Heavy Ion Operation from Run 2 to HL-LHC

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Abstract

The nuclear collision programme of the LHC will continue with Pb-Pb and p-Pb collisions in Run 2 and beyond. Extrapolating from the performance at lower energies in Run 1, it is already clear that Run 2 will substantially exceed design performance. Beyond that, future high-luminosity heavy ion operation of LHC depends on a somewhat different set of (more modest) upgrades to the collider and its injectors from p-p. The high-luminosity phase will start sooner, in Run 3, when necessary upgrades to detectors should be completed. It follows that the upgrades for heavy-ion operation need high priority in LS2.

INTRODUCTION

The LHC started colliding beams of lead nuclei, $^{208}\mathrm{Pb}^{82+}$, in 2010 [2], achieving a significant luminosity within a few days of commissioning. The second one-month run in 2011 was even more successful [3] with a luminosity corresponding to twice the design value [4] (taking account of the natural scaling with energy-squared), as summarised in Table 1.

In 2012, a completely new mode of operation with hybrid proton-lead beams [5] was commissioned in a single pilot fill [6, 7], leading to an immediate harvest of unexpected physics results, and a substantial integrated luminosity was delivered in the LHC's third heavy-ion running period in early 2013 [7]. Allowing again for the natural energy-scaling, the peak luminosity reached 3 times the (unofficial)[1] design value [5, 1], within the first week of the 2013 run.

Unfortunately, because of time-pressure during the short runs and a variety of unlucky circumstances on other occasions, there has been little dedicated machine development (MD) time for the heavy-ion programme. Nevertheless, our understanding of the performance limits is now much better than it was before the start of operation. Broadly speaking the nature of the predicted limitations have been confirmed but they set in at higher levels than was expected on the basis of past, conservative, estimates of the energy deposition that might cause superconducting magnets to quench.

FUTURE RUNS AND SPECIES

Within colliding nuclei, with charges Z_1, Z_2 and mass numbers A_1, A_2, in rings with magnetic field set for protons of momentum p_p[2], the colliding nucleon pairs will have an average centre-of-mass energy

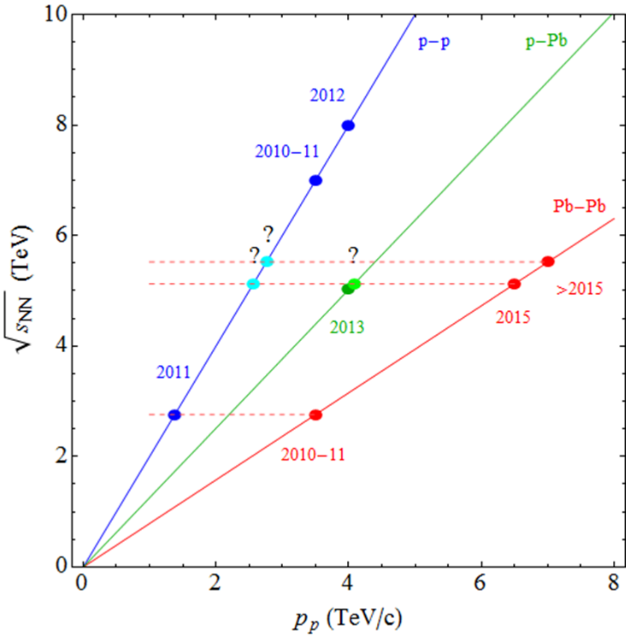

Figure 1: Survey of collision energies (1), and species in past and (some) future LHC runs as a function of the equivalent proton momentum p_p, for p-p, p-Pb and Pb-Pb collisions.

$$\sqrt{s_{\mathrm{NN}}} \approx 2c\,p_p\sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \approx 2c\,p_p \begin{cases} 1 & \text{p-p} \\ 0.628 & \text{p-Pb} \\ 0.394 & \text{Pb-Pb} \end{cases} \tag{1}$$

and a central rapidity shift

$$y_{\mathrm{NN}} \approx \frac{1}{2}\log\left(\frac{Z_1 A_2}{A_1 Z_2}\right) \approx \begin{cases} 0 & \text{p-p} \\ 0.465 & \text{p-Pb} \\ 0 & \text{Pb-Pb} \end{cases} . \tag{2}$$

Figure 1 shows $\sqrt{s_{\mathrm{NN}}}$ according to (1) for past and expected future runs of the LHC. In a typical year the p-p operation will be followed by a month of heavy-ion operation, mainly Pb-Pb interspersed with p-Pb roughly every 3rd year [8].

Generally it will be more efficient to minimise commissioning and optics set-up time by running Pb-Pb or p-Pb at the same equivalent proton momentum, p_p, ie, the same magnetic field, as the preceding p-p run. However the need for comparison data at equivalent $\sqrt{s_{\mathrm{NN}}}$ may require lower energy p-Pb runs or special calibration p-p runs from time to time. Reference data taken in such runs should ideally track the integrated Pb-Pb luminosity [8].

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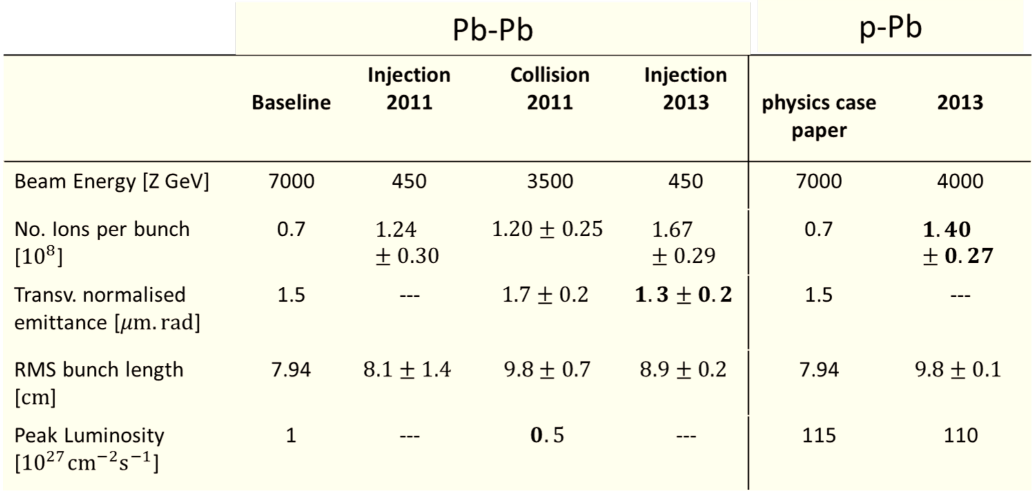
[1] There is no mention of the p-Pb collision mode in [4]

[2] Conditions imposed by the two-in-one magnet design of the LHC.

Table 1: Design baseline and peak performance achieved with nuclear collisions, both Pb-Pb and p-Pb, in LHC Run 1. In the case of p-Pb, the projections of the physics case paper [1] are used as a reference.



	Pb-Pb				p-Pb	
	Baseline	**Injection 2011**	**Collision 2011**	**Injection 2013**	**physics case paper**	**2013**
Beam Energy [Z GeV]	7000	450	3500	450	7000	4000
No. Ions per bunch $[10^8]$	0.7	1.24 ± 0.30	1.20 ± 0.25	1.67 ± 0.29	0.7	**1.40 ± 0.27**
Transv. normalised emittance $[\mu\mathrm{m.rad}]$	1.5	---	1.7 ± 0.2	**1.3 ± 0.2**	1.5	---
RMS bunch length [cm]	7.94	8.1 ± 1.4	9.8 ± 0.7	8.9 ± 0.2	7.94	9.8 ± 0.1
Peak Luminosity $[10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1	---	**0**.5	---	115	110

Collisions of lighter species, such as the $^{40}\mathrm{Ar}^{18+}$ and $^{129}\mathrm{Xe}^{54+}$ that the source will soon produce for fixed-target physics [9], are not considered for the LHC at present. Better estimates of the potential performance can be given once there is some experience with these ions in the injector chain.

RUN 2 PROJECTIONS FOR Pb-Pb

Bunch parameter spreads

As also discussed in [9, 10, 11, 12], there is a considerable spread in Pb bunch parameters, particularly bunch populations, N_b, but also emittances, ε_n, and bunch lengths, σ_z, after injection in the LHC. An example is shown in Figures 2 and 3.

These are due in large part to intra-beam scattering (IBS) as bunch trains are built-up first in the SPS from batches injected from the PS. IBS causes some emittance growth but also losses, mainly longitudinally from the RF bucket. In addition there are effects of RF noise because of the special RF acceleration scheme, involving jumps of the phase, used for heavy ions in the SPS. 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. This leads to the sawtooth pattern seen in Figure 2 when several trains are assembled in the LHC.

These features will be present, but modified quantitatively in future runs. Our estimates of future performance are based on a developing model [12] to provide realistic quantitative predictions for the Pb-Pb luminosity. It works by first fitting data from the 2011 Pb-Pb run [12] 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.

The initial bunch-by-bunch luminosity in ATLAS, Figure 4, at the start of ”Stable Beams” shows a more pronounced version of the pattern of the bunch intensities in Figure 2. The luminosity at ALICE would show a different pattern as the bunch-pair intensities are less correlated.

Optical and operational conditions

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 as are those of ATLAS and CMS and no optical solution for $\beta^* < 0.5\,\mathrm{m}$ is presently available. We therefore envisage heavy-ion operation with $\beta^* = 0.5\,\mathrm{m}$ in IP1, IP2 and IP5 using a conventional LHC optics, ie, without the achromatic telescopic squeeze (ATS) [13]. The ATS optics for p-p operation is being designed to maintain this functionality for Pb-Pb or p-Pb physics. As in 2010 and 2011, the beams will remain separated at LHCb in an unsqueezed optics for Pb-Pb operation.

Generally, this will still allow us to take over most of the ramp and squeeze from the preceding p-p run to expedite commissioning. As usual it will be necessary to implement an additional squeeze and crossing angle set-up for ALICE [4, 14].

We assume the usual run length of about one month each year and present expectations are that 2015 and 2016 will be devoted to Pb-Pb with a p-Pb run (including LHCb) in 2017 and, most likely, Pb-Pb again in 2018, before LS2.

