PROTON-NUCLEUS COLLISIONS IN THE LHC

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Abstract

Following the high integrated luminosity accumulated in the first two Pb-Pb collision runs in 2010 and 2011, the LHC heavy-ion physics community requested a first run with p-Pb collisions. This almost unprecedented mode of collider operation was not foreseen in the baseline design of the LHC whose two-in-one magnet design imposed equal rigidity and, hence, unequal revolution frequencies, during injection and ramp. Nevertheless, after a successful pilot physics fill in 2012, the LHC provided $31\,\mathrm{nb}^{-1}$ of p-Pb luminosity per experiment, at an energy of $5.02\,\mathrm{TeV}$ per colliding nucleon pair, with several variations of the operating conditions, in early 2013. Together with a companion p-p run at 2.76 TeV, this was the last physics before the present long shutdown. We summarise the beam physics, operational adaptations and strategy that resulted in extremely rapid commissioning. Finally, we give an account of the progress of the run and provide an analysis of the performance.

INTRODUCTION

Equal-rigidity D-Au acceleration at RHIC (a double-ring collider) was dropped in favour of equal-revolution frequency acceleration because “modulated long-range beam-beam forces created untunable beam loss” [1] during injection and energy ramp. Since the equal-frequency option is not available to the LHC (a single ring of “2-in-1” magnets) doubts were long extant as to whether the LHC would ever deliver p-Pb collisions, a crucial component of the experiments’ heavy-ion physics programme.

Nevertheless, feasibility was first considered in [2,3], leading to a detailed articulation of the physics case [4]. With the prospect of $>50\,\mu\mathrm{b}^{-1}$ of Pb-Pb luminosity in 2011 ($>150\,\mu\mathrm{b}^{-1}$ in later fact), the pressing need for comparison data led to adoption, subject to experimental demonstration, of p-Pb collisions as part of the LHC programme at [5,6].

Equalising the revolution frequencies forces the beams onto off-momentum orbits with rigidity shifts δ [3]:

$$\delta_{\mathrm{p}} - \delta_{\mathrm{Pb}} \simeq \frac{c^2 \gamma_T{}^2}{2 p_{\mathrm{p}}^2} \left(\frac{m_{\mathrm{Pb}}^2}{Z_{\mathrm{Pb}}^2} - m_{\mathrm{p}}^2 \right), \qquad \delta_{\mathrm{p}} \geq -\delta_{\mathrm{Pb}} \geq 0 \qquad (1)$$

where γ_T is the usual transition energy factor, p_p the proton momentum and Z, m the particle charge and mass. At the collision energy, $E = 4Z$ TeV, the separation of the orbits, $\Delta x_c = 0.6$ mm $(\Delta f_{\mathrm{RF}} = 60$ Hz$)$, in the arcs is acceptable. At injection energy, $E = 0.45Z$ TeV, $\Delta x_c \simeq 70$ mm, $\Delta f_{\mathrm{RF}} = 4.7$ kHz is not. Injection and ramp must be done with unequal revolution (and RF) frequencies.

During 2011, a detailed review was conducted of all LHC systems, including controls software, machine protection (eg, to ensure that a beam could not be injected into the wrong ring), injection and, notably, the operation of the two rings’ RF systems independently for the first time. Many changes to the operational sequence and interlocking [7] were necessary to enable the new mode of operation.

A first, 16 hour, feasibility test on 31 October 2011 [7] demonstrated (1) that a few Pb bunches could be injected against 304 p bunches, (2) a first ramp of a few bunches of each, with unequal RF frequencies in the two beams, (3) re-locking of the frequencies at top energy and (4) “cogging” to shift the bunch encounter points (some 9 km) to their proper positions at the experiments.

A first attempt at p-Pb collisions in 2011 did not take place because of a leak in an injection septum of the PS.

PILOT RUN IN SEPTEMBER 2012

When Pb beams were next available, a pilot run with p-Pb collisions was designed to test the new operational procedures and provide the experiments with an opportunity to set up their triggers sufficiently in advance of the main production physics run (re-scheduled in early 2013). Operating conditions were carefully chosen to satisfy machine protection constraints yet still allow a fast-track to physics conditions. These were achieved in a single fill, within 9 h of injecting the first Pb bunch of the year on 13 September. Injection of $k_b = 15$ single bunches provided $k_c = 8$ colliding pairs in each of the 4 experiments (LHCb participated in the heavy-ion programme for the first time) with 3 bunches sacrificed for an essential off-momentum collimation setup of the unsqueezed optics at flat-top.

Table 1 gives key parameters and [8] is a detailed account of this run which also yielded surprising new physics results [9].

PRODUCTION RUN IN 2013

A few studies to test the crucial feasibility of injection and ramping of many p and Pb bunches together were scheduled in late 2012. For a variety of reasons unconnected with beam physics, all assigned time slots were lost and we had to embark upon the production physics run in January 2013 with a goal of increasing luminosity by three orders of magnitude over the pilot run. Final confirmation that the modulated beam-beam forces were indeed innocuous with the LHC parameters came only on 20 January 2013.

