Chapter 21

Heavy-Ion Operation of HL-LHC

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The heavy-ion physics programme of the LHC will continue during the HL-LHC period with upgraded detectors capable of exploiting several times the design luminosity for nucleus–nucleus (Pb–Pb) collisions. For proton–nucleus (p–Pb) collisions, unforeseen in the original design of the LHC, a comparable increase beyond the 2013 luminosity should be attainable. We present performance projections and describe the operational strategies and relatively modest upgrades to the collider hardware that will be needed to achieve these very significant extensions to the physics potential of the High Luminosity LHC.

1. Introduction

The 2003 Design Report [1] of the LHC set out a “Nominal” design luminosity goal for Pb–Pb collisions in *two* experiments of

$$L_{AA} = 1. \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \text{ at } E_b = 7Z \text{ TeV} = 2.76A \text{ TeV or } \sqrt{s_{NN}} = 5.5 \text{ TeV}, \quad (1)$$

where E_b is the beam energy, $\sqrt{s_{NN}}$, the average center-of-mass energy per colliding nucleon pair and $Z = 82$, $A = 208$ for the lead nuclei accelerated in the CERN complex. These parameters corresponded closely to the capabilities of the specialized ALICE detector and the anticipated performance of the injectors.

About that time, there emerged a number of potential performance limits from beam physics and instrumentation [1–6], some of which were unprecedented, reflecting the projected factor 27 increase in collision energy beyond RHIC, the only previous heavy-ion collider. Within intrinsic uncertainties, most of these limits were expected to occur in a band of about an order of magnitude spanning the design luminosity.

Since then, the performance limits have been clarified considerably as the LHC has delivered two Pb–Pb physics runs, to *three* experiments, in 2010 and 2011. The peak Pb–Pb luminosity has reached

$$L_{AA} \simeq 0.5 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \text{ at } E_b = 3.5Z \text{ TeV} = 1.38A \text{ TeV or } \sqrt{s_{NN}} = 2.76 \text{ TeV}. \quad (2)$$

With the natural scaling $L_{AA} \propto E_b^2$, this translates to roughly twice the design luminosity, Eq. (1), at full energy. The first experience of heavy-ion collisions in the new regime has also given opportunities to test some measures proposed to overcome the performance limits. Single-bunch intensities from the injectors are, with $N_b > 16 \times 10^7$ (for some bunches), already far higher than the design value, $N_b = 7 \times 10^7$. The greatest remaining uncertainties stem from present knowledge of the quench limits of superconducting magnets operating at full field [7].

Hybrid p–Pb collisions were not considered in the design [1] but a luminosity goal of

$$L_{pA} = 1.15 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \text{ at } E_b = 7Z \text{ TeV or } \sqrt{s_{NN}} = 8.8 \text{ TeV.} \quad (3)$$

was set later [8, 9]. This was almost reached — or exceeded by about a factor of 3 if energy scaling is taken into account — with two of the four experiments that took data in early 2013 recording [10]

$$L_{pA} \simeq 1.1 \times 10^{29} \text{ cm}^{-2}\text{s}^{-1} \text{ at } E_b = 4Z \text{ TeV or } \sqrt{s_{NN}} = 5.0 \text{ TeV.} \quad (4)$$

2. Performance with Pb–Pb Collisions

2.1. Experiments' requirements

The ALICE experiment has requested a peak Pb–Pb luminosity of up to $L_{AA} \simeq 7 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ after its upgrade with a view to integrating 10 nb^{-1} over several years operation (cf. the original request of 1 nb^{-1}). Similar requirements come from ATLAS and CMS.

Broadly speaking, the accumulation of comparison data in p–Pb and p–p collisions should keep pace with the Pb–Pb data in terms of integrated nucleon–nucleon luminosity:

$$A^2 \int L_{AA} dt \sim A \int L_{pA} dt \sim \int L_{pp} dt, \quad (5)$$

at equivalent $\sqrt{s_{NN}}$. In practice, p–Pb collisions usually take place at maximum energy for the sake of higher luminosity and faster commissioning. However Run 1 included p–p running at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ to fulfil Eq. (5) for all experiments.