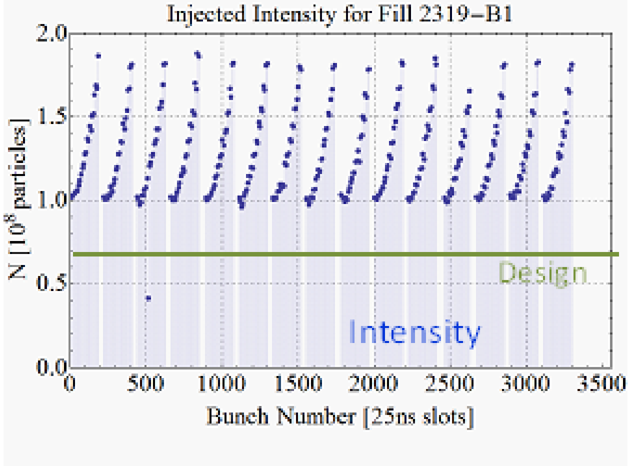


Figure 2: Injected intensity, bunch-by-bunch, along the complete LHC bunch train, composed of several SPS trains, in a typical LHC Pb-Pb fill in 2011.

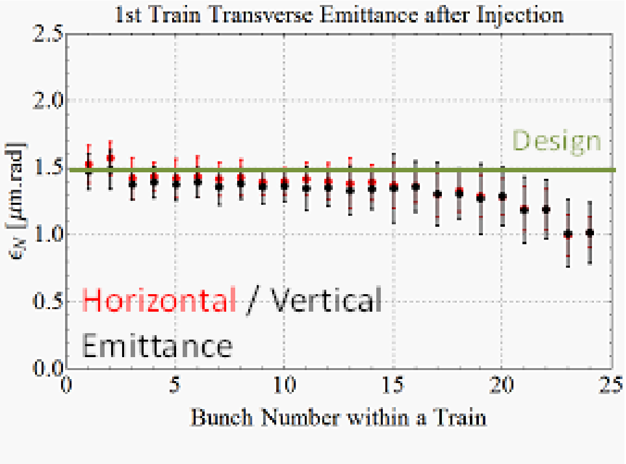


Figure 3: Injected emittance, bunch-by-bunch, from the wire-scanner, along a single SPS train in the LHC, averaged over the first injection in several LHC Pb-Pb fill in 2011.

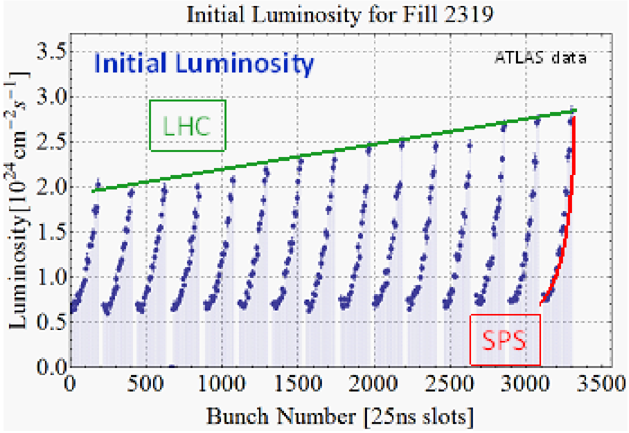


Figure 4: Initial bunch-pair luminosity at ATLAS, over a full revolution period, in a typical LHC Pb-Pb fill in 2011. The red and green curves indicate the dependences used in the predictive luminosity model, to be explained later.

Predictive luminosity model

In the following, the time evolution of colliding bunches during Stable Beams is simulated with the Collider Time Evolution (CTE) program [15, 16, 12]) which includes effects of:

1. Emittance growth and debunching from IBS (much stronger for heavy ions than for protons [4, 17, 15, 16]) including the non-gaussian longitudinal distribution.
2. Radiation damping (twice as strong for heavy ions as for protons [4, 17]),
3. Luminosity burn-off (much stronger for heavy ions than for protons because of the large electromagnetic cross-sections [18, 17, 15]).

The spectrum of initial bunch intensities and emittances implies a spectrum of luminosity lifetimes and bunch-pair luminosities which must be summed to yield realistic integrated luminosity estimates.

The initial distribution over the bunch train is given by a phenomenological model based on ATLAS luminosity data from 2011, as shown in Figure 4. The evolution of three typical bunch-pairs, from the head, middle and tail of an SPS train, representing the range of possibilities, according to CTE, is shown in Figure 5. Since the variations are smooth, we use interpolations between such cases to reduce the number of simulations runs necessary.

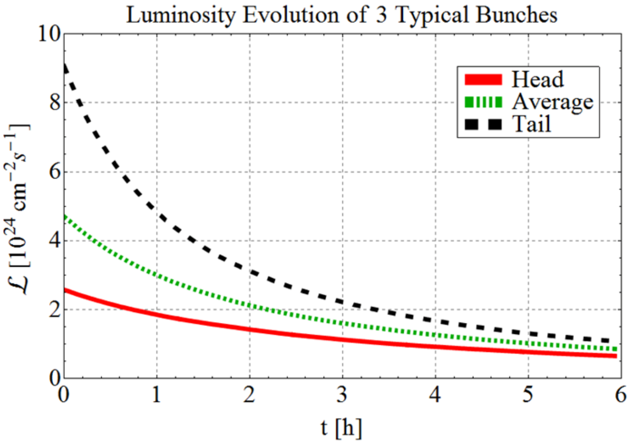


Figure 5: Evolution of the luminosity of three typical bunches, from the head, middle and tail of an SPS batch colliding in the LHC, simulated with the CTE program.

Modelling of the effects in the SPS are based on the distribution within the last train injected into the LHC (red curve in Figure 4) because this train is subject to little degradation as it spends the least time on the LHC injection plateau. Thus we obtain the cleanest picture of the impact on the luminosity from the variable time spent by PS batches at the SPS injection energy.

Table 2: Measured bunch intensities and scaling to future performance. Intensity scaling factor for best transmission means: 29% from LEIR to LHC injection, 96% from LHC injection to Stable Beams, 27% from LEIR to LHC Stable Beams. The F_{N_b} factors in the last row are taken for the cases labelled "2013 performance" and "+40%" in the following.

	2011	**2013**	**+40% out of LEIR**
LEIR pulse intensity [ions]	9×10^8	11×10^8	15.4×10^8
Number of bunches per batch	2	2	4
Intensity per future LHC bunch [ions]	4.5×10^8	5.5×10^8	3.9×10^8
Injected intensity per bunch into LHC [ions]	1.24×10^8 (27%)	1.6×10^8 (29%)	1.1×10^8 (29%)
Intensity in Stable Beams [ions]	1.2×10^8 (96%)	1.4×10^8 (87%)	1.0×10^8 (96%)
Transmission LEIR → LHC SB	26%	25%	27%
Intensity scaling factor for best transmission	1	1.28	0.88

To model the effects of the LHC injection (some bunches may spend over 30 min there), ramp and set-up for physics, we group bunches of equivalent PS batches from all trains, which saw the same SPS injection plateau length (green curve in Figure 4),

Both effects are well described by a fit to a similar functional form, resulting in an expression for the *square-root of the individual bunch-pair luminosity*:

$$\begin{aligned}\sqrt{L_{bb}} &= F_{N_b} F_{\mathrm{norm}} \left(a e^{-b t_{SPS}} + c \right) \\ &\quad \times \left(A e^{-B t_{LHC}} + C \right) \qquad (3)\end{aligned}$$

where t_{SPS} is the time the bunch spent at injection in the SPS, related to the index of the bunch within the bunch train assembled in the SPS and t_{LHC} is a similar quantity related to the index of the SPS train to which it belongs within the full train assembled in the LHC. These correspond to the dependences shown in red and green in Figure 4. The other parameters within the parentheses come from the fits to 2011 data; F_{norm} is a normalisation factor and F_{N_b} is used to rescale the overall intensity according to expectations for future improvements as outlined in Table 2.

The model only takes variations due to the SPS and LHC into account; the ion source, LEIR and PS are assumed to have cycles similar to 2011.

The slides of this talk and future publications provide further details of this predictive luminosity model, including the benchmarking to reproduce the performance in 2011.

Operating energy in Run 2

Our Run 2 performance projections are for

$$E_b = 6.5Z\,\mathrm{TeV} \Rightarrow \sqrt{s_{\mathrm{NN}}} = 5.1\,\mathrm{TeV}$$

Some interest has been expressed in reducing the energy to obtain the same s_{NN} as in the 2013 p-Pb run, ie,

$$\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV} \Rightarrow E_b = 6.3Z\,\mathrm{TeV}$$

Reducing the maximum field in the LHC magnetic cycle after p-p operation is estimated to cost an additional 1–2 days commissioning time. In any case, there will be the usual modified squeeze to implement.

Run 2—2011 Scheme, scaled N_b

Table 3: Injection scheme as in 2011 for Run 2 parameters.

2011 Filling Scheme	**@ E = 6.5Z TeV** **β^*= 0.5m** **F_{Nb} = 1.28**
Spacing PS [ns]	200
Spacing SPS [ns]	200
No. bunches/PS batch	2
No. PS batches/train	12
No. LHC trains	15
No. bunches/beam	358

With this model, a baseline configuration for Run 2 in 2015 could be to use the 2011 filling scheme, according to Table 3, but rescale the intensities to those achieved in the p-Pb run in 2013 [9] . Given that there were new, specific, sources of losses in the ramp and squeeze in the p-Pb run, it is reasonable to assume that the transmission of bunch intensities from injection to Stable Beams would be similar to 2011. On this basis we get the performance indicated in Figure 6 which sums to a maximum peak luminosity in ATLAS or CMS of

$$\hat{L} \simeq 2.8 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}. \qquad (4)$$

Run 2—100 ns Batch Compression

For Run 2, an alternative also discussed in [9] is to use batch compression to reduce the spacing between pairs of

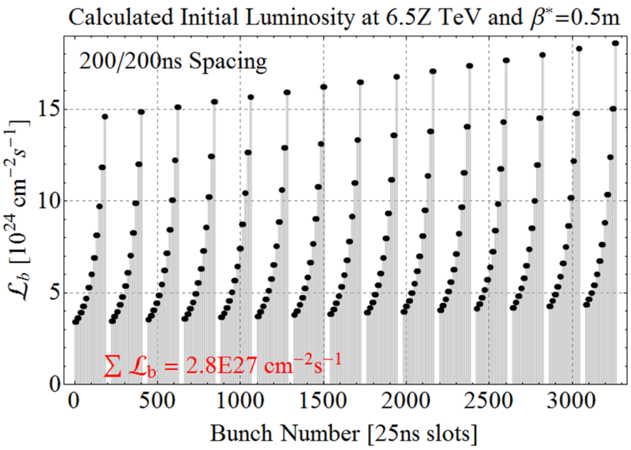


Figure 6: Bunch-pair luminosities in Run 2, with the 2011 filling scheme, 2013 bunch intensity performance and a transmission of intensity from injection to Stable Beams similar to 2011.

