FIRST RUN OF THE LHC AS A HEAVY-ION COLLIDER

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Abstract

A year of LHC operation typically consists of an extended run with colliding protons, ending with a month in which the LHC has to switch to its second role as a heavy ion collider and provide a useful integrated luminosity to three experiments. The first such run in November 2010 demonstrated that this is feasible. Commissioning was extremely rapid, with collisions of Pb nuclei achieved within 54 h of first injection. Stable beams for physics data-taking were declared a little over one day later and the final integrated luminosity substantially exceeded expectations..

INTRODUCTION

The second major physics programme of the LHC, collisions of ^{208}Pb nuclei [1,2], was launched in November 2010. The nucleon-nucleon centre-of-mass energy available in heavy-ion collisions increased by a factor 13.8 to $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$, one of the largest jumps in the history of particle colliders of any species.

Figure 1 shows that, in 2010, both peak and integrated luminosity attained in Pb-Pb collisions after one week were equivalent to those in p-p collisions after 100 days. By the end of the run on 6 December, an integrated luminosity of $10\,\mu\mathrm{b}^{-1}$ had been delivered to each of the three heavy-ion experiments, ALICE, ATLAS and CMS. This paper provides a summary of how this was achieved.

RAPID COMMISSIONING

First Pb beams were injected into the LHC around 20:00 on 4/11/2010 and first collisions were obtained at 00:28 on 7/11/2010 (53.5 h later including 7.5 h downtime). A rapid-commissioning strategy had long been foreseen [3] to maximise time available for physics and minimise risk. A key idea was to recognise that, with a Pb beam of the same magnetic rigidity and initial injection conditions as the protons, minimising the changes to the established proton magnetic configuration would reduce the time taken for the initial commissioning steps (achieving circulating beam, ramp, squeeze) and allow us to move quickly on to dealing with the substantial differences between heavy ions and protons. The steps of the final plan were updated on the Web as they were executed.

With some care taken to establish a proton orbit using similar charge per bunch (hence dynamic range of beam position monitors), circulating beam was achieved within an hour with no orbit steering. The predicted change to the RF frequency (see below) then captured the beams. The ramp and squeeze to $\beta^* = 3.5\,\mathrm{m}$ in the three experiments followed rapidly in the same way.

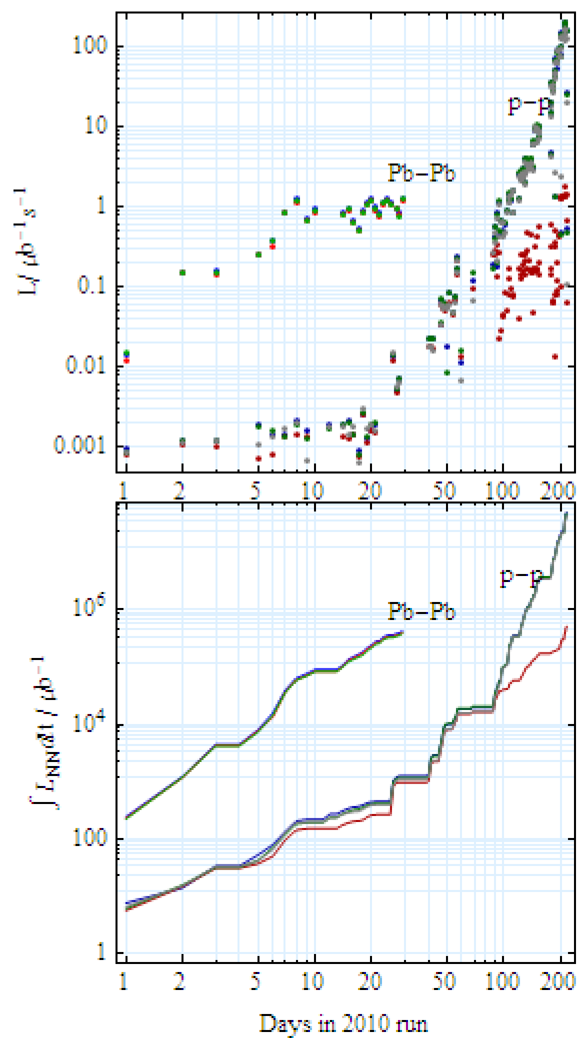

Figure 1: Peak (per fill) and integrated *nucleon-nucleon* luminosity for Pb-Pb collisions (upper, indistinguishable data sets) and p-p collisions during the 2010 runs in ATLAS (blue), ALICE (red) and CMS (green). Days are counted from the first declaration of "Stable Beams".

