ANALYSIS OF THE PERFORMANCE IN THE 2023 LHC Pb-Pb RUN

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Abstract

In 2023, the Pb-Pb run in the Large Hadron Collider (LHC) took place during the last five weeks of operation at a record beam energy of 6.8Z TeV. It marked the first heavy-ion run of Run 3, following a two-day test that took place in 2022 to verify some key machine and beam upgrades. The 2023 run profited for the first time of higher beam intensities than the previous runs and of machine upgrades that enable higher peak luminosities in the ion-dedicated ALICE experiment. This paper addresses two important performance aspects: firstly, it compares the achieved operational efficiency for the different filling schemes employed during the run, and secondly, it quantifies the main factors contributing to performance loss.

INTRODUCTION

The Large Hadron Collider (LHC) [1] accelerates and collides two counter-rotating beams (called B1 and B2) of protons or heavier nuclei, typically Pb-Pb or p-Pb [2]. The LHC heavy-ion program usually takes place in the last month of each operational year with the beams colliding in all four main experiments: ATLAS (IP1), ALICE (IP2), CMS (IP5), and LHCb (IP8). In 2023 the Pb-Pb run took place during the last five weeks of LHC operation, from September 21st to October 30th, at the unprecedented beam energy of 6.8Z TeV. It marked the first physics operation with heavy ions in Run 3 (2022-2025), since the 2022 ion run was cancelled and instead a two-day beam test [3] took place.

The 2023 ion run was the first one to include all foreseen ion upgrades for HL-LHC, and it relied on several new concepts [4–7]: slip-stacked 50 ns beams, crystal collimators, new orbit bumps in the interaction regions (IRs), IR2 and IR8, together with dispersion suppressor collimators (TCLDs) in IR2 to mitigate the risk of magnet quenches from beam losses caused by bound-free pair production [8], and the full β^*-squeeze was implemented in the energy ramp.

The optics in the 2023 ion run was very similar to 2018 [9], and the main parameters of the collision configuration [6] are shown in Table 1. The ± in the IP2 crossing angle shows the reversal of the ALICE spectrometer polarity halfway through the run [10, 11]. Table 2 lists the main operational filling schemes, with 50 ns bunch spacing. The baseline was to use 1240 bunches (b) with a mix of 56-b and 40-b trains, however, during the run, schemes with 1080b and 960b were introduced, using only 40-b trains, both to alleviate intensity-related beam losses and limitations on the injected intensity from protection devices as explained below.

Table 1: Collision Optics in 2023

Parameters	IP1/5	IP2	IP8
β^* [m]	0.5	0.5	1.5
External half crossing [μrad]	170	±170	−135
Net half crossing [μrad]	170	±98	−274

Table 2: Operational Schemes in the LHC 2023 Ion Run; the Last Three Columns Show Colliding Bunches per Experiment

Total bunches	Bunches/train	IP1/5	IP2	IP8
1240	56/40	1088	1088	398
1080	40	960	960	288
960	40	875	875	218

The new concepts were all deployed successfully resulting in a 27% peak intensity increase and a factor 6 higher peak luminosity at the ALICE experiment in IP2 [12]. More integrated luminosity could be collected by the LHC experiments than in any previous Pb ion run (about 2 nb^{-1} at ATLAS, ALICE and CMS, and 0.25 nb^{-1} at LHCb), in a total of 67 physics fills (numbered from fill 9192 and onward). Nevertheless, several unforeseen disruptive machine and beam-related challenges were encountered, without which the performance could have been higher [13]. Figure 1 provides an overview of the ion physics run, excluding the commissioning and starting from the first low-intensity physics run, with the various unforeseen events indicated in red. A short 4-day ramp-up was foreseen to reach full intensity, which, however, ended up requiring 12 days, firstly due to a 1.6-day mitigation campaign addressing unforeseen strong background observed in ALICE and, secondly, due to high transverse losses in the energy ramp causing beam dumps. Beam dumps were also caused by horizontal orbit oscillations in B1 at approximately 10 Hz as in 2018 [14]. Losses often occurred with the crystal collimators not in optimal channeling orientation. The 40b-filling schemes were introduced in an attempt to lower the total intensity, and hence the risk of beam dumps on losses, while providing a higher bunch intensity that would mitigate losses in peak luminosity. Furthermore, single event upsets (SEUs) on the quench protection system, likely due to radiation from collisions, led to further beam dumps and magnet quenches with a sometimes lengthy recovery. Those were partially mitigated through the introduction of luminosity levelling at 3.5×10^{27} cm^{-2}s^{-2}.