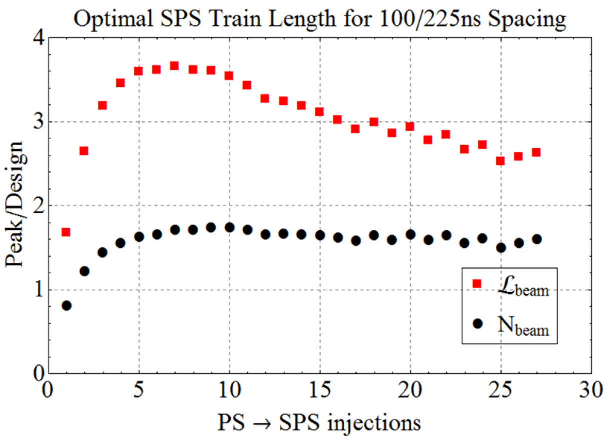


Figure 7: Optimisation of the number of PS batches injected to form a train in the SPS in the Run 2 100/225 ns injection scheme.

bunches in the PS to 100 ns. Several such batches can be injected with a spacing of 225 ns (set by the present SPS injection kicker) to form a train in the SPS.

The model takes into account that: not more than 40% of the SPS circumference should be filled; there should be 900 ns LHC kicker gaps and a 3.3 μs abort gap in the LHC train although final details of the filling scheme are not yet implemented.

Longer SPS trains will allow a larger total number of bunches in the LHC but will be subject to worse degradation on the SPS injection plateau. Figure 7 shows that the optimum number of PS injections for either total stored beam current or peak luminosity in the LHC are similar. Choices which should therefore provide the maximum integrated luminosity are summarised in Table 4.

Table 4: Optimum filling scheme for peak or integrated luminosity with the 100 ns batch compression scheme in Run 2.

Batch Compression	**@ E = 6.5Z TeV** **β^*= 0.5m** **F_{Nb} = 1.28**
Spacing PS [ns]	100
Spacing SPS [ns]	225
No. bunches/PS batch	2
No. PS batches/train	7 / 9
No. LHC trains	29 / 24
No. bunches/beam	406 / 432

Summing over bunch pairs, as before, the peak luminosity turns out to be

$$\hat{L} \simeq 3.7 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{5}$$

The optimisaion gives a 30% improvement over the $3.3 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ that would be obtained with a 2011-like scheme.

Levelling in Run 2

Before the upgrade of the ALICE detector in LS2, its Pb-Pb luminosity must be levelled at the original design value $\hat{L} = 1. \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. On the other hand, ATLAS and CMS can accept the higher luminosity that will be available according to the analysis above.

Since the luminosity decay is dominated by burn-off, operation is largely a conversion of stored beam particles to phyics events. The higher luminosity experiments consume the beam more rapidly, reducing the luminosity very quickly and reducing the time that ALICE can run at the levelled value. The question arises whether ATLAS and CMS should be levelled also?

Figure 8 compares 3 possibilities:

1. Levelling only in ALICE to $1 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (red curves),
2. Levelling all experiments to $1 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (green curves),
3. Levelling ALICE to $1 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, ATLAS and CMS to $2 \times 10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (black dashed curves).

The parameters used correspond to *average bunches* in Run 2. Note that some of the initial very high luminosity is likely to be lost anyway during collision set-up time (typical 10–15 min).

From these examples, we conclude that some level of levelling for all experiments is desirable. This provides a foretaste of future high luminosity p-p operation. If we consider that a typical fill will last about 6 hours, the intermediate levelling scenario (3) looks very equitable for all the experiments. In such a fill, ALICE could expect about 20 $\mu\mathrm{b}^{-1}$, only slightly less than in scenario (2), while

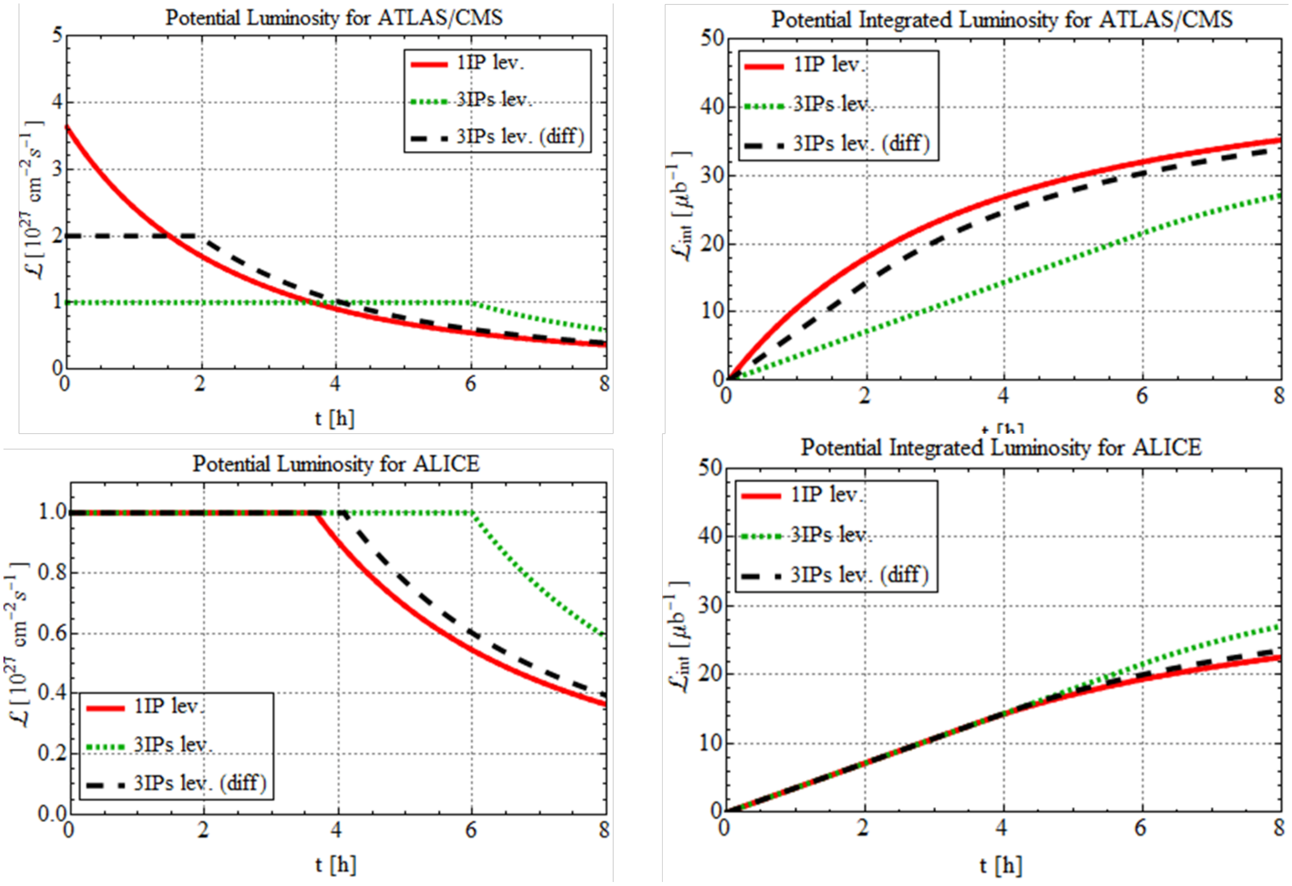


Figure 8: Analytical calculations to compare 3 levelling scenarios for Run 2, as described in the text. The plots in the top row show the instantaneous and integrated luminosity for the ATLAS and CMS experiments. The bottom row shows the same information for ALICE.

ATLAS and CMS could expect 30 $\mu\mathrm{b}^{-1}$, only slightly less than in scenario (1).

Experience in the 2013 p-Pb run was similar because of initial minimum-bias operation of ALICE. There, the solution was to make two catch-up fills with beam separated in ATLAS and CMS. Clearly this remains an option available to the LHC physics coordination during Pb-Pb runs in Run 2. The optimum length of a fill also depends on real turn-around times.

Levelling can be done by the now-routine separation method (or, possibly, by variation of β^* during physics.)

RUN 3 AND BEYOND, Pb-Pb

In Run 3, the main strategy for increasing the luminosity will be to increase the total number of Pb nuclei stored in the LHC.

As also discussed in [9], this can be done by reducing bunch spacing within PS batches and/or decreasing the SPS kicker rise time to reduce the batch spacing in the SPS. These methods increase the number of bunches. There are also prospects to increase the bunch intensity out of LEIR by 40% and perform bunch splitting in the PS and to use slip-stacking in the SPS. Table 5 summarises the main possibilities remaining after recent discussions.

Table 5: The main candidate injection schemes for Pb-Pb in Run 3.

PS Spacing [ns]	SPS Spacing [ns]	No. Bunches/PS Batch	Present with batch
50 or 100	225	**2 (unsplit)** or 4 (split)	compression (100ns)
50 or **100**	**100**	**2** or 4	1. **Baseline** 2. **Batch compression** (50ns) with split bunches
50 or 100	75	2 or 4	
50 or 100	50	2 or **4**	1. **Slip stacking** with split bunches

Run 3—100/100 ns Baseline Scheme

The baseline scheme currently agreed with the LIU project, has the injection scheme parameters shown in Table 6 with the SPS injection kicker upgrade to a rise time of 100 ns. The choice of the number of PS batches per SPS train is based on optimisation shown in Figure 9.

