

# THE 2016 PROTON-NUCLEUS RUN OF THE LHC

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## Abstract

For five of the LHC experiments, the second p-Pb collision run in 2016 offered the opportunity to answer a range of important physics questions arising from the surprise discoveries (e.g., flow-like collective phenomena in small systems) made in earlier Pb-Pb, p-Pb and p-p runs. However the diversity of the physics and their respective capabilities led them to request very different operating conditions, in terms of collision energy, luminosity and pile-up. These appeared mutually incompatible within the available one month of operation. Nevertheless, a plan to satisfy most requirements was developed and implemented successfully. It exploited different beam lifetimes at two beam energies of 4 Z TeV and 6.5 Z TeV, a variety of luminosity sharing and bunch filling schemes, and varying beam directions. The outcome of this very complex strategy for repeated re-commissioning and operation of the LHC included the longest ever LHC fill with luminosity levelled for almost 38 h. The peak luminosity achieved exceeded the "design" value by a factor 7.8 and integrated luminosity substantially exceeded the experiments' requests.

## INTRODUCTION

As explained further in [1], asymmetric collisions of  $^{208}\text{Pb}^{82+}$  nuclei with protons were not included in the LHC design. Following first studies that indicated their feasibility [2], the physics case [3] was based on a luminosity  $L = 1.15 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$  at a beam energy  $E_b = 7 \text{ Z TeV}$ . We refer to these as the "design" parameters as they were determined similarly to those of p-p and Pb-Pb collisions.

After the short—but significant—pilot physics run in 2012 [4] and the first full one-month run in early 2013 [1], during which the design luminosity was attained at the lower energy of  $E_b = 4 \text{ Z TeV}$ , the second full proton-nucleus run of the LHC took place in late 2016. This paper provides an outline summary of the course of this run, which will be further analysed in future publications.

Increased performance of the heavy-ion injectors, even beyond what was achieved in the 2015 Pb-Pb run [5], was crucial to the success of the 2016 p-Pb run and is described in more detail in a separate paper [6].

Among the essential new features of operation with asymmetric collisions in the LHC are the difference in revolution and RF frequencies during injection and ramp and the "cogging" process that equalises them. During "cogging" the beams are pushed transversely, onto opposite-sign off-momentum orbits, and longitudinally, to restore collisions at the proper interaction points (IPs) after their rotation around

the ring during the energy ramp [1,2]. The colliding bunches have different sizes and charges. Moreover, the generation of the beams from the separate proton and heavy-ion injectors leads to complex bunch filling schemes in the LHC rings. Some of the consequences are discussed in [7].

The requests for physics conditions put forward by the LHC experiments at the start of 2016 were quite different:

- ALICE put a strong priority on further data for high-precision measurements at  $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ , the same centre-of-mass energy per colliding nucleon pair as in the p-Pb run of 2013 [1] and the Pb-Pb and reference p-p runs of 2015 [5] (corresponding to a p or Pb beam energy  $E_b = 4 \text{ Z TeV}$ ). The luminosity was to be levelled to the maximum acceptable value  $L \simeq 0.5 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}$  for minimum-bias data-taking.
- ATLAS and CMS, on the other hand, requested the maximum energy,  $E_b = 6.5 \text{ Z TeV} \Rightarrow \sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$ , and maximum luminosity  $L > 1 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ .
- The asymmetric LHCb experiment, which joined the heavy-ion programme in 2012, asked for more luminosity than in the 2013 run at the higher energy, combined with a beam reversal to access different rapidity ranges. ALICE also had interest in a similar dataset.
- The LHCf experiment, located on the Beam 1 downstream side of IP1, requested a short low-luminosity run at the higher energy, with protons specifically in Beam 1, for cosmic ray studies.

A plan was proposed that could potentially satisfy all these apparently incompatible requirements within the one-month time-frame allotted to heavy-ion physics in 2016. After a period of negotiation, establishing compromises and re-prioritisations that might be adopted if time was lost, it was adopted and approved. The following sections outline how it worked, how it was implemented and the results. It involved three main set-ups for physics with different energies, beam optics and beam directions.

In each case, as in 2015 [5], the ALICE interaction point had to be displaced vertically by  $-2 \text{ mm}$  and the beam crossing angle minimised to ensure a clear path to ALICE's Zero-Degree Calorimeters for spectator neutrons.

## OPERATION AT $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

A few days of initial set-up, included measurement and correction of a new optics [8], in which only the ALICE experiment was squeezed to  $\beta^* = 2 \text{ m}$ , set up of collimators and validation (via collimation loss maps and asynchronous beam dumps). Then physics data-taking started with ALICE

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Table 1: Average initial values of representative beam parameters in fill 5513 at  $\sqrt{s_{NN}} = 5.02$  TeV, throughout which luminosity was levelled at a constant value in ALICE (IP2).

