine configurations and commissioning, as well as the flexibility and availability of expert teams that had to react on short notice to schedule changes and unforeseen demands. This run demonstrated the potential for future operation with new nuclear species, of both the LHC and its injectors.

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