Applying the luminosity model, with the assumption of 2013 transmission from injection to Stable Beams, gives

Table 6: Injection scheme parameters in the Run 3 100/100 ns baseline injection scheme.

100/100ns Scheme **PS Bunch Splitting**	E = 7Z TeV β^*= 0.5 m F_{Nb} = 1.28
Spacing PS [ns]	100
Spacing SPS [ns]	100
No. bunches/PS batch	2
No. PS batches/train	8
No. LHC trains	36
No. bunches/beam	576

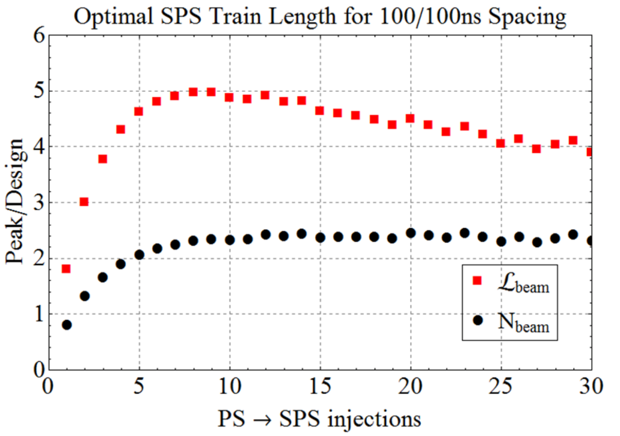


Figure 9: Optimisation of the number of PS batches injected to form a train in the SPS in the Run 3 100/100 ns baseline injection scheme.

the peak luminosity: $\hat{L} = 4 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ while the higher transmission that one can reasonably expect, as in 2011, yields

$$\hat{L} = 5 \times 10^{27}\,\mathrm{cm^{-2}s^{-1}}. \tag{6}$$

In the latter case, the bunch pair luminosity spectrum is as shown in Figure 10.

Run 3—other filling schemes

In this section we compare range of possible injection schemes, some no longer under consideration, to illustrate the potential for further improvement beyond the present "baseline" scheme presented in the previous subsection. Peak and integrated luminosities for various injections schemes are shown in Figures 11 and 12. Note that the upgrade to the SPS injection kicker, recently agreed upon [9], will provide a rise time of 100 ns so the shorter rise times are unlikely to be accessible and are shown here only for completeness.

We note that the peak luminosity will be higher for the 100 ns spacing in the PS with unsplit bunches. On the other hand, the higher brightness bunches decay faster so the effect on integrated luminosity is less. The luminosity decay curves for typical bunch pairs are shown in Figure 13. With these assumptions, it turns out that a somewhat higher integrated luminosity is obtained for the 50 ns PS spacing with

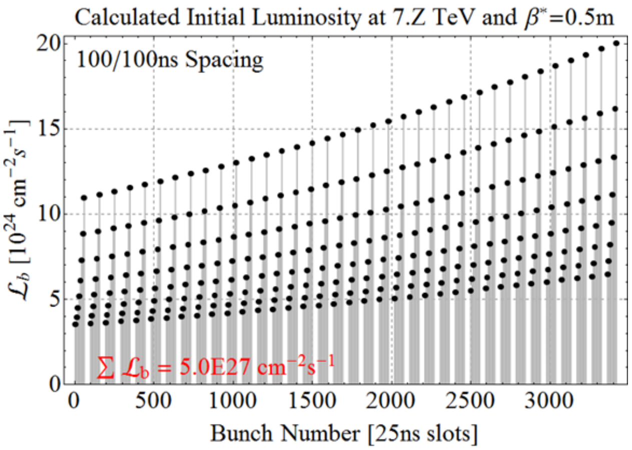


Figure 10: Initial bunch pair luminosities at ATLAS or CMS in the Run 3 100/100 ns baseline injection scheme.

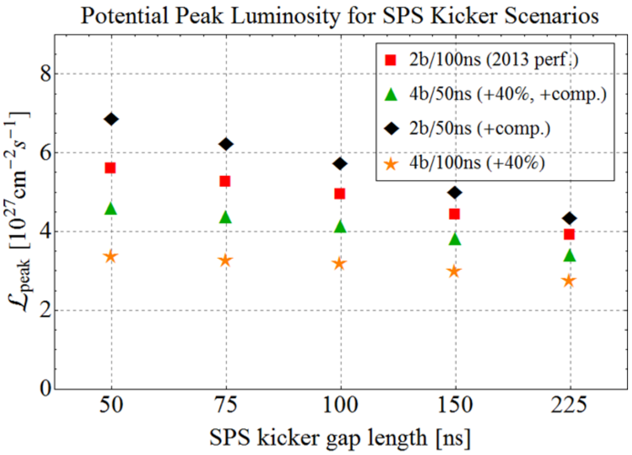


Figure 11: Peak luminosity versus SPS kicker rise time for various forms of PS batch, with and without the assumption of a 40% increase in single-bunch intensity.

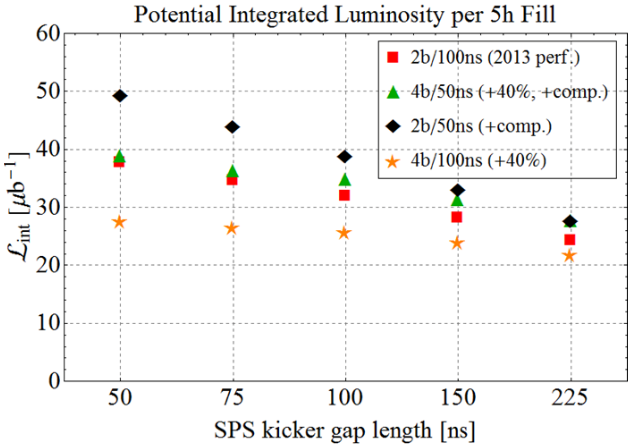


Figure 12: Integrated luminosity versus SPS kicker rise time for various forms of PS batch, with and without the assumption of a 40% increase in single-bunch intensity. Note that the red and green points for 100 ns have switched places between these two figures.

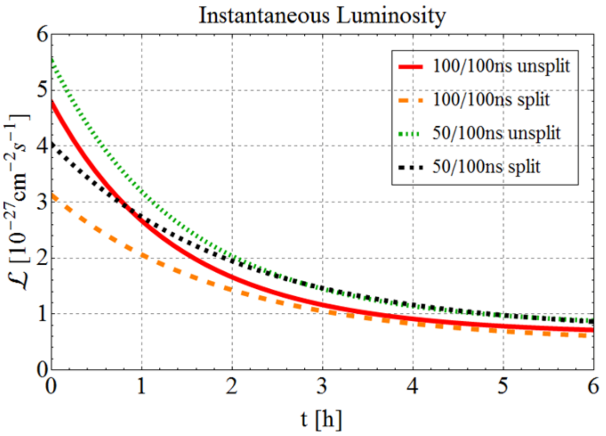


Figure 13: Luminosity decay in Run 3 for injection schemes with and without bunch-splitting in the PS.

Table 7: Summary of performance of possible injection schemes in Run 3, including what is presently available.

Injection scheme	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	
100/225ns	19	25	0.8 nb^{-1}	Present
100/100ns	25	32	1.0 nb^{-1}	Baseline
50/50ns	29	39	1.2 nb^{-1}	Slip Stacking
50/100ns	26	35	1.1 nb^{-1}	Batch compression

split bunches, which gives $k_b \simeq 1000$ to compare with the $k_b \simeq 600$ without bunch-splitting. However, at present, it appears that the 50 ns spacing is unlikely to be available for the reasons given in [9].

Luminosity Evolution, Main Upgrade Scenarios

As discussed in [9], there are reasonable prospects for a 40% increase in bunch intensity and for a slip-stacking scheme which could allow a 50 ns bunch spacing in the trains assembled in the SPS.

Taking into account different initial bunch luminosities and bunch luminosity decay times that one can expect in these schemes, the evolution of the instantaneous and integrated luminosities are shown in Figures 14 and 15. A summary of the expected integrated luminosity in individual fills and over a typical one-month run is given in Table 7.

Pb-Pb LUMINOSITY SUMMARY

The projections discussed in the preceding sections are summarised in Table 8. These predictions are somewhat conservative in that they do not include any improvements beyond the injection schemes, including intensity scaling, and the natural reduction of $\beta^* = 0.5\,\mathrm{m}$ and beam size that are to be expected from the increase of energy to $7Z\,\mathrm{TeV}$.

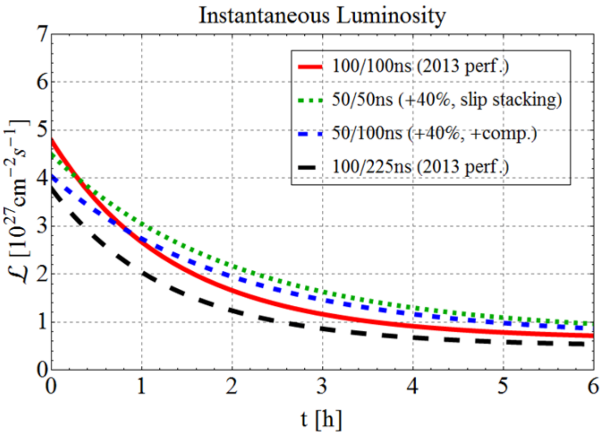


Figure 14: Luminosity decay for Pb-Pb in Run 3 estimated for the main upgrade injection schemes.