With 500 ns bunch spacing [4], there were essentially no unwanted beam-beam encounters in the interaction regions. At IP2, the crossing angle was adjusted to cancel the large angle induced by the ALICE spectrometer bump and collisions were head-on (Figure 2).

The vertical tertiary collimators in IR2 were then fully opened to allow the spectator neutrons from the colliding nuclei to pass unimpeded to the Zero-Degree Calorimeter of the ALICE experiment. At the other two experiments, ATLAS and CMS, the crossing angles were reduced to zero. Since the LHCb experiment did not take collisions, its dipole spectrometer magnet and its orbit compensation magnets were switched off to save power and beams were kept separated. The beam sizes, though equal in the nominal parameter lists, were not so in practice. Much of the commissioning time was taken up with carefully re-establishing the collimation setup in the new configuration. The complex interactions of Pb nuclei with the carbon of the primary collimators resulted in a higher collimation inefficiency than for protons; a companion paper [5] describes first results.

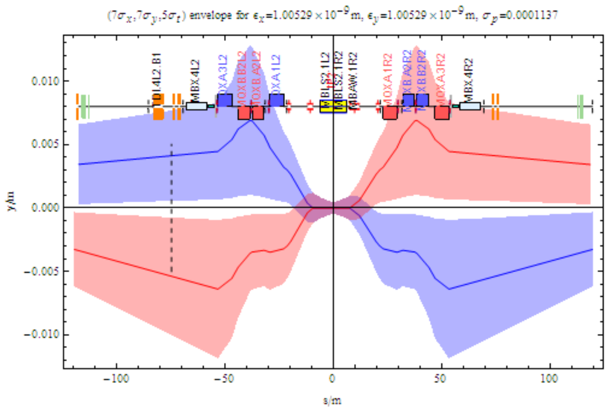

Figure 2: Vertical beam envelopes around ALICE

"Stable Beams" were declared for physics data-taking at 11:20 on 8 November 2010. In the following days, the number of bunches per beam increased on subsequent fills, through $k_b = 2,5,17$ (1 fill each), 69 (3 fills), 121 (24 fills), injecting single bunches or batches of 4 from the SPS in variants of the "Early" filling scheme [1]. In the last few days of the run, injection of batches of 8 bunches allowed $k_b = 137$ and a final performance as in Table 1, some 3 times beyond expectation.

The LHC was shut down for its winter stop at 18:00 on 6/12/2010. Of the intervening time, about 6 days were devoted to electron cloud studies with protons, refills of the ion source and cryogenics down-time, leaving about 23 days for Pb-Pb physics operation.

Table 1: Effective parameters (averaging over bunch-to-bunch and horizontal-vertical variations) at peak luminosity in Fill 1541 (values in blue are design).

Beam energy	$E = 1.38A$ TeV $= 3.5Z$ TeV
No. of bunches/ring	$k_b = 137(62)$
Ions/bunch	$N_b = 11.2\times10^7 (7\times10^7)$
Normalised emittance	$\varepsilon_N = 2.(1.5)\ \mu$m
Optical function	$\beta^* = 3.5$ m
Luminosity	$L = 3.\times10^{25}$ cm^{-2}s^{-1}

