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EXCEEDING HIGH-LUMINOSITY LHC PERFORMANCE TARGETS DURING THE 2024 Pb-Pb ION RUN*

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Abstract

We review the 2024 Pb-Pb ion run at the CERN Large Hadron Collider (LHC), in terms of the operational experience, the problems encountered and the main results. With only 18 days scheduled for physics data-taking, the key objective was to address the problems encountered in the 2023 Pb-Pb run and establish stable and efficient operation. Thanks to several mitigation measures, the 2023 limitations were overcome, significantly improving the machine availability. Together with substantially higher intensity, thanks to the excellent performance of the Pb ion injectors, this paved the way for a record-high performance in terms of average daily integrated luminosity with ion beams at the LHC.

INTRODUCTION

CERN's Large Hadron Collider (LHC) [1] began its heavy-ion programme in 2010 [2], colliding fully stripped $^{208}\mathrm{Pb}^{82+}$ nuclei for about one month per year. In Run 1[1] (2010–2013), two such runs were carried out at 3.5 ZTeV beam energy (Z is the atomic number of the beam nuclei) and two more were done in Run 2 (2015–2018) at 6.37 ZTeV [3, 4]. A total integrated luminosity of $\mathscr{L}_{\mathrm{int}} \approx 1.5\ \mathrm{nb}^{-1}$ was delivered to the heavy-ion-focused ALICE experiment at interaction point 2 (IP2), hence exceeding the target of $1\ \mathrm{nb}^{-1}$ for the first 10 years of operation [5]. At the experiments ATLAS [6] at IP1 and CMS [7] at IP5, where luminosity levelling was not needed as for ALICE [3], about $2.5\ \mathrm{nb}^{-1}$ were collected, while LHCb [8] at IP8, the last experiment to join the heavy-ion programme, integrated about $0.25\ \mathrm{nb}^{-1}$.

The High-Luminosity Large Hadron Collider (HL-LHC) upgrades [9] are designed to significantly enhance the LHC performance. Most of the proton upgrades are foreseen for Run 4 (2030–2033), while the heavy-ion upgrades were completed before the present Run 3 (2022–2026). The HL-LHC ion physics goals are shown in Ref. [10, 11] and the LHC machine configuration in [12, 13]. Upgrades to the injector complex enabled a new Pb beam production scheme, with slip-stacking [14] reducing the bunch spacing to 50 ns and so allowing about 50% more bunches in the LHC than in Run 2. The LHC collimation system [15–17] has been upgraded with new bent crystals [18, 19], and new dispersion suppressor collimators around IP2 [20, 21] together with detector upgrades [22] increased the tolerable luminosity at ALICE by more than a factor 6.

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1 We follow the CERN convention of calling annual operating periods "runs" and multi-year operating periods between shutdowns "Runs".

Table 1: Target Beam And Machine Parameters For a 1-month HL-LHC Pb Run [9, 13, 14], Shown With Achieved 2023 and 2024 Parameters

	HL-LHC	2023	2024
Beam energy (Z TeV)	6.8	6.8	6.8
β^* at IP1,IP2,IP5 (m)	0.5	0.5	0.5
β^* at IP8 (m)	1.5	1.5	1.5
Half crossing IP1,IP5 (μrad)	170	170	150
Half crossing IP2 (μrad)	100	98	78
Half crossing IP8 (μrad)	-305	-274	-71
N.o. bunches per beam	1240	1080	1240
N.o. ions per bunch	1.8	1.67	2.31
Stored beam energy (MJ)	20.5	17.4	26.9
Normalized emittance (μm)	1.65	2.0	2.4
Days scheduled for physics	24	32	18
Total $\mathscr{L}_{\mathrm{int}}$, IP1,2,5 ($\mathrm{nb}^{-1}$)	2.5	2.0	1.9
Daily $\mathscr{L}_{\mathrm{int}}$, IP1,2,5 ($\mu\mathrm{b}^{-1}$)	118	80	142
Total $\mathscr{L}_{\mathrm{int}}$, IP8 ($\mathrm{nb}^{-1}$)	0.39	0.249	0.505
Daily $\mathscr{L}_{\mathrm{int}}$, IP8 ($\mu\mathrm{b}^{-1}$)	20	6.5	37

In this article, we first briefly recall the outcome of the first full physics run with all HL-LHC ion upgrades in place in 2023, which initially encountered several problems. We then present considerations for the 2024 machine configuration to overcome the 2023 limitations, followed by the performance achieved in 2024, comparing the results with 2023 and the targets for HL-LHC Pb ion operation.

