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THE 2018 HEAVY-ION RUN OF THE LHC

J.M. Jowett*, C. Bahamonde Castro, W. Bartmann, C. Bracco, R. Bruce, J. Dilly, S. Fartoukh,
A. Garcia-Tabares, M. Hofer, M.A. Jebramcik, J. Keintzel, A. Lechner, E.H. Maclean, L. Malina,
T. Medvedeva, T. Persson, B. Petersen, S. Redaelli, M. Schaumann, M. Solfaroli, R. Tomas,
J. Wenninger, J. Coello, E. Fol, N. Fuster-Martinez, E.B. Holzer, A. Mereghetti, B. Salvachua,
C. Schwick, M. Spitznagel, H. Timko, A. Wegscheider, D. Wollmann, CERN, Geneva, Switzerland
D. Mirarchi, University of Manchester, Manchester, UK

Abstract

The fourth one-month Pb-Pb collision run brought LHC Run 2 to an end in December 2018. Following the tendency to reduce dependence on the configuration of the preceding proton run, a completely new optics cycle with the strongest ever focussing at the ALICE and LHCb experiments was designed and rapidly implemented, demonstrating the maturity of the collider's operating modes. Beam-loss monitor thresholds were carefully adjusted to provide optimal protection from the multiple loss mechanisms in heavy-ion operation. A switch from a basic bunch-spacing of 100 ns to 75 ns was made as the beam became available from the injector chain. A new record luminosity, 6 times the original design and close to the operating value proposed for HL-LHC, provided validation of the strategy for mitigating quenches due to bound-free pair production (BFPP) at the interaction points of the ATLAS and CMS experiments. Most of the beam parameters of the HL-LHC Pb-Pb upgrade were attained during this run and the integrated luminosity goals for the first 10 years of LHC operation were substantially exceeded.

INTRODUCTION

From the first Pb-Pb collision run in late 2010, the LHC heavy-ion programme has evolved to include p-Pb runs and a short Xe-Xe run in 2017. Each run has been unique in terms of beam energy, colliding species, bunch filling schemes, beam optics and other collision conditions [1]. The 3rd Pb-Pb run in 2015 [2] saw the design luminosity, $L = 1{\times}10^{27}\,\mathrm{cm^{-2}s^{-1}}$, exceeded by a factor 3.6 at a new beam energy of 6.37 Z TeV, thanks to the high beam intensities delivered by the heavy-ion injector chain [3–5] and measures implemented to mitigate performance limits, mainly related to beam losses, in the LHC [6]. LHCb took its first Pb-Pb collisions at a lower luminosity.

The principal goals of the 4th Pb-Pb run in late 2018 were to complete the delivery of 1 nb^{-1} of luminosity to the ALICE, ATLAS and CMS experiments, substantially increase the luminosity for LHCb, and demonstrate the peak luminosity $L > 6.5 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ specified for future runs [1, 7, 8].

NEW OPTICS AND MAGNETIC CYCLE

Since 2010, when they were essentially identical [1, 9], the p-p and heavy-ion optics cycles used in a given year have steadily accrued their own specificities, including lower β^* at IP2 for heavy ions. Following the implementation of telescopic (ATS) collision optics for p-p in 2017 [10], the decision was taken, weighing commissioning time against cycle length, to fully decouple the two cycles, which now only share the injection conditions. The Pb-Pb cycle for 2018 aimed for the smallest ever β^* in ALICE and LHCb. The combined ramp and squeeze (CRS) [11] was redesigned, bringing β^* down to $\beta^* = (1, 1, 1, 1.5)$ m at IP1(ATLAS), IP2(ALICE), IP5(CMS) and IP8(LHCb), compared to $\beta^* = (1, 10, 1, 3)$ m at the end of the p-p ramp. After the CRS, a short squeeze segment (4.5 min) at constant energy was enough to establish the target collision configuration $\beta^* = (0.5, 0.5, 0.5, 1.5)$ m, keeping LHCb constant, while reducing β^* by a further factor of 2 in the other three experiments. Figure 1 shows the efficient timing of these two beam processes (CRS and squeeze at collision energy).