LONGITUDINAL ASPECTS

With 7×10^7 ions per bunch, the total charge was slightly above the proton pilot (5×10^9) and no change was required in the RF front end of the beam phase loop (BPL). At SPS extraction, the bunch had a 4σ length $\tau_z = 1.5$ ns. The total RF voltage at first capture was $V_{RF} = 3.5$ MV while the matched voltage is 3 MV. The main difference with protons was the capture frequency: 400.784210 MHz for Pb vs. 400.788860 MHz for p. Very fast bunch lengthening (up to 1000 ps/h) was observed on the flat bottom, caused by intra-beam scattering (IBS). The first ramp used a linear voltage function, from 3.5 MV (start ramp) to 8 MV (end ramp). The bunch length was $\tau_z = 1.5$ ns at injection, 1.8 ns at start ramp, 1.1 ns at end ramp. There was no significant loss during the ramp. With a constant $V_{RF} = 8$ MV, bunch lengthening was 200 ps/h at flat top, later reduced to 110 ps/h after transverse emittance blow-up in the PS.

Fighting IBS induced debunching during filling

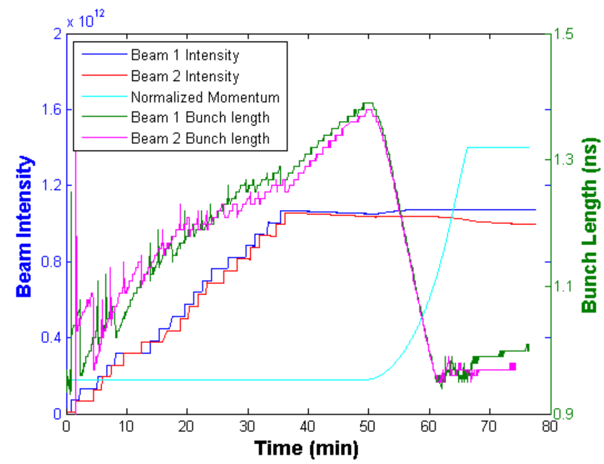

Figure 3: Capture with $V_{RF} = 7$ MV, increased to 12 MV through the ramp with longitudinal blow-up on; Fill 1539, $k_b = 137$ (intensity given in units of charge, not reliable in ramp because of bunch-length change).

The fast bunch lengthening during filling was unacceptable as it would take ~1 h to fill the nominal number of bunches. By then, bunches injected first would have filled the bucket and a significant intensity would have debunched, resulting in severe capture loss at the start of the ramp. A 10 % loss with five bunches per ring was measured on 9/11/2011. A large spread in τ_z was observed at flat top, eg, $\tau_z = 1.32-1.72$ ns in a $k_b = 69$ (11/11/2011). To counter this, we tried a scheme in which V_{RF} was increased to 7 MV, except for 3 s around the injection pulses, when it was reduced to 3.5 MV to keep the RF bucket almost matched to the bunch from the SPS. The larger V_{RF} gave a larger momentum spread that reduced IBS growth rate. Thanks to the larger bucket, the debunching was much reduced, resulting in almost no loss at the start of the ramp. Unfortunately, the V_{RF} manipulations created "ghost" bunches, with 0.1–0.2 % of nominal intensity, all around the ring. There was debunching at each voltage reduction followed by recapture in nearby buckets when V_{RF} returned to 7 MV.

We then tried a flat 7 MV during filling (). It led to 3% capture loss at start ramp but did not produce ghosts. This was adopted for the rest of the run with a linear increase from 7 MV to 12 MV during the ramp with longitudinal blow-up (see below). The bunch lengthening in physics was 40-50 ps/h over 8 h long fills.

The longitudinal emittance blow-up [6] kept the mean τ_z above a minimum (set at 1 ns), thereby reducing the IBS effects during physics. Clearly visible on Figure 4 is the stabilization at 1 ns, counteracting the adiabatic bunch shortening during the ramp, resulting in a longitudinal emittance $\varepsilon_z = 1.3Z$ eVs in a $4.7Z$ eVs bucket at $3.5Z$ TeV. It also reduced the spread in bunch length among the bunches. Figure 4 shows the mean τ_z, in Beam 1, through the ramp: the overall ±350 ps spread at the start of the ramp is reduced to ±100 ps at flat top. The standard deviation is reduced from 150 ps to 50 ps, giving better conditions for physics data-taking.