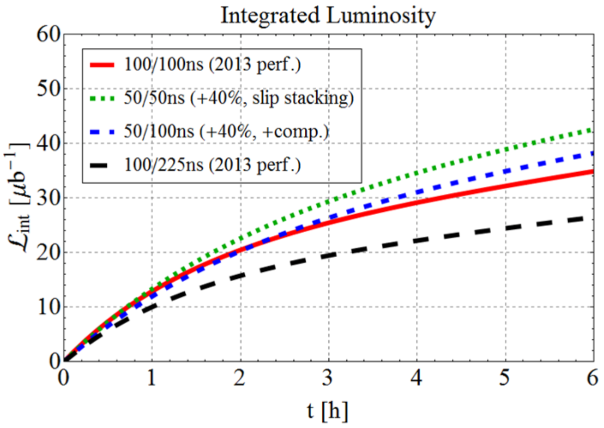
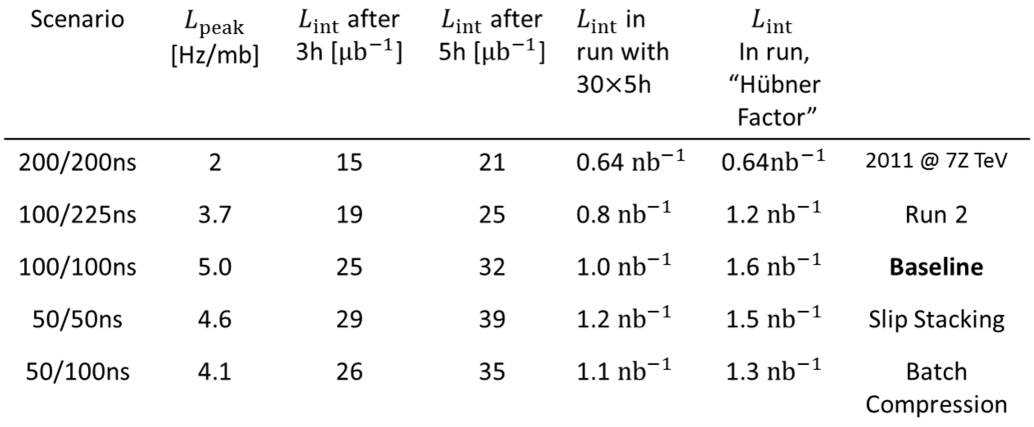


Figure 15: Integrated luminosity for Pb-Pb in Run 3 estimated for the main upgrade injection schemes.

The predictive luminosity model should be re-fitted to the real injector chain performance in the run-up to a given Pb-Pb run to re-optimise the length of the SPS trains. Some further remarks on the uncertainties in these estimates are in order:

- Any reductions of beam losses on the SPS flat bottom that can be achieved will have a big impact on the total luminosity.
- If peak luminosity limits (eg, the BFPP losses in ATLAS and CMS) are encountered, the initial luminosity may have to be levelled.
- Integrated luminosity estimates for a 24 day run are always very sensitive to a few days down-time of any essential system. So far we have been fairly lucky.
- No time has been deducted for possible p-p reference data runs.
- A 200 MHz RF system in LHC is in principle very beneficial for heavy ions (reduced IBS, better injection capture, ...) although theses benefits would need to be weighed against the disruption of replacing the base harmonic RF system.

Table 8: Summary of performance of possible injection schemes in Run 2, including what is presently available, and in Run 3.



Scenario	L_{peak} [Hz/mb]	L_{int} after 3h [μb^{-1}]	L_{int} after 5h [μb^{-1}]	L_{int} in run with 30×5h	L_{int} In run, "Hübner Factor"	
200/200ns	2	15	21	0.64 nb^{-1}	0.64nb^{-1}	2011 @ 7Z TeV
100/225ns	3.7	19	25	0.8 nb^{-1}	1.2 nb^{-1}	Run 2
100/100ns	5.0	25	32	1.0 nb^{-1}	1.6 nb^{-1}	**Baseline**
50/50ns	4.6	29	39	1.2 nb^{-1}	1.5 nb^{-1}	Slip Stacking
50/100ns	4.1	26	35	1.1 nb^{-1}	1.3 nb^{-1}	Batch Compression

- Greater operational efficiency than in 2011 would help, obviously.

RUN 2 PROJECTIONS FOR p-Pb

Although it had to work in a mode that was almost unprecedented at previous colliders, the LHC performed remarkably well as a p-Pb collider for a single fill in 2012 [6] and then for a one month run in 2013 [7, 19, 20, 21]. Before considering future proton-nucleus operation it is worth recalling a few of the special features of this run which, it is fair to say, was of unprecedented complexity in the history of hadron colliders.

Reminder of 2013 p-Pb run

Operating experience at all previous colliders is often said to have taught us that gradual optimisation of constant operating conditions is the path to high luminosity. In this run, the LHC experiments[3] asked us, on the contrary, to change operating conditions every few days. The most significant of these was the reversal of beam directions, from p-Pb to Pb-p, about half-way through the run which meant reversing not only the RF frequencies of the two rings during injection and ramp but also the off-momentum chromatic corrections applied to the optics during the squeeze after the re-locking of the RF frequencies. Figures 16 and 17 provide an overview of the luminosity production during these two phases. In addition, there were fairly complex luminosity levelling requirements at different times and reversals of the ALICE and LHCb spectrometer fields. Nevertheless we fulfilled all requests, thanks to the quality of the LHC hardware, software and operation, meticulous planning and some judicious risk-taking (with performance).

So, in our opinion, with the LHC, there is no *a priori* reason to fear complicated physics requests and we can indeed, with due care, flout the conventional wisdom of incremental improvement to constant operating conditions.

Bunch intensity in p-Pb operation

The p-Pb operation in 2012 and 2013 was constrained by the behaviour of the beam position monitors (BPMs).

On the one hand, fills were almost always dumped somewhat prematurely by some Pb bunch going below an intensity threshold. To avoid this in future, the monitors of the IR6 interlock BPMSs are being replaced by matched terminated striplines so that the high attenuation (used to reduce reflections in p beams in 2013 run) will not be needed. This will require tests with beams but low intensity Pb-bunches should no longer trigger the beam dump.

On the other hand, the maximum proton bunch intensity achieved in 2013 was $N_b \simeq 1.8 \times 10^{10}\,\mathrm{p/bunch}$. A test with $3\times10^{10}\,\mathrm{p/bunch}$ showed misreadings of a few BPMs whose source is still under investigation. If manageable (perhaps by the change of a few cards, or recalibration), we could go up to $5 \times 10^{10}\,\mathrm{p/bunch}$, the limit of the high sensitivity range of the BPMs [22]. Again tests with beams are most probably required to clarify the observation. In this case it is not obvious that the situation can be improved.

The total integrated luminosity per fill, summed over all experiments,

$$\sum_{\text{experiments}} \int_{\text{fill}} L_{AA}\, dt \leq \frac{\sum_c N_{\text{Pb}}}{\sigma_t} \qquad (7)$$

is bounded by the total intensity of the colliding Pb bunches and the total cross-section σ_t, and is independent of the proton intensity[4]. Higher proton bunch intensities will not increase the integrated luminosity per fill but will simply allow it to be delivered in a shorter time. This may not be useful in the 2017 run where the peak luminosity in ALICE should be levelled.

Given the turn-around time to refill the LHC beams, it follows that *the priority for improvements in BPM behaviour should be to avoid dumps due to low intensities of individual Pb bunches.* This will allow the left-hand member of the inequality (7) to approach equality with the right.

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[3] ALICE, in particular

[4] To an excellent approximation

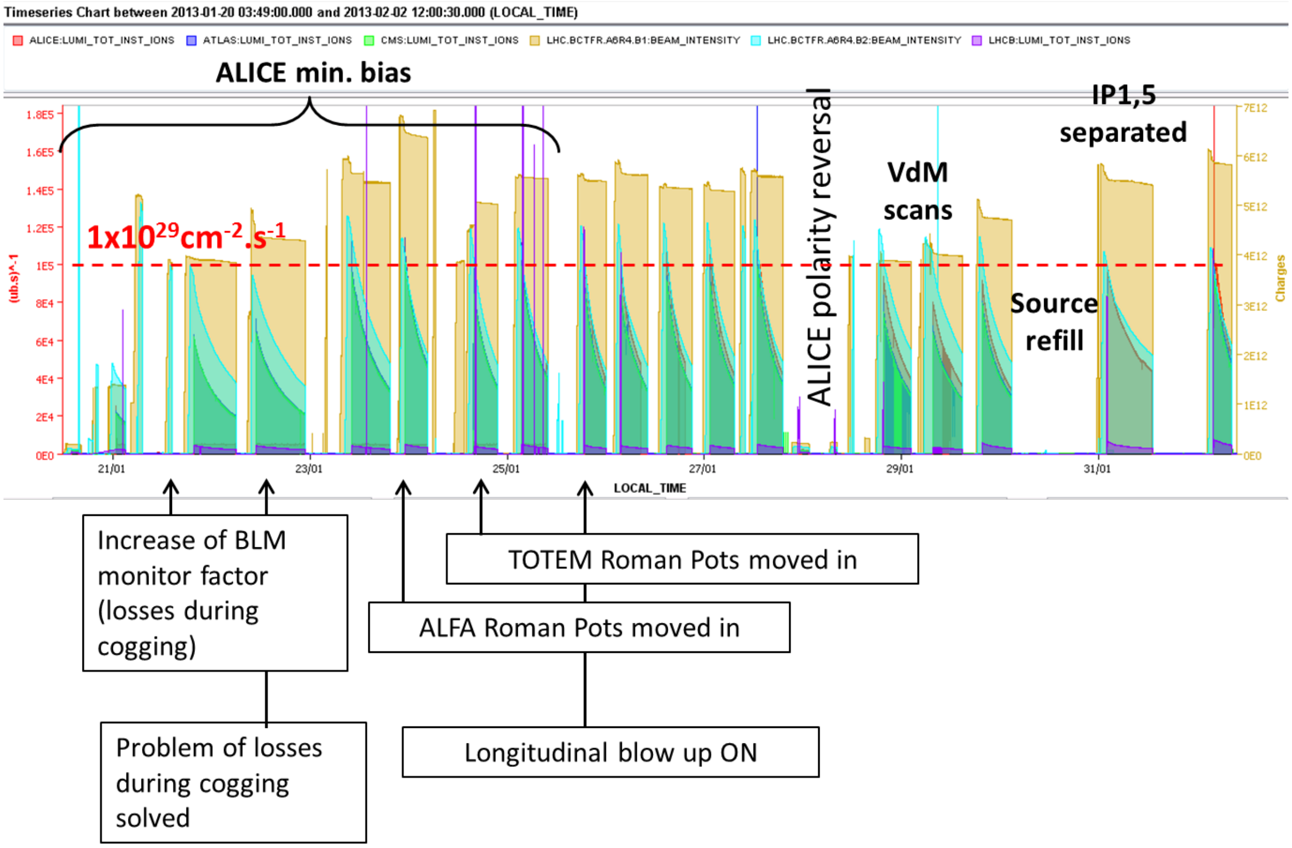

Figure 16: Overview of beam intensity and p-Pb luminosity production in 2013.

