THE 2015 HEAVY-ION RUN OF THE LHC

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Abstract

In late 2015 the LHC collided lead nuclei at a beam energy of $6.37Z$ TeV, chosen to match the 5.02 TeV per colliding nucleon pair of the p-Pb collision run in 2013. In so doing, it surpassed its design luminosity by a factor of 3.6. In 18 days of operation for physics, integrated luminosities of up to $0.7\,\mathrm{nb}^{-1}$ per experiment were produced. Besides the higher energy, the operational configuration had a number of new features with respect to the previous Pb-Pb run at $3.5Z$ TeV in 2011: unusual bunch patterns providing collisions in the LHCb experiment for the first time, luminosity levelling and sharing requirements, a vertical displacement of the interaction point in the ALICE experiment, and operation closer to magnet quench limits with mitigation measures. We present a summary of the commissioning and operation and what has been learned in view of future heavy-ion operation at still higher luminosity.

INTRODUCTION

The first run colliding Pb nuclei ($Z = 82$, $A = 208$) at almost the full LHC energy was shortened by a week to collect a reference sample of p-p ($Z = A = 1$) collisions. The set-up of this proton run was interleaved with the commissioning steps for the Pb-Pb run but we shall not discuss it further here. In these runs, the Pb beam energy was reduced slightly, and the proton energy considerably, from their potential $6.5Z$ TeV to obtain the same nucleon-nucleon centre-of-mass energy $\sqrt{s_{\rm NN}} = 2\sqrt{Z_1 Z_2/A_1 A_2}E_p$, where $E_p = E_b/Z$ is the energy of a proton, as in the p-Pb run in 2013 [1]. Table 1 summarises the energies and final integrated nucleon-nucleon luminosities that will allow precise comparison, at equivalent energies, of the phenomena occurring in nuclear systems of ascending complexity.

Table 1: LHC runs at $\sqrt{s_{\rm NN}} = 5.02$ TeV and integrated nucleon-nucleon luminosity $\mathcal{L}_{\rm NN} = A_1 A_2 \int L\,dt$ (values are given for the ATLAS experiment and L is the nucleus-nucleus luminosity).

Run start	Species	E_b/ TeV	$\sqrt{s}$/ TeV	$\mathcal{L}_{\rm NN}/\mathrm{pb}^{-1}$
Nov 2015	p-p	2.51	5.02	28
Jan 2013	p-Pb	4.00 Z	72.4	6.4
Nov 2015	Pb-Pb	6.37 Z	1045	30

With the Pb-Pb collisions, the LHC established a new world-record nuclear collision energy by packing a total $\sqrt{s} = 2E_b > 1$ PeV into a volume of a few fm^3.

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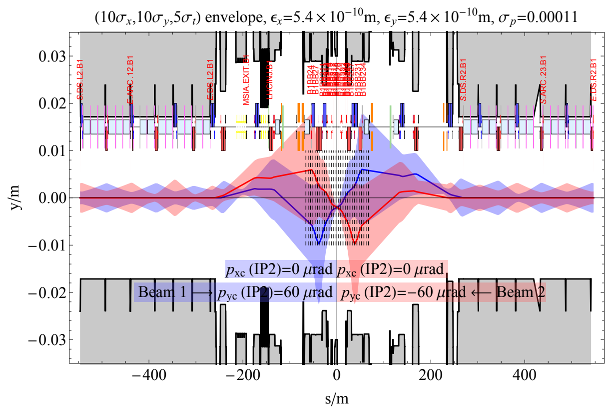

Figure 1: Vertical beam envelopes around the ALICE experiment in physics conditions with spectrometer bump angle $-77\,\mu$rad, external bump $+137\,\mu$rad for Beam 1.

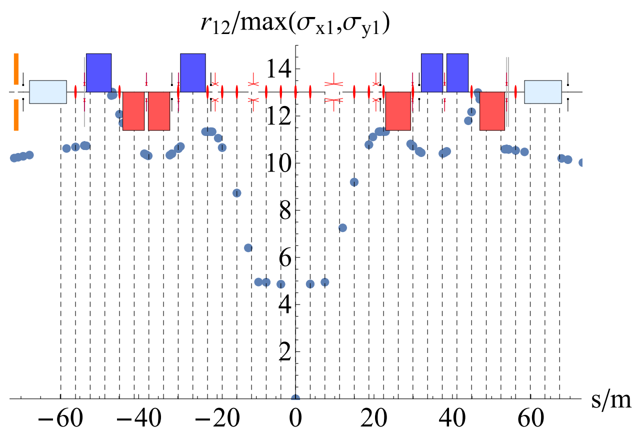

Figure 2: Beam-beam separation in units of the larger horizontal/vertical beam size close to ALICE. Vertical lines represent possible encounter points.