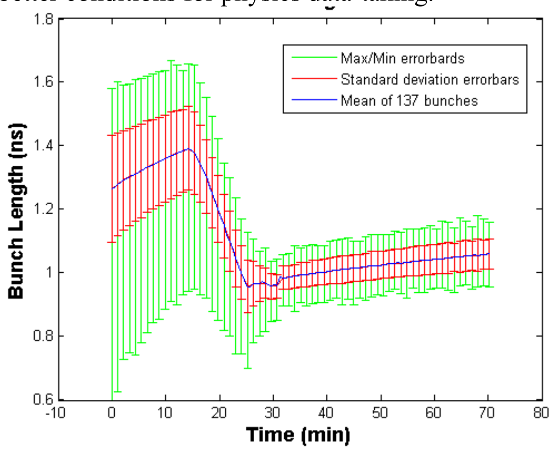

Figure 4: Statistics on bunch length (mean, min, max and standard deviation as error bars) during the ramp (Beam 1, Fill 1539, $k_b = 137$).

The evolution of longitudinal and transverse emittances and luminosity are discussed in a companion paper [7].

BEAM LOSSES

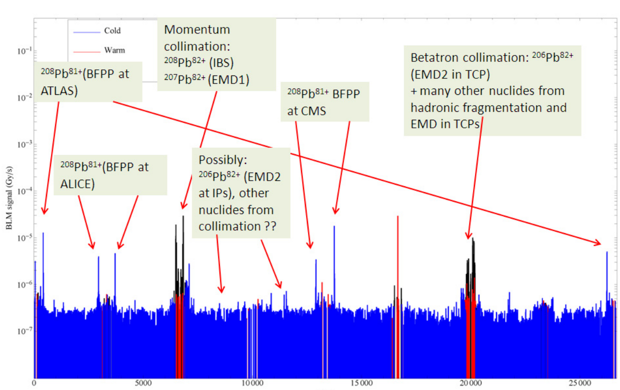

Figure 5: Global view of losses with Pb-Pb stable beams, in the Fill 1541, the last of 2010, which provided record luminosity. The identification of the loss peaks is done according to long-standing expectations.

A variety of beam loss mechanisms, all related to the large nuclear charge, have long been expected to limit the performance of the LHC as a nuclear collider. Figure 5 shows a global view of the losses from all the beam loss monitors in the ring in the final Fill 1541 with indications of how the primary loss peaks can be interpreted. The passive losses in the collimation insertions IR7 and IR3 [1,8] are discussed in a companion paper [5]. The bound-free pair production (BFPP) and electromagnetic dissociation (EMD) processes [1,9,10] occurring in collisions produce loss peaks in the dispersion suppressor magnets to left and right of each active experiment and contribute to the losses in the momentum collimation insertion IR3; they will be discussed in a forthcoming paper. Debunching losses from IBS [11,7] also contribute to the losses in IR3. In addition to these, there are some less well understood peaks in the arcs and beam-dump insertion IR6.

As expected, the vacuum did not degrade and losses related to beam-gas interactions were insignificant.

Losses in the dispersion suppressors around collimation insertions increased the level of single-event upsets [12].

CONCLUSIONS

The LHC works well as a nucleus-nucleus collider with many past concerns now laid to rest. Thanks to the qualities of the heavy-ion injector chain, the LHC hardware and software systems, optics and operational procedures, this mode was commissioned extremely quickly. The 2010 run set the strategy for future years and led to an immediate harvest of new physics results [13].

Future runs will increase the number of bunches, and reduce β^* to increase luminosity. The 2010 run gave us a first glimpse of the rich and novel beam physics that will limit performance when the beam energy is increased.

Acknowledgements: The success of the first Heavy Ion run was built on the efforts of many who constructed and commissioned the LHC and the heavy-ion injector chain.

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