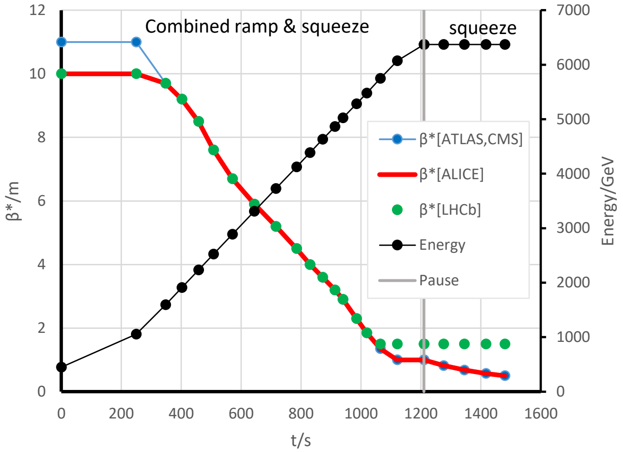

Figure 1: Timing structure of the CRS (left) and of the small squeeze segment at top energy (right) in terms of the β^* values at the experimental IPs. Changes of the multiple crossing-angle, separation and other orbit bumps are not indicated. Dots indicated fully matched two-ring optics.

The variously horizontal and vertical half-crossing angles in collision were brought to 160 µrad in ATLAS and CMS, θ_b −170 µrad in LHCb, and θ_A±137 µrad in ALICE, where θ_A =77 µrad and θ_b =−150 µrad are the angles generated by the internal spectrometer compensation bumps of ALICE and LHCb. The ALICE spectrometer polarity was reversed half-way through the run, requiring a passage of the external crossing angle through zero at the end of the squeeze. To reduce the associated risk, the horizontal separation was increased from 2 to 3 mm. As in 2015 [2], the ALICE interaction point was lowered by 2 mm.

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* john.jowett@cern.ch

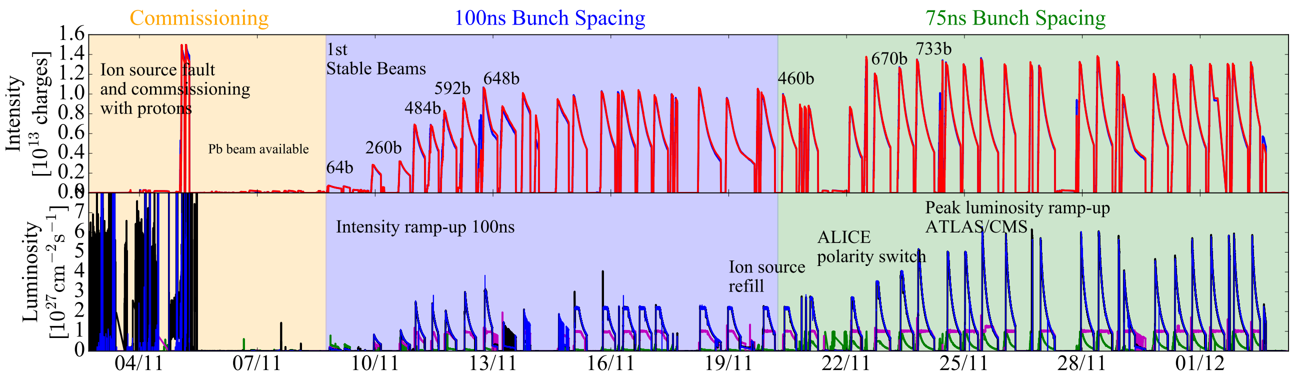
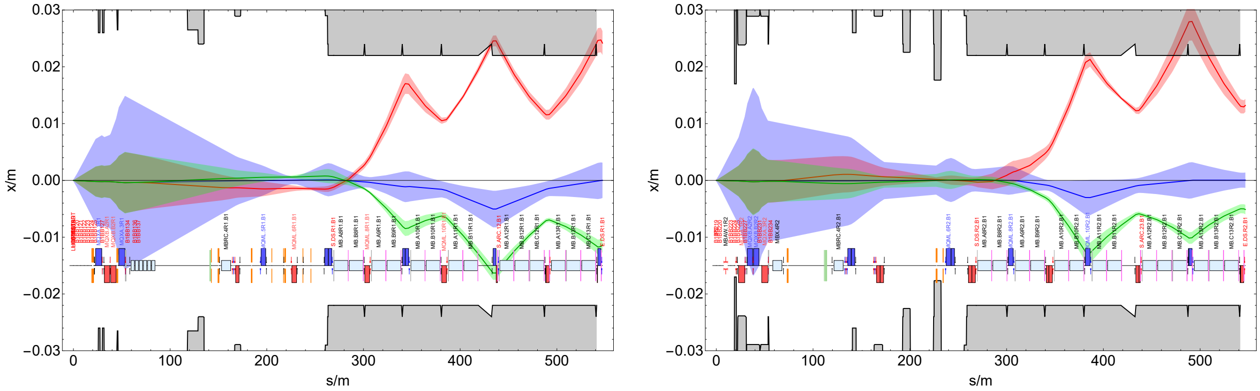
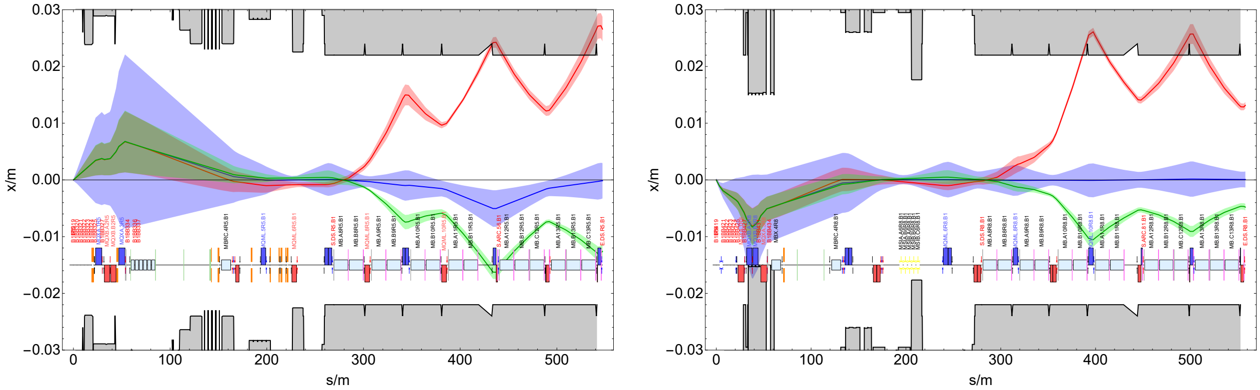