$\beta^*$ in IP1/5, 2, 8	(11, 2, 10) m
No. of p, Pb bunches	702, 548
Protons/bunch	$2.2 \times 10^{10}$
Pb/bunch	$1.8 \times 10^8$
Collisions in IP1/5, 2, 8	81, 389, 54
$\varepsilon_{n(x,y)}$ (p/Pb)	$(1.4 \pm 0.2, 1.6 \pm 0.2) \mu\text{m}$
Luminosity at IP2	$1 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}$
Stable beams duration	14.9 h

alone and levelled luminosity. Although the fractional rigidity shifts of the p/Pb beams  $\delta = \pm 2.3 \times 10^{-4}$  were the same as in 2013 [1], the reduced chromaticity of the optics meant that the special  $\beta$ -beating corrections implemented then [9] could be skipped, shortening the set-up time. The ALICE squeeze was implemented during the energy ramp, a further gain of time in the set-up and every fill thereafter. The second fill, no. 5506, of the intensity ramp-up prescribed for reasons of machine protection, collided 252 proton bunches with 196 Pb bunches in ALICE alone. It demonstrated the key principle of the strategy: the low intensity burn-off in ALICE meant that the luminosity lifetime could be kept infinite for many hours, allowing for very long fills and unprecedented operational efficiency. The beams were kept colliding at the constant levelled luminosity for 37.8 h, the longest ever fill of the LHC. At that point they were dumped to refill with more bunches and allow the other experiments join in the data-taking. Later fills (see Table 1) for an example) could have been held at constant luminosity for several days but were interrupted by various external contingencies. In the week spent at this energy, the LHC was in "Stable Beams" for more than 75% of the time.

All experiments took data, with a gas-jet target in the case of LHCb.

## OPERATION AT $\sqrt{s_{NN}} = 8.16$ TeV

The high operational efficiency at 5.02 TeV, together with a number of shortcuts and optimisations carefully worked into the commissioning plan, meant that enough time was left to re-commission and deliver physics data at 8.16 TeV, not once but twice, for each direction of the beams. A new optics had to be commissioned with  $\beta^*$  squeezed to low values in ATLAS, CMS and LHCb (the latter further than ever before, see Table 2). Despite this, the lower fractional rigidity shifts at the higher energy,  $\delta = \pm 8.8 \times 10^{-5}$ , allowed the special chromatic correction to be skipped again.

### *p-Pb*

The high-energy run started with protons in Beam 1, Pb in Beam 2. Part of the optics commissioning and correction had been done earlier but a complete set of collimation loss maps and asynchronous dumps had to be carried out to validate the configuration. The high luminosities in ATLAS and

Table 2: Average initial values of peak beam parameters in fill 5559 at  $\sqrt{s_{NN}} = 8.16$  TeV, Pb in Beam 1, p in Beam 2, used for luminosity calibration (van der Meer) scans.

$\beta^*$ in IP1/5, 2, 8	(0.6, 2, 1.5) m
No. of p, Pb bunches	684, 540
Protons/bunch	$2.8 \times 10^{10}$
Pb/bunch	$2.1 \times 10^8$
Collisions in IP1/5, 2, 8	405, 351, 251
$\varepsilon_{n(x,y)}$ (p/Pb)	$(1.3 \pm 0.2, 1.6 \pm 0.4) \mu\text{m}$
Luminosity at IP1/5	$8.9 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1}$
Stable beams duration	2.5 h

CMS reduced the luminosity lifetime [7] and fills became much shorter with a larger fraction of the time spent in the turn-around between fills.

Several different filling schemes were used to optimise the distribution of luminosity among the experiments, resulting in quite different lifetimes among the Pb bunches and some difficulties in the use of the fast beam current transformers as some bunches fell out of the operational dynamic range.

The experience of the 2013 run, had been that a few bunches fell below a visibility threshold of dedicated beam-position monitors (BPMs) interlocked to the beam dump system. Most fills in 2013 were dumped by triggers of this interlock. In anticipation of this, a modification involving amplification of the signals from these BPMs was prepared. However the spread of bunch intensities in 2016 remained within bounds and the amplifiers turned out to be unnecessary.

The p-Pb phase was terminated once the integrated luminosity goal of  $50 \text{ nb}^{-1}$  had been reached, to allow time for physics after beam reversal. The last fill was dedicated to the LHCf experiment, which shares collisions at IP1 with ATLAS. It had requested a low luminosity with many bunches colliding to achieve a low pile-up. This proved possible at the same time as minimum bias data-sets were delivered to ATLAS and CMS and regular luminosity to LHCb.

### *Pb-p*

Reversal of the beams, as requested by the asymmetric experiments LHCb and ALICE, required the commissioning of a third configuration. Validation steps and intensity ramp-up had to be repeated as collimation loss maps for proton and Pb beams [10] are quite different. However physics data-taking resumed rapidly and the integrated luminosity quickly caught up with what had been accumulated in p-Pb mode.