This paper provides a comprehensive analysis of the 2023 performance, with focus on intensity, luminosity, and the impact of the various problems, which are crucial inputs for future ions runs [13].

INTENSITY AND EMITTANCE ANALYSIS

Figure 2 shows the beam intensity per fill during the run as measured at different stages of the LHC cycle: start (light blue) and end (blue) of injection, and start of physics op-

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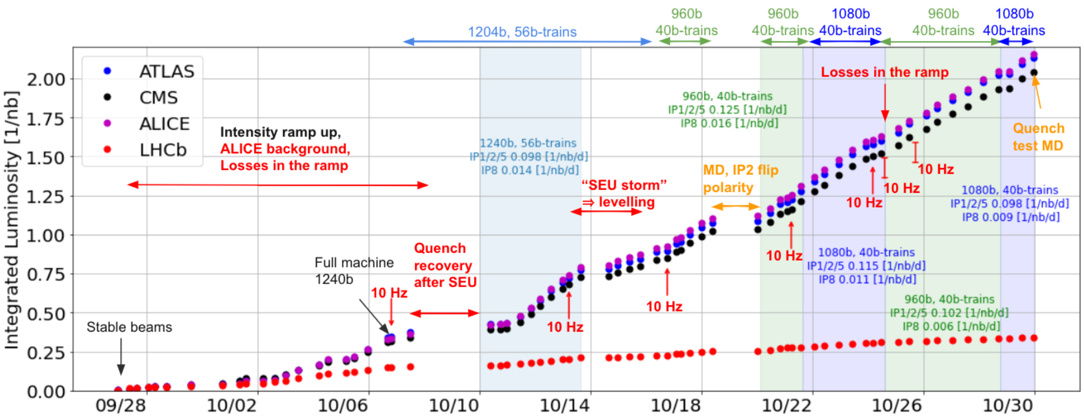

Figure 1: Evolution of the integrated luminosity per experiment during the 2023 ion run with main events noted. The shaded areas indicate periods of uninterrupted operation with the daily luminosity production also shown.

eration, referred to as stable beams (SB) (dark blue). The displayed values correspond to the average over all bunches in the machine. The shaded areas indicate the different filling schemes used. This analysis focuses on the 56-b (yellow) and 40-b (red) trains since the others were used for special fills beyond this study's scope.

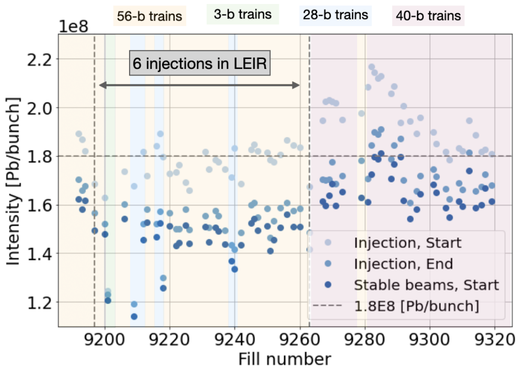

Figure 2: Measured bunch intensity to all 2023 physics fills at three different stages of the LHC cycle. Shaded areas indicate the different filling schemes used and 1.8×10^8 Pb/bunch is the LIU target [5]. Only B1 is shown, but B2 data are quantitatively similar.