Figure 2: Evolution of the total beam charge ZN for Beam 1 (blue) and 2 (red) and luminosity of ATLAS (black), CMS (blue), ALICE (violet) and LHCb (green) throughout the 2018 run with major changes indicated. Spurious luminosity values have been filtered out from the logged data except during the initial commissioning period where proton beams were used for lack of Pb from the source. After recovery of the source, the number of bunches was increased from fill to fill in accordance with machine protection requirements. After the ALICE polarity reversal and correction of the betatron coupling at IP2, it was increased further with the transition from a basic bunch spacing of 100 ns to 75 ns implemented in the injectors [5]. During the physics fills both ALICE and LHCb were levelled at the design value 1×10^{27} cm^{-2}s^{-1}, by means of beam separation at the IP, while peaks of over 6.1×10^{27} cm^{-2}s^{-1} were reached in ATLAS and CMS.



IR1 far beyond quench level, mitigated by bump. *IR2 levelled below quench level, with bump.*



IR5 far beyond quench level, mitigated by bump. *IR8 levelled below quench level. No mitigation by bump.*

Figure 3: Calculated secondary beams from collisions in the four experiments. The 10σ main-beam envelope is shown in blue, and the 5σ BFPP and EMD secondary-beam envelopes are shown in red and green. Note that these beams are smaller than the main beam at the IP since their source is the luminous region but their size varies differently along the beam line because of chromatic effects. In IR1 and IR5 the orbit bumps displace the BFPP beam into the connection cryostat, allowing luminosity, 6.1×10^{27} cm^{-2}s^{-1}, far beyond the quench level, 2.4×10^{27} cm^{-2}s^{-1} found in 2015 [6]. In IR2 the luminosity is levelled at 1×10^{27} cm^{-2}s^{-1}, the design and present saturation value of the ALICE detector, but the risk of quenches is further mitigated with a bump that distributes the losses between two locations [6, 19]. In IR8 no mitigation was implemented but the luminosity was levelled at 1×10^{27} cm^{-2}s^{-1}.

COMMISSIONING AND OPERATION

Starting with a few shifts in advance of the heavy-ion run, optics measurement and correction [12] with low-intensity proton beams converged rapidly. Figure 2 provides an outline of the course of the one-month Pb-Pb run itself. Because of a fault in the ion source, protons had to be used to advance commissioning for longer than planned in the first few days. When Pb beams became available, the delicate optimisations of the collimation set-up [13] and the BFPP orbit bumps [6] in collision conditions, could proceed. Final validation of the definitive collision configuration for machine protection was then possible. During the week of source recovery, the quality of the Pb beam was degraded, resulting in lower beam intensity, longer turn-around time, shorter levelling periods and less time in physics.