Although the values of crossing angles and $\beta^* = (0.8, 0.8, 3)$ m in the ATLAS, CMS and LHCb experiments, were carried over from the preceding p-p run [2], substantial changes to the LHC optics and magnetic cycle (itself changed from 6.5 to $6.37Z$ TeV) had to be implemented. A parallel squeeze to $\beta^* = 0.8$ m for the ALICE experiment had to be started earlier in order to terminate at the same time as that of the other experiments. The collision point in ALICE had to be lowered by 2 mm to partially compensate a sinking of the experiment. Together with the compensation of the ALICE spectrometer dipole and the usual constraints on the crossing angle to allow spectator neutrons to reach the zero degree calorimeter, this resulted in a complex superposition of orbit bumps around IP2 (Fig. 1) and parasitic beam-beam encounters with separations of order 4σ (Fig. 2).

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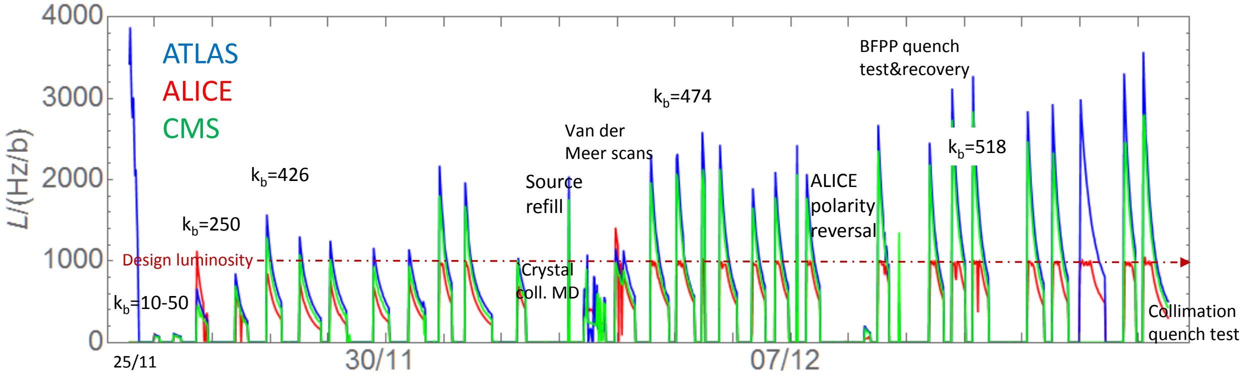

Figure 3: Luminosity for 3 of the 4 experiments, during the 2015 Pb-Pb run showing the progressive increase of stored bunch number k_b and the various interruptions of regular data-taking. The dashed line shows the design luminosity [3].

Further orbit bumps were implemented in the dispersion suppressors around the experiments to mitigate the risk of magnet quenches from the bound-free pair production (BFPP) process, long foreseen as the major Pb-Pb luminosity limit at the LHC [3,4]. They later proved to be essential to avoid limiting luminosity for ATLAS and CMS. This major topic, including the first successful steady state quench test of an LHC magnet, is discussed in a companion paper [5].

After implementation, measurement and correction of the new optics and orbit, partly with proton beams, first Pb-Pb collisions were found on 18/11/2016, some 10 hours after the first injection of Pb beams and still before the main p-p reference data-taking. A few days later a number of shifts were devoted to aperture measurements, collimator set-up and loss maps [6], and other operations required to validate the protection status of the machine. Finally stable beams for Pb-Pb physics were declared on 25/11/2016. In subsequent fills the number of stored bunches was increased through a sequence prescribed by machine protection (Tab. 2) to the foreseen maximum of $k_b = 426$.

This left some 18 days of the 4 weeks scheduled for heavy-ion physics from the first declaration of "Stable Beams" for physics data-taking. As can be seen in Fig. 3, this period was further interrupted by a refill of the ion source, Van der Meer scans, a reversal of the ALICE spectrometer polarity and studies of crystal collimation, and quench tests using BFPP [5] and collimation losses [7].