Thanks to the quality of the hardware and controls of the LHC and its injectors, and detailed preparation and planning, the commissioning of the new mode of operation was achieved within 10 days of the restart of the LHC after the end-of-year technical stop.

Unlike previous Pb-Pb runs, the squeeze sequence was re-implemented from scratch; see [10] for the optical corrections necessary for off-momentum operation and the collimation setup.

The unequal frequency acceleration and cogging processes were fully automated (Figure 1) and worked quickly and smoothly.

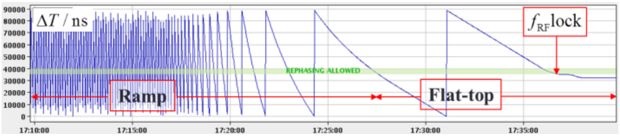

Figure 1: Time interval, ΔT , between leading RF bucket of the two beams (scale is revolution time) during the ramp and cogging process at flat-top. The RF frequencies are locked together when ΔT is close to the value placing the encounter points of the leading buckets at IP1, then a final adjustment is made (Figure 2).

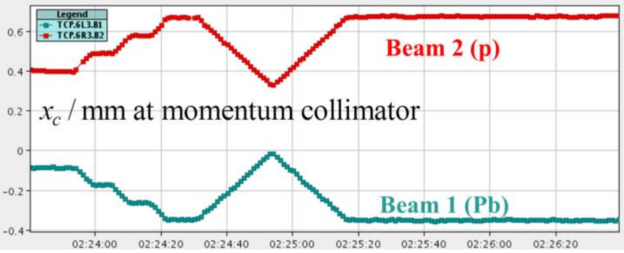

Figure 2 Orbit at primary momentum collimators $(D_x \simeq 2\text{ m})$ during the final cogging steps in a Pb-p fill.

Although equal orbit displacements, $\delta_{\rm p} = -\delta_{\rm Pb}$, were the starting point, it was necessary at times to choose $\delta_{\rm p} > |\delta_{\rm Pb}|$ to avoid losses and beam dumps due to the larger Pb beam size (Figure 2). Particularly in Pb-p operation, we had to slow down RF frequency trims and raise dump thresholds on beam-loss monitors (BLMs).

The ALICE experiment required:

- Initial minimum-bias running with $L \approx 0.5\times10^{28}$ cm^{-2}s^{-1} and $L \le 1\times10^{29}$ cm^{-2}s^{-1} later, both achieved through levelling by separation at the IP, and a total integrated luminosity of 30 nb^{-1} equivalent to the 2011 Pb-Pb data.
- Beam reversal from p-Pb (protons in Ring 1, Pb in Ring 2) to Pb-p half-way through the run.
- Reversal of their muon spectrometer polarity consistent with a half-crossing angle $\theta_c / 2 \le 80\ \mu$rad required for the interception of spectator neutrons by the Zero Degree Calorimeter.

Two special fills with full separation at IP1 and IP5 to increase luminosity lifetime allowed ALICE to catch-up with ATLAS and CMS who required a similar integrated luminosity. LHCb requested a few nb^{-1} and the forward detectors TOTEM, ALFA and LHCf also took data.

Figure 3 portrays the course of the entire run, indicating major changes in operating conditions. In the end, all the above goals were fully attained under extreme time pressure (except for a second polarity reversal in Pb-p).

Table 1 Indicative parameters of peak performance in the p-Pb pilot and Pb-p production runs; some numbers are averages because of the wide distribution of individual bunch parameters. Sets of four values correspond to the interaction points IP1(ATLAS), IP2(ALICE), IP5(CMS), IP8 (LHCb).

	2012 pilot	**2013 production**
$E / (Z\text{ TeV})$	4	4
k_c	(8,8,8,8)	(296,288,296,39)
β*/m	(11,10,11,10)	(0.8,0.8,0.8,2.0)
γε(p)/ μm	1.7	2
γε(Pb)/ μm	1.2	1.5
N_{bp}	1.2×10^{10}	1.6×10^{10}
$N_{b\rm Pb}$	7×10^{7}	12×10^{7}
$L / (10^{29}\text{ cm}^{-2}\text{s}^{-1})$	0.001	(1.12,1.01,1.16,0.05)

Table 1 gives key parameters; our initial plan to gradually increase the proton bunch intensity, N_{bp} , was not feasible because of dynamic range limitations of interlock beam position monitors (BPMs) causing beam dumps. However record Pb intensities, $N_{b\rm Pb}$, and beam quality were provided by the injectors [11].

Individual bunches had a complex distribution of emittances, intensities and decay rates resulting from the initial pattern imprinted by the injectors [11] but also from intra-beam scattering (IBS) on the injection plateau and the filling pattern in the LHC, eg, the requirement to collide two bunch trains in IP8 resulted different decay rates for those bunches. The luminosity lifetime was determined by the large cross section (2 barn), IBS and, possibly, the unequal beam sizes of the two beams in collision [8]. Analysis continues but is complicated by an unfortunate lack of emittance measurement capability during this run. Luminosity was driven by the Pb intensity (Figure 3).

Fills were most often dumped when some Pb bunch fell below a dynamic range threshold in the interlock BPMs.