2.2. Optical configuration

In heavy-ion, as opposed to proton, operation, a low value of β^* , is required at three, rather than two, experiments. The triplet quadrupoles around the ALICE experiment are not being upgraded within the HL-LHC project as are those of ATLAS and CMS. As a baseline, we envisage heavy-ion operation with $\beta^* = 0.5 \text{ m}$ in IP1, IP2 and IP5 using a conventional LHC optics, i.e., without the achromatic

telescopic squeeze (ATS). The ATS optics for p–p operation is being designed to maintain this functionality for Pb–Pb or p–Pb physics [11]. The changes in phase advance with respect to the previous optics may provide some additional tunability for $\beta^* < 0.5$ m which can be explored although the beam–beam separation around ALICE may become marginal at small values of β^* (see below). As in 2010 and 2011, the beams will remain separated at LHCb in an unsqueezed optics for Pb–Pb operation.

When the beams are colliding, the vertical half-crossing angle at the ALICE experiment is [12]

$$\theta_{yc} = \frac{\pm 490 \mu\text{rad}}{E_b/(7Z \text{ TeV})} + \theta_{y\text{ext}} \quad (6)$$

where the first term is the angle created by the orbit bump (entirely inside the innermost quadrupoles) required to compensate the detector’s muon spectrometer magnet (whose field can vary in polarity, less often in magnitude) and the second term is the contribution of an “external” bump created by orbit correction dipoles further out.

In order to provide an unimpeded path for “spectator” neutrons emerging from the collisions to the Zero-Degree Calorimeter (ZDC) [13, 14], the condition

$$|\theta_{yc}| < 60 \mu\text{rad} \quad (7)$$

has been imposed in heavy-ion operation up till now. With bunch spacings, $S_b/c = 100$ ns, as foreseen in the original LHC design [1], this provides adequate separation at the parasitic beam–beam encounters around the IP.

Some developments in the injectors [15] are aimed at increasing the number of bunches by achieving $S_b/c = 50$ ns — half of the original design — for at least some of the spacings between bunches in the LHC. Figure 1 shows that, for this value, it is no longer possible to satisfy the usual separation requirements in ALICE together with Eq. (7) at the closest parasitic encounters to the IP. However, experience [12] suggests that, given the relatively low charge of the Pb bunches (compared to p bunches), it may be possible to operate with more relaxed conditions, say, $r_{12}/\max(\sigma_x, \sigma_y) \gtrsim 3$ where r_{12} is the transverse distance between the closed orbits of the two beams. This is sufficient to reduce the parasitic luminosity to acceptable levels [14]. Thus the efforts to achieve shorter bunch spacing remain well-motivated; it is unlikely, although not strictly excluded, that the data quality of the ZDC may be somewhat compromised by a need for a larger crossing angle.

The ATLAS and CMS experiments do not have a muon spectrometer and separation requirements for Pb beams are less demanding than those established for protons.

Fig. 1. Beam-beam separation in IR2 as a function of the net half-crossing angle at the IP, θ_{yc} for $E_b = 7\text{Z TeV}$ with $\beta^* = 0.5\text{ m}$, the design Pb emittance of $\varepsilon_n = 1.5\text{ }\mu\text{m}$ and a regular bunch spacing of 50 ns and with the ALICE spectrometer polarity such as to contribute a positive crossing angle at the interaction point. At $\theta_{yc} = +70\text{ }\mu\text{rad}$, the external angle is zero and parasitic head-on collisions occur. Separations are shown in units of the larger of the horizontal and vertical beam sizes, both at the first parasitic encounter (on either side of the IP) and at the minimum over all encounters excluding the IP itself.

2.3. Intensity, emittance and luminosity

Estimation of the future luminosity of Pb beams is complicated by the very large variation of bunch parameters [16], notably the emittances, ε_n , bunch populations, N_b , and bunch lengths, σ_z , due, principally, to intra-beam scattering (IBS) as bunch trains are built-up first in the SPS from batches injected from the PS. When these SPS batches are subsequently injected in the LHC, a similar pattern, on a larger scale, is imposed on the entire LHC bunch train as the SPS batches spend different times at the LHC injection energy. Injecting shorter trains in the SPS would allow its cycle length to be reduced so that the earliest injected bunches would suffer less. However the final LHC bunch train would contain more kicker gaps, reducing the total number of bunches and it would take longer to fill the LHC.