Once design luminosity (1×10^{27} cm^{-2}s^{-1}) was reached, the ALICE experiment could run in its saturation mode with luminosity levelled at that value by adjusting the horizontal separation between the bunches. Levelling was also employed briefly in ATLAS and CMS but only for reasons of equitable luminosity-sharing. The LHCb experiment took Pb-Pb collision data for the first time at a lower luminosity.

Initially, the trains of bunches injected from the SPS had an alternating 100/225 ns spacing (see also [8]). Thanks to a progressive reduction of the SPS injection kicker rise time [9], it turned out to be possible to achieve a 100/150 ns spacing and further increase the number of bunches in the latter part of the run (Fig. 3, Table 2).

The run concluded with a second successful quench test, this time using collimation losses [7].

Table 2: Filling schemes used, with the SPS kicker rise time, T_k/ns, total number of bunches $k_{b1,2}$ in each beam and the number of colliding bunch pairs k_c in the experiments.

T_k	$k_{b1,2}$	$k_{c1,5}$	k_{c2}	k_{c8}
225	48	24	24	24
225	250	216	236	24
225	426,424	400	362	24
175	474	424	430	24
150	518,516	492	444	24

BEAM PARAMETERS

A large spread in bunch intensities and other parameters due to beam losses in the injectors are characteristic of the LHC heavy-ion runs [1,8,10,11,13]. The substantial performance gains since 2011 due to the injectors are clear from Fig. 4.

Table 3: Average beam parameters in fill 4720 (the last in 2015). Emittances $\varepsilon_{n(x,y)}$ are normalised values from synchrotron light monitors.

Fill number	4720
Ions per bunch N_b	$(1.96 \pm 0.20) \times 10^8$
Bunches colliding in IP1/5 k_{c5}	492
Bunch length σ_z	9.2 ± 0.3 cm
$\varepsilon_{n(x,y)}$ (Beam 1/2)	$(2.08, 1.15) \pm 0.2$ μm

The record luminosity reported by the 4 experiments was obtained in fill 4720 with the parameters shown in Table 3 and Fig. 5. The intensities along the train and how they were transmitted from injection to physics conditions can also be seen. Note that this fill allowed ALICE to be levelled for nearly 4 hours and was kept longer than would be optimal had it not been the last fill of the run.

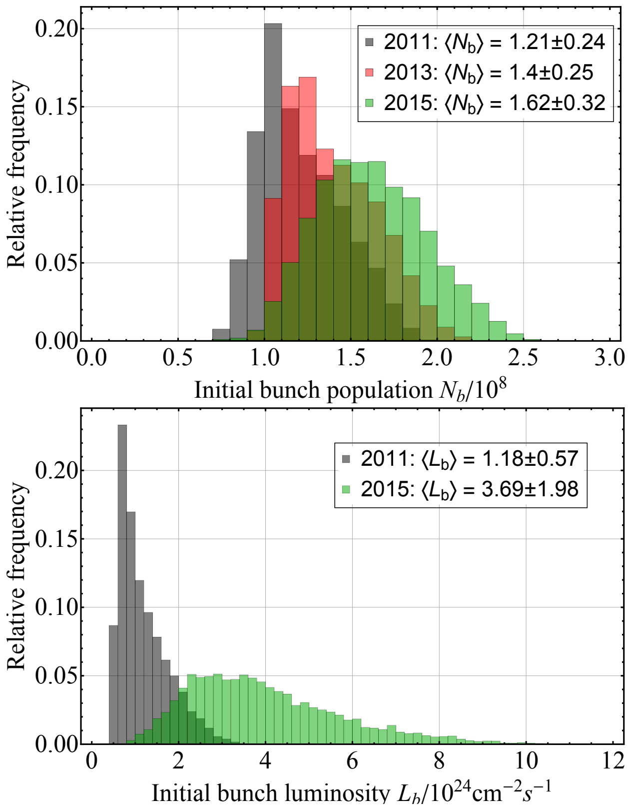

Figure 4: Top: Distribution of bunch populations at the start of collisions over all Pb-Pb fills in 2011 and 2015 and all p-Pb fills in 2013. Bottom: Distribution of initial bunch pair luminosities over all Pb-Pb fills in 2011 and 2015.