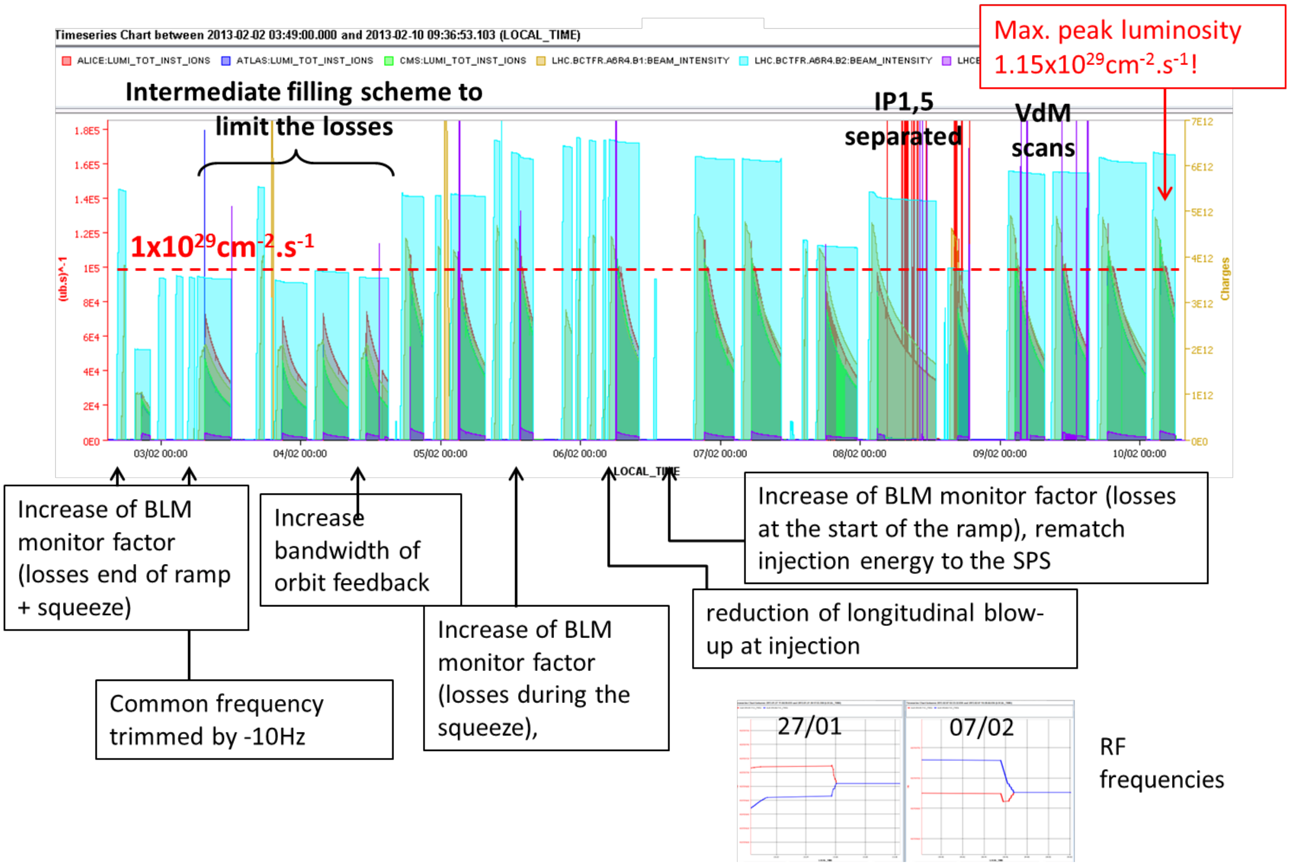

Figure 17: Overview of beam intensity and Pb-p luminosity production in 2013.

In the 2013 run, the difference was about a factor of 2 in most fills.

Performance for p-Pb in Run 2 and beyond

Table 9: Potential p-Pb parameters in Run 2.

E (Z GeV/c)	4	7
γ_p	4264	7463
N_p (10^{10} p/bunch)	1.8–5?	1.8–5?
N_{Pb} (10^{8} Pb/bunch)	1.6	1.6
k_b	430	430
β^* (m)	0.5	0.5
$\varepsilon_{n,p}$ (µm.rad)	3.5	3.5
$\varepsilon_{n,Pb}$ (µm.rad)	1.5	1.5
f (kHz)	11.245	11.245
L_{peak} (10^{29} cm^{-2}.s^{-1})	2.5–7?	4.3–12
L_{int} (nb^{-1})	60 (up to 110?)	110 (up to 220?)

Tentative parameters for the next p-Pb run (probably in 2017) are given in Table 9 with some indication of the effect of raising the proton intensity. In any case, this may be constrained by stability of the Pb beam (moving long range encounters) and $5 \times 10^{10}\,\mathrm{p/bunch}$ is the maximum reachable proton intensity in any case because of the BPM limits. The number of bunches per beam is taken from the baseline scenario for a Pb-Pb run in 2015-2016. The integrated luminosity estimates assume the same integrated to peak luminosity ratio as in 2013. In any case, as in 2013, ALICE will level at $1\times10^{28}\,\mathrm{cm^{-2}s^{-1}}$ (for some minimum-bias operation) and then at $1 \times 10^{29}\,\mathrm{cm^{-2}s^{-1}}$ in Run 2.

Considering the choice between the two possible energies given in Table 9, it should be remembered that a run at the same proton energy as the preceding p-p physics will be more efficient in several ways (less setup time, smaller momentum shifts, ...) than a run at reduced energy. Setting up a run at reduced energy would further complicate these hybrid colllision runs with their many changes of configuration and higher risk. Detailed plans for this run will also attempt to increase the luminosity delivered to LHCb.

Further increases of p-Pb luminosity in Run 3 and beyond will depend mainly on being able to inject higher total Pb intensity with more bunches but other limits (eg BFPP losses from the Pb beam) may come into play.

PEAK LUMINOSITY LIMITS

As has been discussed extensively elsewhere, see for example [18, 23, 24, 25, 26, 17, 27, 28, 29, 30], the intense electromagnetic fields accompanying the colliding nuclei can cause a number of interactions which make small changes to their mass, m or charge, Q. Each of these makes a secondary beam emerging from the IP with a fractional rigidity change

$$\delta = \frac{1 + \Delta m/m}{1 + \Delta Q/Q} - 1 \tag{8}$$

In the case of the Pb-Pb collisions in the LHC, these include, with the highest cross-section, the first-order bound-free pair production (BFPP1):

$$^{208}\mathrm{Pb}^{82+}{+}^{208}\mathrm{Pb}^{82+}{\to}^{208}\mathrm{Pb}^{82+}{+}^{208}\mathrm{Pb}^{81+} + \mathrm{e}^{+} \tag{9}$$

with

$$\sigma = 281\,\mathrm{b}, \delta = 0.01235. \tag{10}$$

The double bound-free pair production process (BFPP2):

$$^{208}\mathrm{Pb}^{82+}{+}^{208}\mathrm{Pb}^{82+}{\to}^{208}\mathrm{Pb}^{82+}{+}^{208}\mathrm{Pb}^{80+}{+}2\mathrm{e}^{+} \tag{11}$$

may also be detectable despite its much lower cross-section [31]

$$\sigma \approx 6\,\mathrm{mb}, \delta = 0.02500. \tag{12}$$

More significant processes are electromagnetic dissociation with emission of a single neutron (EMD1):

$$^{208}\mathrm{Pb}^{82+}{+}^{208}\mathrm{Pb}^{82+}{\to}^{208}\mathrm{Pb}^{82+}{+}^{207}\mathrm{Pb}^{82+} + \mathrm{n} \tag{13}$$

with

$$\sigma = 96\,\mathrm{b}, \delta = -0.00485 \tag{14}$$

or two neutrons (EMD2):

$$^{208}\mathrm{Pb}^{82+}{+}^{208}\mathrm{Pb}^{82+}{\to}^{208}\mathrm{Pb}^{82+}{+}^{206}\mathrm{Pb}^{82+} + 2\mathrm{n} \tag{15}$$

with

$$\sigma = 29\,\mathrm{b}, \delta = -0.00970. \tag{16}$$

The cross-sections for some of these processes are much larger than those of the hadronic interactions, $\sigma = 8\mathrm{b}$, that occur when the nuclei overlap; these contain much less power in their debris[5].

For the LHC, the consequences of BFPP1, in particular have been discussed since [24, 25] and in most detail in [32]: the secondary beams hit the beam pipe in the dispersion suppressor, depositing enough power to potentially quench a superconducting dipole magnet, as illustrated for ALICE in Figure 18. Note that the BFPP1 beam is smaller than main beam because its source is the luminous region, not the Beam 1 distribution.

The losses corresponding to these effects were clearly detected in the 2010 and 2011 Pb-Pb operation. Figure 19 shows beam-loss monitor signals clearly peaking at the predicted location of the BFPP1 loss.

Further evidence of the direct correlation of these signals with luminosity while the luminosity decayed during a regular physics fill and during the van der Meer scans, when the luminosity was deliberately varied, are shown in Figures 20 and 21.