A model to provide realistic quantitative predictions for the Pb–Pb luminosity is in development. It works by first fitting data from the 2011 Pb–Pb run [16] to describe the intensity and emittance decay with time spent at injection in both the SPS and LHC. It then predicts the optimum number of PS injections per SPS cycle and can be used to compare different schemes for preparing batches in the PS. A further important ingredient is the minimum spacing of PS batches in the SPS

which depends on the proposed upgrade of the injection kicker for ion beams in the SPS [15]. Here we shall assume a modest upgrade of the kicker which would allow a 100 ns spacing between the PS batches.

For present purposes, this model can be applied to one of the filling schemes [15] in which the PS delivers batches of four bunches, spaced at 50 ns to the SPS.^a

On the basis of the injector performance in the 2013 run, it turns out the optimum SPS batches are built-up by injection of nine such PS batches, spaced at 100 ns. Finally 28 of these SPS batches are injected into each LHC ring. The model has to take into account the various cycle lengths and accumulation times in the filling scheme. The pattern of 1008 bunch intensities finally brought into collision in the LHC is shown in Fig. 2. Although this pattern includes major features such as the LHC injection kicker rise time and the abort gap in the LHC, the number of bunches may be slightly less in practice because of other constraints on

Fig. 2. Intensities of the individual Pb bunches at the start of collisions. The variation within each of the 28 batches injected from the SPS is due to IBS and other effects acting for different times at SPS injection. Each of the nine dots visible within each SPS batch represents four bunches injected simultaneously into the SPS from the PS. The abort gap appears at the right hand end of the plot.

^aIn more recent developments, a scheme providing two bunches spaced at 100 ns has been deemed the “Nominal” one for post LS2 operation. Moreover the manipulations required to produce the 50 ns spacing have not yet been demonstrated in the PS. On the basis of present injector performance the 100 ns scheme would yield higher single-bunch intensities and a similar final luminosity in the LHC. However we prefer to retain the 50 ns scheme here as it has greater potential for future improvement. The new “Nominal” scheme will be described in more detail elsewhere.

the filling scheme that are not yet included in the model. In addition the number of collisions occurring in a given experiment will vary according to where in the ring the leading bunch of each beam collides (up to now this has been IP1 and IP5).

Once in the LHC, the bunches suffer emittance increases and intensity losses from debunching, both effects arising from IBS, according to the time they spend at injection, the first train to be injected suffering the most. Further losses occur during the ramp and squeeze processes. These effects are also taken into account by the model, leading to a prediction for the final distribution of bunch populations as the beams are put into collision, N_b , as shown in Fig. 2. There is a corresponding distribution of emittances.

As the bunches collide pair-wise, the differences in their intensities and emittances produce a spectrum of initial luminosities which shows an even stronger variation along each SPS train and along the whole LHC train. Figure 3 shows an example of the luminosity distribution in an IP where the leading bunches collide.

Fig. 3. Luminosities of the individual Pb–Pb bunch pairs at the start of collisions.

3. Integrated Luminosity Projections

The next stage of the modelling is to look at the evolution over a fill using the Collider Time Evolution simulation program [16–18], a multi-particle simulation that includes the effects of IBS, luminosity burn-off, radiation damping, etc. Here again, of course, the spread in bunch parameters differentiates the rate of intensity and luminosity decay along the bunch train. To simplify the picture, Fig. 4 shows the luminosities of three bunch pairs, sampling each end, and the middle, of the luminosity spectrum. Naturally, the rate of luminosity decay is higher for the higher

Fig. 4. Evolution of the luminosity of three representative Pb bunches in the course of a fill.