2023 ION RUN OUTCOME AND PREPARATIONS FOR 2024

The 2023 Pb-Pb run, with achieved parameters shown in Table 1, faced several challenges [23]. The beam quality was lower than expected, with intensity and emittance not reaching their targets, and unforeseen issues caused machine downtime and performance degradation. Important beam losses at the end of the energy ramp and from uncontrolled 10 Hz orbit oscillations caused frequent beam aborts, limiting the number of bunches. Although the issues lessened after increasing the beam loss monitor (BLM) thresholds, losses remained significant and prevented operation with the maximum number of bunches (1240). Drifts in crystal colli-

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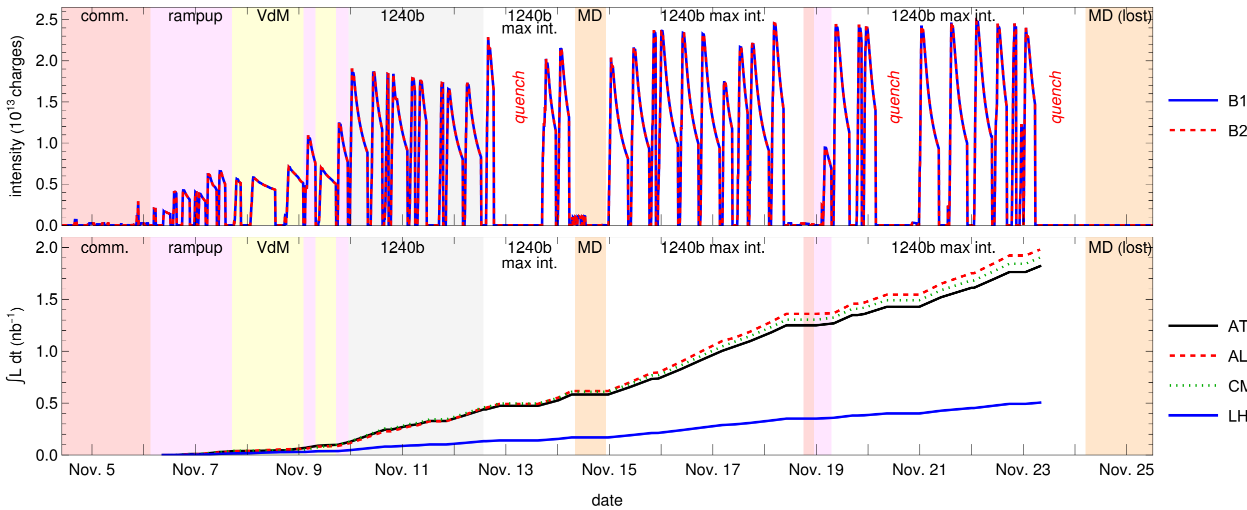

Figure 1: The intensity in B1 and B2 (top), and $\mathscr{L}_{\text{int}}$ (bottom) over the full duration of the 2024 Pb-Pb run. The background colors indicate different phases of the run: commissioning (comm.), intensity rampup, operation with a full machine (1240b), Van der Meer scans (VdM), machine development (MD), and operation with a full machine and maximum intensity from the injectors (1240b, max int.). The indicated quenches were not beam-induced but caused by radiation on the QDS.

mator orientation increased the sensitivity to losses [19], and time spent on alleviating strong backgrounds in the ALICE detector led to lost time for physics operation. Radiation from the collisions on the quench detection system (QDS) triggered several spurious firings of quench heaters causing magnet quenches, which led to more than 5 days of downtime as well as a reduction of the luminosity levelling target from the foreseen $6.4 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$ to $3.5 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$.

As a result, only about two-thirds of the initial luminosity target was met at ALICE, ATLAS, and CMS, and the average daily luminosity production was two-thirds of the HL-LHC goal. At LHCb, a higher luminosity levelling target of $1.5 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$ could be used instead of $1 \times 10^{27}\,\text{cm}^{-2}\text{s}^{-1}$, thanks to the relocation of collisional losses [24]. However, due to fewer collisions at LHCb in the reduced filling schemes, the average daily luminosity production was less than half of the HL-LHC target.