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[5] For completeness, we should mention the double BFPP process where both nuclei gain an electron and the analogous double EMD process. For present purposes, without coincidence measurements, they are practically indistinguishable from BFPP1 and EMD1

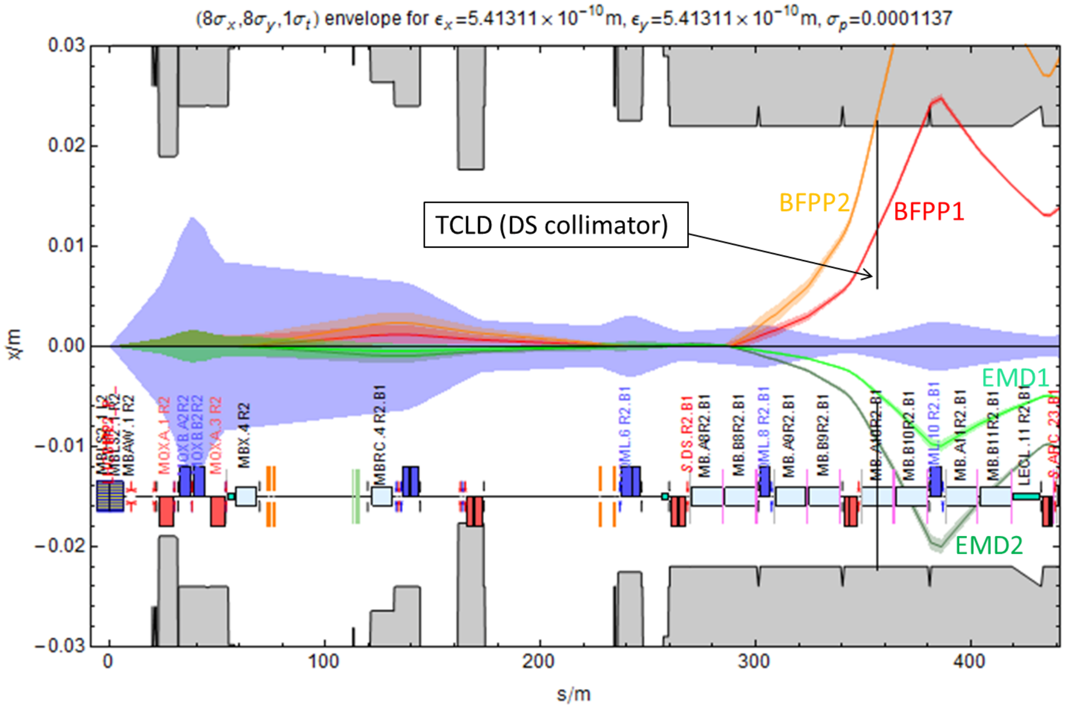

Figure 18: Horizontal projection of the secondary beams on the right side of IR2, emerging from the transformation of Beam 1 nuclei at the ALICE interaction point ($s = 0$). Beam 2 is similarly transformed on the left of the IP. Note that the EMD1 beam does not hit the beam pipe (it has a smaller $|\delta|$ but propagates through the arc to IR3 where it will be intercepted by the momentum collimation system).

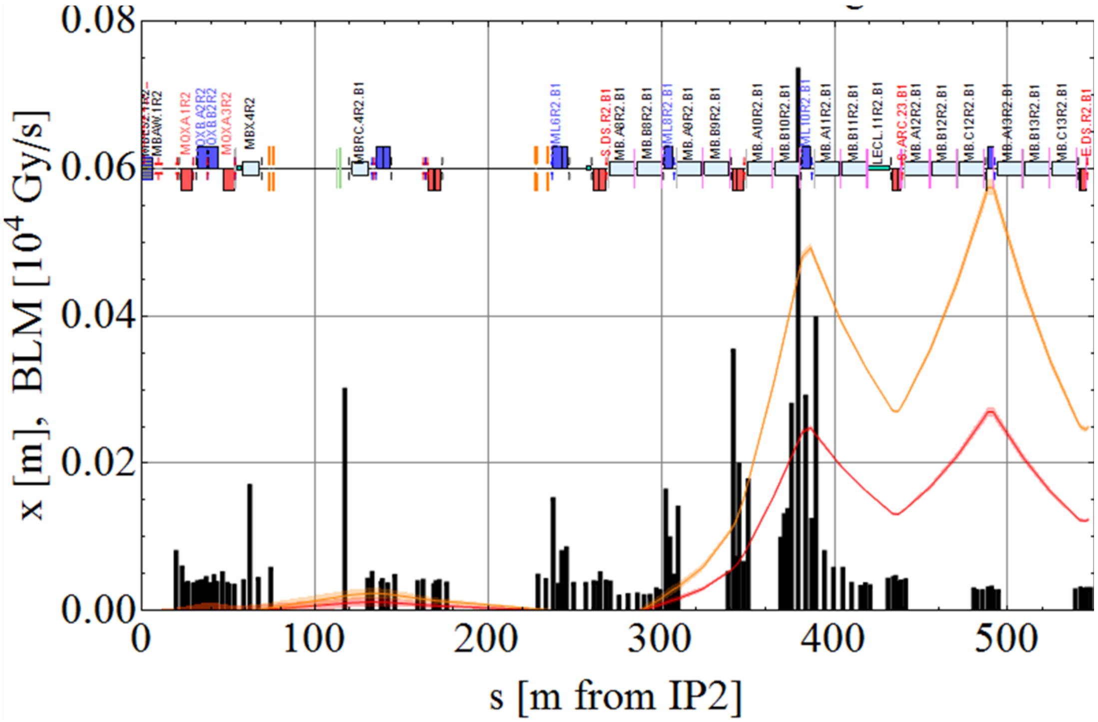

Figure 19: Beam-loss monitors in the dispersion suppressor right of IR2 during Pb-Pb collisions in 2011. The maximum losses occur precisely at the location expected from the calculations of BFPP1 shown in Figure 18.

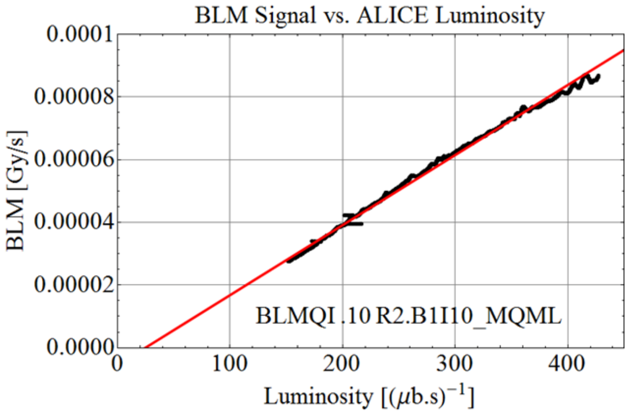

Figure 20: Correlation of highest BLM in IR2 signal with ALICE luminosity during a regular Pb-Pb physics fill in 2011.

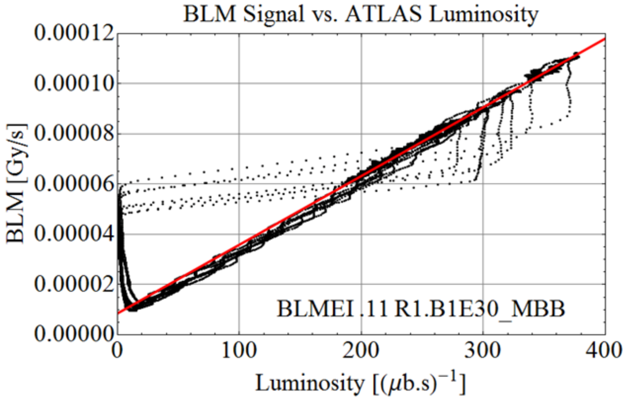

Figure 21: Correlation of highest BLM signal in IR1 with ATLAS luminosity during Pb-Pb van der Meer scans in 2011.

Luminosity goals

The ALICE experiment has set the Pb-Pb luminosity goal of $10\,\mathrm{nb}^{-1}$ for the period following its upgrade in LS2, some 10 times the initial LHC goal. For comparison with p-p running, this is equivalent to $0.43\,\mathrm{fb}^{-1}$ nucleon-nucleon luminosity. Moreover, approximately one annual run out of every three is expected to be devoted to p-Pb operation. To achieve the Pb-Pb goal, the annual integrated luminosity (1 month run) will need to be of order $1.5\,\mathrm{nb}^{-1}$. Accordingly, the detector upgrade will allow peak luminosities up to

$$\hat{L} \simeq 6\times 10^{7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} = 6\times\text{(original design)}. \quad (17)$$

While this value is somewhat beyond those given on the basis of the rather conservative predictions above, it is by no means out of reach if we consider some of the possibilities for improvement that we alluded to above. With this luminosity, the two most powerful secondary beams emerging on each side of the IP will carry powers of

$$P_{\mathrm{BFPP1}} \simeq 155\,\mathrm{W} \quad (18)$$

$$P_{\mathrm{EMD1}} \simeq 53\,\mathrm{W}. \quad (19)$$

We should of course consider that, with three experiments taking data, the peak luminosity will not last long because of the rapid burn-off. If need be, levelling strategies could be used to reduce peak luminosity but we must in any case aim for high total intensity in the beams.

It should also be remembered that the BFPP1 losses during p-Pb runs at high luminosity may become comparable to Pb-Pb (on one side of the IP). The cross-sections are smaller but the luminosity is correspondingly higher.

Quench limit

Estimates of the power density in the superconducting cable due to BFPP1 were given in [32] (see the FLUKA shower simulation in Figure 7) and have been recently confirmed by further FLUKA studies reported in [33]. According to these calculations, the maximum power density in the dipole coil at $E_b = 7Z$ TeV for a luminosity L is

$$P = \frac{L}{10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}} \times 15.5\,\mathrm{mW/cm}^{3} \quad (20)$$

whereas the latest quench limit estimates require

$$P < \begin{cases} 200\,\mathrm{mW/cm}^3 & \text{at } E_b = 4Z\text{ TeV} \\ 40\,\mathrm{mW/cm}^3 & \text{at } E_b = 7Z\text{ TeV} \end{cases} \quad (21)$$

Although these are considerably more optimistic than estimated in the past, it is clear that the levelled luminosities expected for ATLAS and CMS in Run 2 will already approach the limit and that the luminosity requested by the ALICE upgrade will be well beyond it and we can expect to quench the MB magnet and possibly also the adjacent MQ quadrupole.

Mitigation of the peak energy deposition by the bump method is expected to help but cannot yet be counted upon at this level. This is the basis for the proposal to implement the solution described in the following and recommended at the 2013 Collimation Review.