Table 3 summarises the typical values of intensity, transmission, and nromalized RMS emittance for the 2023 ion run as obtained from measured data, averaged over all bunches of B1 and B2 and over respective fills with more than 900b (fills ≥ 9222). The average bunch intensity at the start of SB reached the target, 1.8×10^8 Pb ions, only in a few fills, where also the highest injected intensities of ~2.1-2.2×10^8 Pb/bunch was achieved. An increase of intensity at start of SB with the injected intensity is also observed [15]. The highest intensity loss is observed during the injection plateau, likely due to longitudinal losses out of the RF bucket caused by strong intrabeam scattering (IBS).

Comparing the fills with 56-b and 40-b trains, it is clear that the latter exhibited higher bunch intensities. However, this comparison is not fully conclusive because the injected intensity for 56-b trains was restricted by an interlock set at 1.9×10^8 Pb/bunch to protect an injection protection absorber operating in a degraded mode due to vacuum leaks [16, 17]. Because of that, the first circular accelerator in the ion injector chain, LEIR, took only 6 out of 7 injections from the LINAC in most fills with 56-b trains. The final impact of this is not yet fully understood, as comparison with data with 7 injections is very limited. The intensity constraints were partially alleviated by the use of shorter 40-b trains, for which the achieved intensity declined over time (fills > 9280) due to increased losses along the injector chain. Maintaining the maximum performance over time might therefore require more regular injector optimizations.

Table 3: Typical Parameters Measured in 2023

Parameters	**56-b trains**†	**40-b trains**
Intensity at injection [Pb/b]	1.78×10^8	1.97×10^8
Intensity at start SB [Pb/b]	1.49×10^8	1.67×10^{81}
Transmission injection-SB	0.84	0.86
Transmission ramp-SB	0.95	0.95
$\epsilon_{nx}/\epsilon_{ny}$, at start SB [µm]	2.26/1.74	2.23/1.68

† Computed from fills after more than 900b were established in the machine, fills ≥ 9222, with 6 injections in LEIR

Since the synchrotron light monitor typically used for emittance measurements was not calibrated for ions, the emittance values in Table 3 were instead computed using the beam size from the ATLAS luminous region, as provided and calibrated by the experiment, although they carry significant uncertainty. The obtained emittance was higher than the target value of 1.65 µm, primarily in the horizontal plane. Lastly, similar emittance values were observed for both 56-b and 40-b trains at the start of SB.

LUMINOSITY PERFORMANCE

During periods not affected by long faults, an average daily luminosity production of $\mathscr{L}_{\text{day}} \approx 100\,\mu\text{b}^{-1}$ was achieved

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at ATLAS, ALICE, and CMS, for all filling schemes (see Fig. 1), with an average of about 40 μb^{-1} per fill. In total, 1/3 of the time was spent in SB. Significant fluctuations in intensity and emittance not related to the beam type, makes it difficult to conclude on which scheme is best using only these data. Therefore, luminosity simulations were performed using the CTE program [18, 19], which tracks bunches of macro particles influenced by several physical effects such as betatron motion, IBS, luminosity, and radiation damping. The CTE simulations have been shown to give an excellent agreement with the measured evolution [19]. Here $20{\times}10^6$ macroparticles per beam were tracked for 10^5 turns, simulating 6 h of SB time as in typical fills, with initial conditions taken from Tables 1–3.

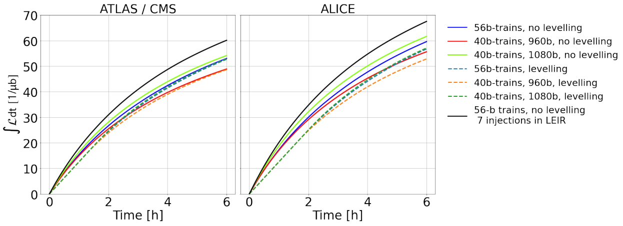

Figure 3: Luminosity evolution for different beam types as obtained with CTE simulations.