OUTLOOK

Proton-nucleus collisions at high luminosity have been implemented and exploited in the LHC, the first upgrade beyond its baseline design.

At $4Z$ TeV per beam, the luminosity is already close to the projection and request for $7Z$ TeV [2,3,4]. With the coming energy upgrade and lifting of the artificial

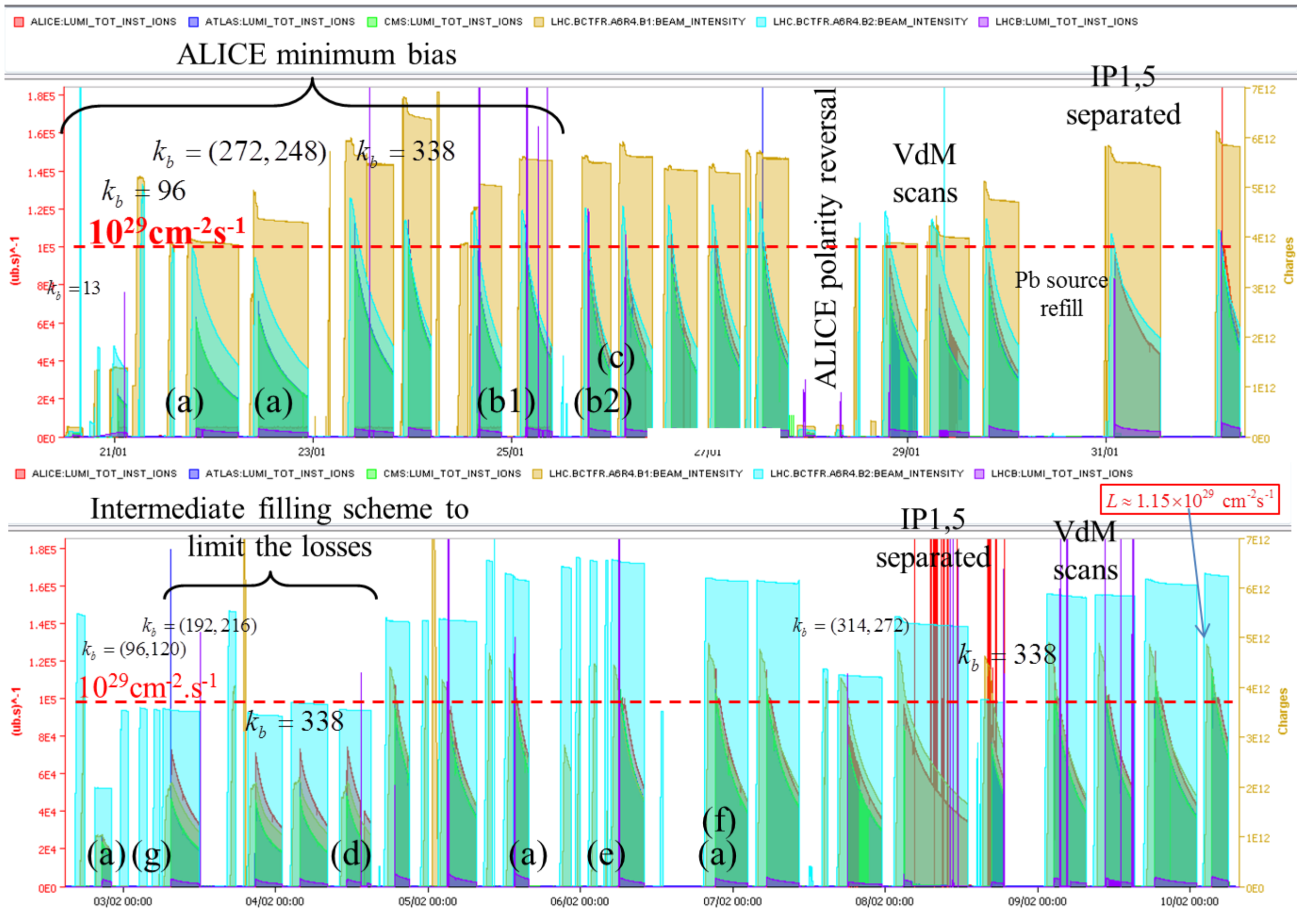

Figure 3: Luminosity and total beam intensity during the 2013 run (p-Pb top and Pb-p bottom plot) indicating some important steps: the rapid increase to the maximum number of bunches per beam, with some steps back to reduce beam losses, $k_b = 338$, (a) BLM threshold increases for losses during cogging, ramp or squeeze, (b1,b2) Roman pots moved in for ALFA, TOTEM forward detectors (c) RF longitudinal blow-up employed (d) orbit feedback bandwidth increase (e) reduction of RF blow-up (f) rematch of injection energy to SPS (g) adjustment of common frequency by 10 Hz.

restrictions on proton intensity, substantially higher luminosity, approaching 10^{30} cm^{-2}s^{-1} will be available in future runs.

The gain of a factor 25 in collision energy over previous comparable collisions [1] was one of the largest in the history of particle accelerators.

ACKNOWLEDGMENT

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