For the 2024 Pb-Pb run, the target $\mathscr{L}_{\text{int}} = 1.9\,\text{nb}^{-1}$ was slightly below the $2.0\,\text{nb}^{-1}$ collected in 2023 over 32 days. With only 18 days assigned for Pb-Pb physics in 2024, this target was very challenging. To achieve this, mitigation measures were studied and implemented to address the problems encountered in 2023, aiming to increase machine availability and establish stable operation. Identical optics to 2023 was proposed to minimize the risks, with a change in the polarity of final-focus quadrupoles around ATLAS imposed by requirements for proton operation [25].

Increasing intensity from the injectors was also crucial but required overcoming the beam loss limitations in the LHC, for which several measures were taken. The collimation cut was increased from $4.75\,\sigma$ to $6\,\sigma$, to give more room for the large-emittance beam. Slightly reduced crossing angles were therefore needed to gain aperture and maintain protection by the collimators. The net crossing angle at LHCb, a superposition of an external angle and a spectrometer compensation bump, could also be reduced by inverting the spectrometer polarity so that the two angles compensate. The impact on dynamic aperture from the smaller crossing angles was found to be tolerable in simulation. Part of the dynamic optics changes to reduce β^* was moved out of the energy ramp to top energy, and smoother orbit corrections were implemented. Simulations of collimator damage limits allowed higher BLM thresholds, and updating crystal collimation controls enabled dynamic angular optimization during the ramp. Discovered correlations between the 10 Hz orbit oscillations and cryogenic valve openings led to operational adjustments with a delayed valve opening, fully mitigating this effect. Finally, to suppress the single-event upsets on the QDS, almost 200 electronic circuit boards were exchanged to more radiation-tolerant versions.

Under the assumption that the LHC limitations could be overcome, a campaign of studies in the injector complex led to significantly improved beam quality, most notably in the Super-Proton Synchrotron (SPS) through compensation of 50 Hz noise from power converters [26].

OVERVIEW OF THE 2024 RUN

The 2024 Pb-Pb run was scheduled for 3–24 November, with 18 days for physics operation, 1 day for machine development, and 2 days for commissioning. Initial optics measurements and corrections were done earlier in the year with protons, as was the case in 2023 [27], and a first block of Pb ion commissioning took place a week before the run to finalize machine settings. Figure 1 shows the achieved intensity and integrated luminosity over the full run. Some key parameters are shown in Table 1, summarizing the stable configuration used in the last part of the runs. The bunch intensity and the emittance are average values at the start of

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collision. The crossing angles refer to the net angle from the superposition of any external angle and spectrometer bumps.

The run started on November 4, a day later than planned. Physics production began with a small number of bunches, ramping up in steps to identify potential problems at low intensity. This ramp-up was interleaved with Van-der-Meer scans for luminosity calibration. Thanks to the injector optimizations, a substantially improved intensity of 2.6×10^8 Pb/bunch was obtained at LHC injection. As it was uncertain if the LHC could operate reliably with this intensity, the ramp-up in bunches was done at a lower intensity of 2.0×10^8 Pb/bunch at injection, reaching the maximum of 1240 bunches in less than 4 days. Beam losses in the ramp were low, and no 10 Hz oscillations were observed, demonstrating the success of the mitigation measures. The angular drifts found in 2023 on the crystal collimators were still present, but the optimum orientation could be maintained most of the time thanks to the automatic optimization [19,28]. When it was clear that the 2023 limitations were successfully mitigated, the LHC started taking the maximum bunch intensity from the injectors. After an increase of the RF voltage from 8 MV to 12 MV at injection, the transmission improved significantly and an average 2.3×10^8 Pb/bunch was obtained at the start of collision, 28% higher than the HL-LHC target. The peak stored beam energy was 26.9 MJ, compared to the HL-LHC target of 20.5 MJ.

The types of single-event upsets on the QDS observed in 2023 were not seen in 2024, showing the effectiveness of the new electronics cards. However, three magnet quenches occurred due to a new QDS failure mode, leading to a total downtime of about 3.5 days, including the last two days of the run, penalizing both machine development time and physics operation. Machine availability reached around 75% over the full run, with 43% of the time for physics operation spent with colliding beams and 25% in fault, which was substantially better than in 2023. In total, 48 fills were attempted for physics, with 45 reaching collisions. Operators dumped 28 fills after an average of 6 h in collision, while the rest were dumped prematurely due to faults.