Fig. 5. Evolution of the total luminosity, summed over all bunches (dashed line), and its integral (solid line) in the course of a fill.

luminosity bunch pairs so there is a tendency for all bunch pairs to equalize their luminosities after some time. This is nevertheless still a simplification since some bunches make fewer collisions than others.

Since each bunch pair luminosity is a smooth monotonic function, the model can fit them with similar functional forms. It then interpolates the fit parameters among the simulations run for representative bunches in order to estimate the luminosity evolution for the other bunch pairs with a good accuracy. Finally, the luminosities of all bunch pairs can be summed to predict the evolution of the total luminosity and the integrated luminosity, shown in Fig. 5.

For comparison, the most recent Pb–Pb run which took place in 2011 occupied about 24 days of calendar time and yielded 39 fills totalling just under 8 days of

Stable Beams time. The average during of the Stable Beams for physics was therefore 4.9 h. According to Fig. 5, such a fill would provide an integrated luminosity of $34 \mu\text{b}^{-1}$. So for the same run duration and operational efficiency as in 2011, the total integrated luminosity would be 1.3 nb^{-1} .

A naive “Hübner factor” calculation, scaling the integrated luminosity obtained in 2011 with the ratios of the peak luminosity then, $5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ to that shown in Fig. 3 yields as similar value.

We emphasize here that these estimates are very conservative, assuming no gains over the injector performance in 2011 or in operational efficiency. There is every likelihood that the luminosity will be higher, particularly if the intensity limits in LEIR can be overcome, the degradation of beam quality and intensity on the SPS injection plateau can be reduced, or if schemes permitting the injection of more high intensity bunches can be implemented.

3.1. Mitigation of losses from collisions

In the past decade, there have been extensive discussions of the potential limitation of peak Pb–Pb luminosity by the process of bound-free pair production [1, 2, 4, 5, 19–22] in collisions. This creates a secondary beam of one-electron Pb ions emerging from the interaction point and being lost in a well-defined spot in a dispersion suppressor dipole magnet. At design luminosity, Eq. (1), the power in the beam emerging from each side of the interaction points is some 25 W, potentially enough to induce quenches of the magnet. In 2003, when this problem first came to light [3], it was too late for the obvious solution of installing collimators or masks in the cryogenic sections of the dispersion suppressors to intercept these beams. Although recent quench test measurements [7, 23] have indicated that the quench limit is somewhat higher than estimated in the past, quenches remain likely to occur with the upgraded Pb–Pb luminosity. For this reason, priority has been given to the installation of collimators in the dispersion suppressors on either side of the ALICE experiment as part of the High-Luminosity LHC upgrade [24].

Dispersion suppressor collimators may also be needed around ATLAS and CMS also although there is some scope for mitigation of the effect using orbit bumps [21], a method which was already tested in the 2011 run.

4. Performance with p–Pb Collisions

Although it had to work in a configuration that was almost unprecedented at previous colliders, the LHC performed remarkably well as a p–Pb collider for a single fill in 2012 [25] and for a one month run in 2013 [10, 26–28].

Table 1. Indicative parameters of peak performance in the 2013 Pb–p production run and in future operation in Run 2 at higher energy; 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).

Parameter	2013 production	Run 2
$E/(Z \text{ TeV})$	4	7
k_c	(296, 288, 296, 39)	$\simeq (400, 380, 400, 50)$
β^*/m	(0.8, 0.8, 0.8, 2.0)	(0.5, 0.5, 0.5, 2.0)
$\gamma\epsilon_p/\mu\text{m}$	2	2
$\gamma\epsilon_{pb}/\mu\text{m}$	1.5	1.5
$N_{b,p}$	$1.8\text{--}5 \times 10^{10}$	1.6×10^{10}
$N_{b,Pb}$	14×10^7	14×10^7
$L/(10^{29}\text{cm}^{-2}\text{s}^{-1})$	(0.98, 1.08, 0.98, 0.035/0.056)	$\simeq 4\text{--}12 \times (1, 1, 1, 0.1)$

Operation in the first run was complicated by the need to supply collisions to the LHCb experiment, to several changes of operating conditions requested by the ALICE experiment, the intrinsic complexity of injection and ramping with unequal revolution frequencies and relocking RF frequencies at collision energy to collide “off-momentum”.