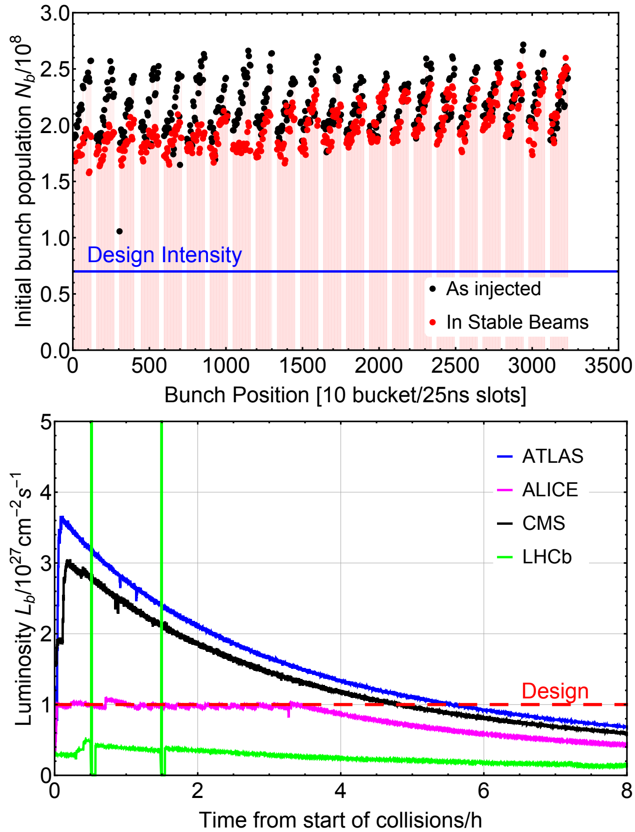

Figure 5: Bunch populations at injection and start of collisions (top) and luminosity evolution (bottom) in fill 4720 (the LHCb luminosity contains two unphysical glitches).

CONCLUSIONS

Figure 6 summarises the accumulation of integrated luminosity in all the LHC Pb-Pb and p-Pb runs to date [1, 12, 13].

After a total of 12 weeks operation since 2010, the LHC has now substantially surpassed its design Pb-Pb luminosity [3], at close to design energy, and is on course to fulfil the integrated luminosity goal of 1 nb^{-1} (or $\mathcal{L}_{\mathrm{NN}} = 43\,\mathrm{pb}^{-1}$, c.f., Fig. 6) set for its first decade of operation. Note that a p-Pb run is scheduled for 2016 and a Pb-Pb one for 2018.

Firm foundations have been laid for the upgraded heavy-ion performance required by the experiments in the 2020s [14]. Indeed about 35% of this “HL-LHC” Pb-Pb performance is already in hand.

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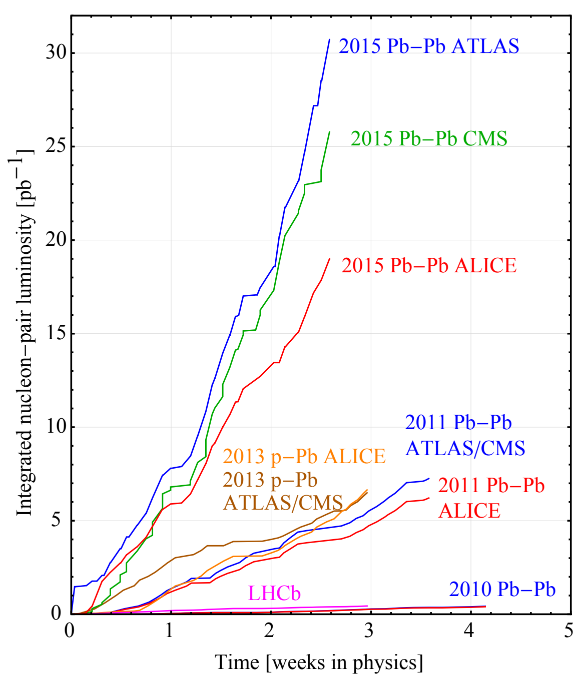

Figure 6: Nucleon-nucleon integrated luminosity in each experiment in all LHC heavy-ion runs to date [1, 12, 13], from the first declaration of Stable Beams.

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