Because of the very high intensity, an excellent luminosity performance was achieved, despite a larger-than-nominal transverse emittance. Figure 2 shows the instantaneous and integrated luminosity in the best fills of 2023 and 2024 with the simulated HL-LHC prediction from [13]. The nominal HL-LHC luminosity levelling target of 6.4×10^{27} cm^{-2}s^{-1} was established in 2024 at the high-luminosity experiments, with more than double the HL-LHC levelling time. The LHCb levelling time was 1.7 h at the higher levelled luminosity of 1.5×10^{27} cm^{-2}s^{-1} in the best fills.

In terms of $\mathscr{L}_{\text{int}}$, ALICE collected 99 μb^{-1} after 6 h in the best 2024 fill, an 80% increase compared to 2023 and a 29% increase over HL-LHC predictions. Similar gains were seen for ATLAS and CMS. The $\mathscr{L}_{\text{int}}$ obtained at LHCb in the best fill was a factor of 7 higher than in 2023 and 95% higher than the HL-LHC prediction. The larger improvement at LHCb was due to more collisions than in 2023, a

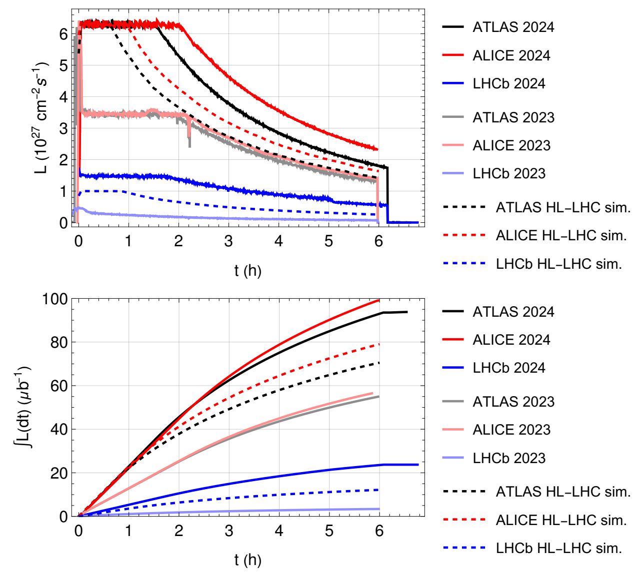

Figure 2: The measured instantaneous (top) and integrated (bottom) luminosity in the best fills in 2024 (fill 10400), in 2023 (fill 9285), and the HL-LHC prediction [13] for three of the experiments. CMS (not shown) is similar to ATLAS.

higher levelling target than in HL-LHC, and the reduced crossing angle. The average $\mathscr{L}_{\text{int}}$ per day, in the period with the maximum number of bunches, reached 142 μb^{-1} at ALICE, ATLAS and CMS, and 37 μb^{-1} at LHCb, with similar improvement ratios to 2023 and HL-LHC as for the best single fill. Thanks to this unprecedented performance, the integrated luminosity over the full run reached the target of 1.9 nb^{-1} at the high-luminosity experiments, despite the very challenging improvement needed.

CONCLUSIONS

Since the 2023 Pb ion run, the full HL-LHC upgrades for ion operation have been available, including more bunches from the injectors and collimation upgrades to handle higher intensity. However, the 2023 Pb run faced various issues, preventing the achievement of the performance targets. Throughout 2024, substantial efforts were made to understand and mitigate remaining limitations, focusing on beam losses, availability, and beam quality. The implemented mitigation measures were generally very successful. Combined with significant improvements in intensity from the injectors, this allowed for the production of the same total integrated luminosity as in 2023, but in only about half the time, thereby meeting the challenging integrated luminosity targets. Both the luminosity production in a single fill and the daily average reached record highs. The HL-LHC performance was substantially surpassed, marking an important milestone. Operation with Pb ions is planned to continue for about one month per year in the future. These runs could see additional improvements by using the maximum available intensity from the start and by further reducing downtime with foreseen QDS electronics upgrades, as well as smaller β^* and crossing angles if deemed feasible.

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