Despite the apparent soundness of the optics corrections, the luminosity in ALICE was initially about 50% less than expected. After eliminating other possible explanations (waist shift, spurious dispersion, etc.), the local betatron coupling at IP2 was varied using a knob developed for flat-optics experiments [14], consisting of anti-symmetric excitations of skew quadrupole correctors around IP2. This induced a local coupling "bump", maximal at the IP and invisible in terms of observables such as local and global coupling resonance driving terms. A setting was found that restored the luminosity, cancelling what turned out to be an erroneous swap of the skew corrector settings in the set-up phase [15]. The correction was introduced with the re-validation of the configuration for the second half of the run with reversed polarity of the ALICE spectrometer.

Luminosity, levelling duration and fill length in the second half also benefited from increased bunch intensity and number of bunches thanks to the implementation of a filling scheme with a basic bunch spacing of 75 ns in the injectors [3–5]. This filling scheme also created many more bunch encounters at LHCb. Fills were generally kept until luminosity could no longer be levelled in ALICE.

BEAM LOSSES, MACHINE PROTECTION

In the LHC itself, beam intensity is limited, and fills sometimes dumped prematurely by losses. Collimation efficiency is lower than for protons due to nuclear reactions occurring in collimators [13, 16]. The hierarchy of dump thresholds of the beam-loss monitors (BLMs) in the collimation insertion IR7 were adjusted to the new magnetic cycle and the quench level with nuclide loss patterns [13, 16, 17].

Luminosity is limited by the secondary beams created by the BFPP and electromagnetic dissociation (EMD) processes at the IPs [6,18,19]. At the peak luminosity achieved in 2018, four tightly focused BFPP secondary beams emerging from IP1 and IP5 each carried over 140 W of $^{208}\text{Pb}^{81+}$ ions. Magnet quenches were avoided by the implementation of orbit bumps as described in [6, 20] and Fig. 3. Beam dumps and quenches were avoided by a detailed optimisation of BLM thresholds in the impact regions. In IR8, where no bump mitigation was possible, the quench detection threshold and evaluation time were lowered to increase the protection level in the Q10 quadrupoles in case of symmetric quenches.

Table 1: Key beam parameters at the start of the highest luminosity physics fills in 2015 and 2018 compared with design values [21]. Peak luminosities are averages for ATLAS and CMS, ALICE being levelled at the design value.

Quantity	Design	Achieved	
Year		2015	2018
Weeks in physics	-	2.5	3.5
Fill no. (best)		4720	7473
Beam energy $E\,[A\,\text{TeV}]$	2.76	2.51	
Collision energy $\sqrt{s_{\text{NN}}}$ [TeV]	5.52	5.02	
Bunch intensity N_b [10^8]	0.7	2.0	2.2
No. of bunches k_b	592	518	733
Norm. emittance ϵ_N [μm]	1.5	2.1	2.0
β^* [m] (IP1/5)	0.55	0.8	0.5
Stored energy MJ/beam	3.8	8.6	13.3
Luminosity $L\,[10^{27}\text{cm}^{-2}\text{s}^{-1}]$	1	3.6	6.1

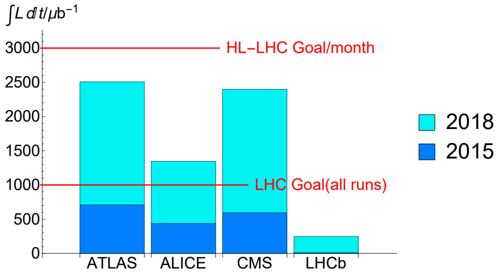


Figure 4: Integrated Pb-Pb luminosity for each experiment in 2015 and 2018, compared to the initial LHC Goal for all runs until now and the goal for each 1-month run at the future "HL-LHC".

SUMMARY AND OUTLOOK

The peak luminosity of the ALICE experiment was always levelled at the saturation luminosity of $1 \times 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$ and its integrated luminosity in 2018 was equivalent to spending 10.4 days, continuously at this constant luminosity.

Apart from the number of bunches, k_b, which awaits the implementation of slip-stacking in the SPS [22], all the "HL-LHC" upgrade parameters (compare Table 1 with Table 1 in [1] and [7, 8]) were very close to being achieved by the end of the 2018 run. In future, the upgraded ALICE will accept similar luminosity to ATLAS and CMS.

Figure 4 shows that, despite the limitations during the first half of the run, the integrated luminosity achieved in 2018 was already comparable to the goal for future "HL-LHC" operation. This establishes the 75 ns filling scheme as a backup for the 50 ns scheme that should be enabled by slip-stacking in the SPS [5, 22].

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