In all p-Pb operation so far, the intensity of the proton beams had to be restricted to values  $N_b \leq 5 \times 10^{10}$  to allow the stripline BPMs, common to both beams, to operate in the low dynamic range required to measure the Pb beams of charge  $ZN_b \approx 1.5 \times 10^{10}$ . More specifically, those BPMs, could return false data because of the varying passage times of bunches of the two beams with too different charges. At this point in the run, a new synchronous orbit mode of

Table 3: Datasets, both primary and additional goals, delivered in the 2016 p-Pb run

$\sqrt{s_{NN}}$	Experiments	Primary goal	Achieved	Additional
5.02 TeV p-Pb	ALICE	$7 \times 10^8$ min. bias events	$7.8 \times 10^8$	$> 0.4 \text{ nb}^{-1}$ min. bias SMOG p-He, etc.
	ATLAS, CMS LHCb			
8.16 TeV p-Pb <i>or</i> Pb-p	ATLAS, CMS	$100 \text{ nb}^{-1}$	194, 183 $\text{nb}^{-1}$	
8.16 TeV p-Pb	ALICE, LHCb	$10 \text{ nb}^{-1}$ (9–12 h) $\times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$	14, 13 $\text{nb}^{-1}$ 9.5 h	min. bias
	LHCf ATLAS, CMS, ALICE			
8.16 TeV Pb-p	ALICE, LHCb	$10 \text{ nb}^{-1}$	25, 19 $\text{nb}^{-1}$	

these BPMs, gating the signals to avoid measurements when bunches of the two beams passed through a BPM too close together in time, was implemented and successfully removed this restriction.

A first step in increasing the proton intensity, operating in this new BPM mode, allowed the luminosity to soar to a new record, some 7.8 times beyond the design value (see Table 2). Unfortunately the high level of luminosity debris from fragments of the Pb beam, being lost at the start of the dispersion suppressor right of IP1, risked exceeding beam dump thresholds. The thresholds here were lower than elsewhere because it was imperative to avoid quenches in that sector, which contained a dipole magnet with a suspected short-circuit in its coils. In the last few days of the run, when it was no longer possible to attempt a re-optimisation of the appropriate collimator settings, the luminosity therefore had to be restrained for machine protection reasons.

Finally, the high luminosity accumulated in the Pb-p mode allowed a return to 5.02 TeV operation to top up ALICE's minimum bias dataset on the last day.

## CONCLUSIONS

Table 3 and Figure 1 show that all primary goals of the run were surpassed (very substantially in the case of high luminosity operation at the higher energy) and that opportunities were taken to deliver further useful datasets parasitically.

More generally, this run showed that the LHC is capable of far more than its designers dreamed.

With a total of only 8 weeks operational experience, the luminosity with asymmetric proton-nucleus collisions has reached almost 8 times the design and could already go further. The long-term integrated luminosity goal of  $100 \text{ nb}^{-1}$  from [3] has been surpassed in some experiments. However this was the last p-Pb run for several years. In the interregnum before the next, the number and intensity of Pb bunches for Pb-Pb collisions should increase substantially [6, 11–13]. When p and Pb collide again, one can reasonably hope to better manage the Pb luminosity debris, increase the proton bunch intensity further and deliver a few times more integrated luminosity than in 2016 (in a similar time).

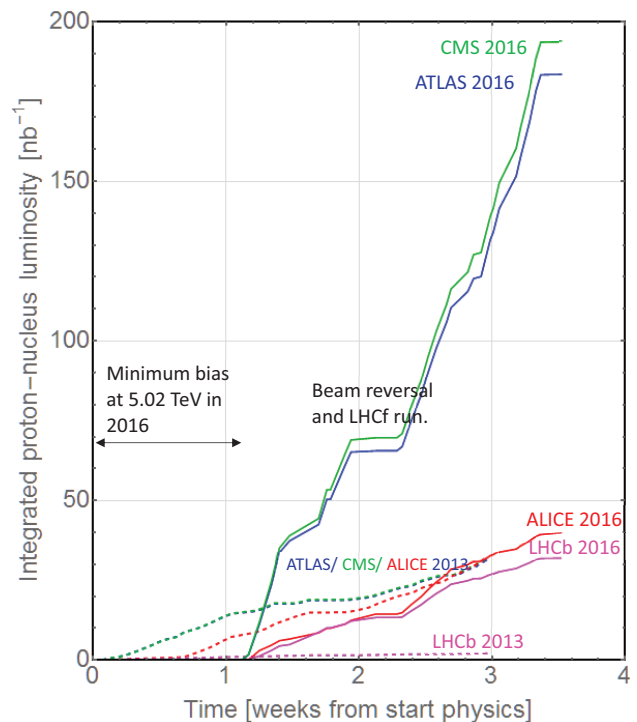


Figure 1: Accumulation of integrated luminosity in each LHC experiment in the p-Pb runs of 2013 [1] and 2016, counted from the first declaration of Stable Beams.

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