Figure 3 shows the simulated integrated luminosity over time for typical fills with 56-b and 40-b trains with (solid lines) and without (dashed lines) luminosity levelling at ALICE, ATLAS and CMS. The case with 56-b assuming all 7 injections in LEIR, resulting in $1.62{\times}10^8$ Pb/bunch at start of SB, was also simulated. This could be achievable if the intensity limits from losses in the ramp and injection absorbers are alleviated. The CTE simulations predict that the configuration giving the highest integrated luminosity is the 56-b trains when 7 injections can be taken in LEIR (black). Overall there is no major difference in luminosity evolution between the other schemes. The second best scheme seems to be the 40b-trains with 1080 bunches without leveling (light green). The lowest performance is predicted with 40b-trains with 960 bunches (red, orange). However, the highest instantaneous luminosity in 2023 was recorded with 960b, since, by chance, the injected beam quality was better. The levelling has no impact for ATLAS and CMS after 5-6 h, while there is ~ 2-4% loss for fills lasting less than 4 h. For ALICE a ~ 7-10% loss per fill is predicted even for 5 h fills.

PERFORMANCE IMPACT FROM OPERATIONAL CHALLENGES

In order to direct improvement efforts as efficiently as possible, we show in this section an approximate estimation of the performance impact from the encountered operational issues, as well as from the loss in beam quality, in terms of lost integrated luminosity. The loss due to luminosity leveling is computed as the difference between the levelled and unlevelled performance from the CTE simulations in Fig. 3, considering the actual duration of each 2023 fill. The performance loss due to lower intensity and larger emittance was taken as the difference between the simulated performance with ideal and achieved parameters [15] per fill for the achieved SB time independently of the other performance loss factors. For the other issues, the performance loss was calculated as $T_{\mathrm{lost}}\mathscr{L}_{\mathrm{day}}$, with T_{lost} being the time lost.

The results are shown in Fig. 4. In total, about 1.5 nb^{-1} more integrated luminosity might have been achieved without the encountered problems. The SEU and the sub-optimal beam quality at the start of SB are the dominating factors that affected the performance. ALICE seems to be affected the most, in particular from the leveling. Nevertheless, it is important to consider that the relationship between the different factors is very complex and that with the design beam parameters, various beam losses might have been higher.

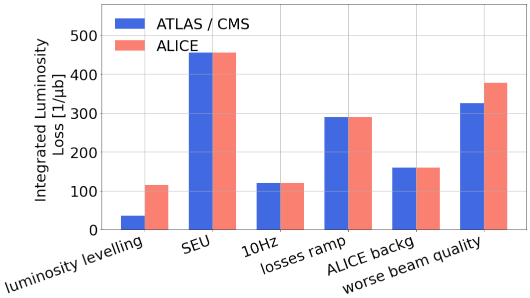

Figure 4: Main factors of performance loss in 2023.

SUMMARY AND OUTLOOK

The 2023 Pb-Pb run at the LHC relied on several new concepts that were successfully put in operation. Higher instantaneous and integrated luminosities were recorded than in any previous ion run. On average, luminosity production was constant at approximately 100 μb^{-1} per day, excluding long faults and intensity ramp-up. Nevertheless, the intensity and emittance goals were not met in most fills, and the collected luminosity could have been even higher in the absence of several unforeseen operational challenges and faults. Comparisons of achieved performance between 56-b and 40-b trains yielded inconclusive results due to limitations in injected intensity for most of the 56-b trains fills. However, simulations indicate that without the 2023 limitations on injected intensity, for which alleviation measures are being put in place, filling schemes using 56-b trains could deliver higher luminosity to all experiments. The primary factors contributing to performance loss were identified as SEU events and the sub-optimal beam quality, in particular the intensity. A campaign to mitigate SEU effects with hardware upgrades is ongoing [20]. Solutions to address the beam quality issues could include increasing intensity from the injectors, or mitigating the losses at the LHC injection plateau by increasing the RF voltage. Mitigation measures are under study also for the encountered limitations [13]. These results provide crucial inputs to guide the choice of machine configuration for optimizing integrated luminosity in the 2024 ion run and further future ion operation.

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