Detailed plans for p–Pb runs in the HL-LHC era should take account of the potential increases in bunch intensity and bunch number in some detail. Injection schemes matching the proton bunch trains to the lead ones have to be worked out and the intrinsic beam-dynamical and instrumental (beam-position monitors, in particular) limitations of this mode of operation have to be further explored. For the moment we can only give some provisional estimates of the main parameters indicating some typical numbers of collisions at each IP, k_c , and a range of initial luminosities that could be accessed by varying the proton bunch intensity. Note that increasing this parameter will directly reduce the luminosity lifetime, leading to quite short fills.

5. Stochastic Cooling of Pb Beams

The RHIC collider has demonstrated the effectiveness of a bunched-beam stochastic cooling system against IBS [29] and a first study [30] has shown the potential of a similar installation to cool heavy ion beams in the LHC. In the HL-LHC, the benefits of the cooling lie in the reduction of colliding beam sizes at later stages of the fill. This maintains a high luminosity even when the bunch populations have been substantially eroded by the earlier luminosity burn-off. This is a much more efficient way to operate a collider since more of the particles stored in the beam are converted into collisions. A much smaller fraction are dumped at the end of the fill.

Fig. 6. Evolution of bunch-pair luminosity for three typical bunches in a train, with (solid curves) and without (dashed curves) the effect of stochastic cooling in all three planes. Bunch parameters are similar to the examples shown in the paper [30], except that luminosity burn-off is stronger with three experiments taking collisions. The bunch parameters are different from those shown in Fig. 4.

Studies are beginning to see whether the promise of a stochastic cooling system, at an apparently modest cost, can be realized in the LHC. Space for the system (roughly 20 m per beam for the kickers) must be found. They will be connected to the broadband pickups by fibre optics lines in the tunnel, avoiding chordal microwave links on the surface. As in RHIC, the kickers will have to come very close to the beam at physics energy so must open at injection where a larger aperture is needed. In the open position, the design must have a low enough high-order mode impedance to avoid overheating in the presence of the high-intensity proton beams.

6. Operational Aspects

Heavy-ion operation in the HL-LHC era will continue the advantageous pattern of a short run of about one month at the end of each year, generally preceding a short end-of-year shutdown. This allows the activation level of the accelerator complex due to high-intensity proton operation to decline before interventions. Each run so far has broken new ground and yielded important physics discoveries and the rhythm of data delivery and opportunities, changes of colliding species and other experimental conditions has been well-matched to the research programmes of the experimental and theoretical physics community.

Since each run is short, there is a high premium on being able to commission the new mode of operation very quickly. By the same token, the impact of any down-time can be significant.

7. Summary

High-luminosity heavy-ion operation of the LHC can start a few years earlier (in “Run 3”) than the high-luminosity proton operation designated “HL-LHC” since it does not require the upgraded inner-triplet quadrupoles around ATLAS and CMS or the crab cavities. Conservative extrapolation from past performance indicates that it will be possible to accumulate an integrated Pb–Pb luminosity of $\simeq 1.3 \text{ nb}^{-1}$ in an annual one month run (cf. the initial goal of 1 nb^{-1} for the entire first phase of LHC). This depends on upgrades to the Pb–ion injector chain allowing the implementation of new filling schemes.

Present expectations concerning quench levels of the magnets indicate that the peak luminosity will exceed the limits imposed by the BFPP losses and the installation of the dispersion suppressor collimators around experiments, as foreseen for ALICE, is necessary.

There are reasonable prospects for a further doubling of the integrated luminosity, particularly if intensity limitations in LEIR can be overcome, the intensity decay of Pb bunches in the SPS can be mitigated and/or a stochastic cooling system can be implemented at collision energy in the LHC.

It should be remembered that some annual runs will be devoted to p–Pb operation, where substantially higher luminosity can also be expected, and that there will also be requirements for p–p reference data at equivalent $\sqrt{s_{\text{NN}}}$ to the Pb–Pb runs.

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