DS collimator solution

The BFPP1 and main beam are not sufficiently separated in the warm area so the TCLs are not useful as a mean to intercept the BFPP1 beam. The solution now planned for implementation in LS2 is also indicated in Figure 18. This is to install a collimator (TCLD) in the dispersion suppressor region before the impact point, where the BFPP1 beam is sufficiently well separated from the main beam. The favoured location for this collimator is indicated. It is also clear that, by varying the gap between the jaws of the TCLD, one can choose to intercept the EMD1 beam in addition to BFPP1 and EMD2. However it is not easy to select the very weak BFPP2 beam with a collimator located primarily to intercept BFPP1.

This solution was first discussed at [25] but rejected at the time since it would involve replacing or moving superconducting magnets in the cold section. The solution now adopted will replace one dipole with a geometrically equivalent assembly consisting to two shorter, higher-field magnets (now under development) with a collimator between them, as shown in Figure 22. Further information about the hardware is given in [33].

Resources expected in LS2 are sufficient only for an installation in IR2. Of course, the same problem of BFPP losses exists in the dispersion suppressors around ATLAS and CMS although the details of the loss locations somewhat different because of optical differences. Potential locations for TCLD collimators are shown in Figure 23.

In 2011, the highest BLM signals from BFPP in 2011 actually occurred on the right of IP5. We have some scope for mitigation using the orbit bump method tested in 2011 which will be made operational for Run 2 anyway. A final assessment of the need for these collimators should be possible at the end of the Pb-Pb run in 2015.

In the event that the high-field magnets are not ready, a possible alternative[6] might be to use a permanent orbit bump to pull the BFPP1 beam away from the beam pipe wall so that it would hit a collimator installed in the connection cryostat (where there are no magnets). This idea has still to be evaluated in detail.

ALICE Crossing Angle

When the beams are colliding, the vertical half-crossing angle at the ALICE experiment is [14]

$$\theta_{y_c} = \frac{\pm 490\,\mu\mathrm{rad}}{E_b/(7Z\,\mathrm{TeV})} + \theta_{y\mathrm{ext}} \tag{22}$$

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 but not 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) [34, 35], the condition

$$|\theta_{y_c}| < 60\,\mu\mathrm{rad} \tag{23}$$

has been imposed in heavy-ion operation up till now. With bunch spacings, $S_b/c = 100\,\mathrm{ns}$, as foreseen in the original LHC design [4], this provides adequate separation at the parasitic beam-beam encounters around the IP.

Some developments in the injectors (see [9] are aimed at increasing the number of bunches by achieving $S_b/c = 50\,\mathrm{ns}$—half of the original design—for at least some of the spacings between bunches in the LHC. Figure 24 shows that, for this value, it is no longer possible to satisfy the usual separation requirements in ALICE together with (23) at the closest parasitic encounters to the IP. However, experience [14] 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, $r_{12}/\max(\sigma_x.\sigma_y) > 3$ which should reduce the parasitic luminosity to acceptable levels [35]. 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. These considerations may lead to an upgrade of the TCLIA collimator to provide additional aperture clearance.

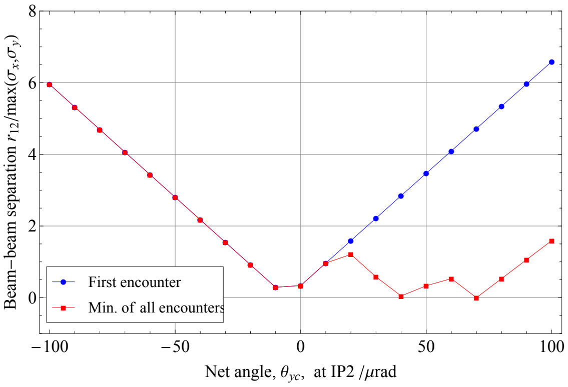

Figure 24: Beam-beam separation in IR2 as a function of the net half-crossing angle at the IP, θ_{yc}, for $E_b = 7Z$ TeV with $\beta^* = 0.5\,\mathrm{m}$, the design Pb normalised emittance of $\varepsilon_n = 1.5\,\mu\mathrm{m}$ and a regular bunch spacing of 50 ns and with the ALICE spectrometer polarity such as to contribute a positive crossing angle at the interaction point. At $\theta_{yc} = +70\,\mu\mathrm{rad}$, 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.

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.

Collimation Inefficiency

As discussed extensively in the past [36, 37, 38, 39, 40] the nuclear interactions [30] of heavy ions with the collimators reduce the collimation to a single-stage system with a higher collimation inefficiency. This translates into a limit on total intensity of Pb beams. Such limits have been encountered already in some unfavourable operational situations (eg, with Pb beam sizes larger than p, putting beams into collision with off-momentum p-Pb orbits). Again some mitigation has been achieved with a bump strategy in IR7 [7]. At present, this is not expected to be a principal limit in Run 2 or Run 3 but new work to improve the tracking simulations is starting and it is important to keep an eye on this problem.

STOCHASTIC COOLING OF Pb BEAMS

Inspired by spectacular luminosity enhancement [41] by 3D stochastic cooling of bunched Au and U beams at

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[6] Thanks to M. Giovannozzi and L. Bottura for a useful discussion in which this idea emerged.

[7] This should work even better for protons and may be worth trying in 2015.

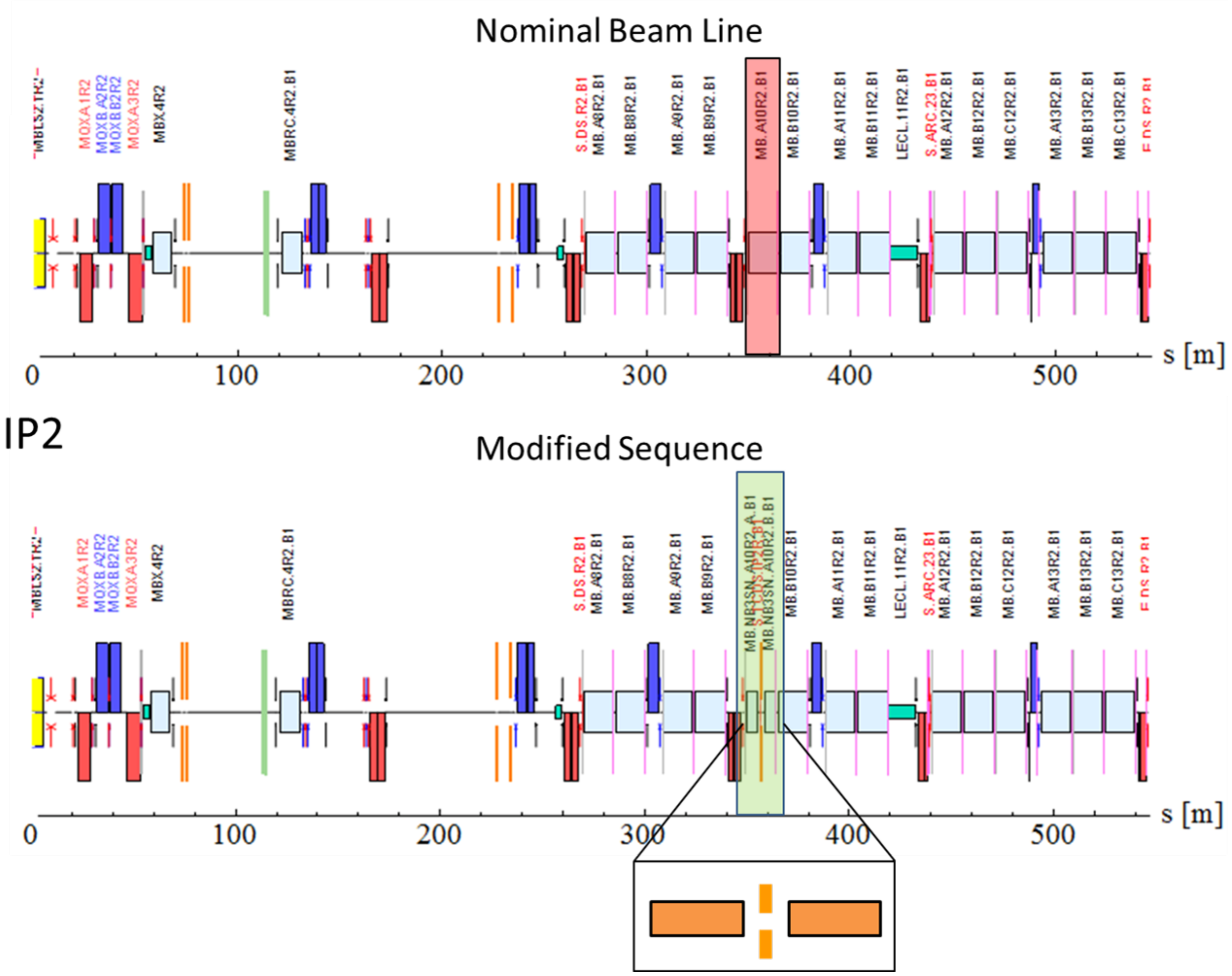

Figure 22: DS collimator installation in IR2. Magnet MB.A10R2 to be replaced by two 11T dipoles each with L = 5.3m sorrounding a collimator jaw with L = 1m.

RHIC, we have established an informal collaboration with Brookhaven National Laboratory (the latest step was a visit from Mike Blaskiewicz in early summer) and undertaken a first study of the potential of a similar installation to cool heavy ion beams in the LHC. Simulation results were presented at the recent COOL13 workshop [42]. Figure 25 shows the potential for luminosity enhancement for typical bunch pairs in similar conditions to [42] except that three experiments are taking data so the cooling has to counter a much stronger luminosity burn-off. Nevertheless a substantial gain in integrated luminosity is evident.

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.

Studies are beginning to see whether the promise of a stochastic cooling system, at an apparently modest cost, can be realised 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 they 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.

At present we are considering a possible demonstration of longitudinal cooling in 2015-16. The aim would be to use the existing Schottky pickup and an “off-the-shelf” 5 GHz amplifier. One of the unused shaker chambers in IR4 could be replaced with a suitable kicker (when ready) in a technical stop before the Pb-Pb run (to avoid the question of compatibility with proton beams). If successful, we would hope to strengthen our collaboration with BNL, to benefit from their experience and define fast-track implementation of a full system.

The 200 MHz RF system proposed for p-p could also be

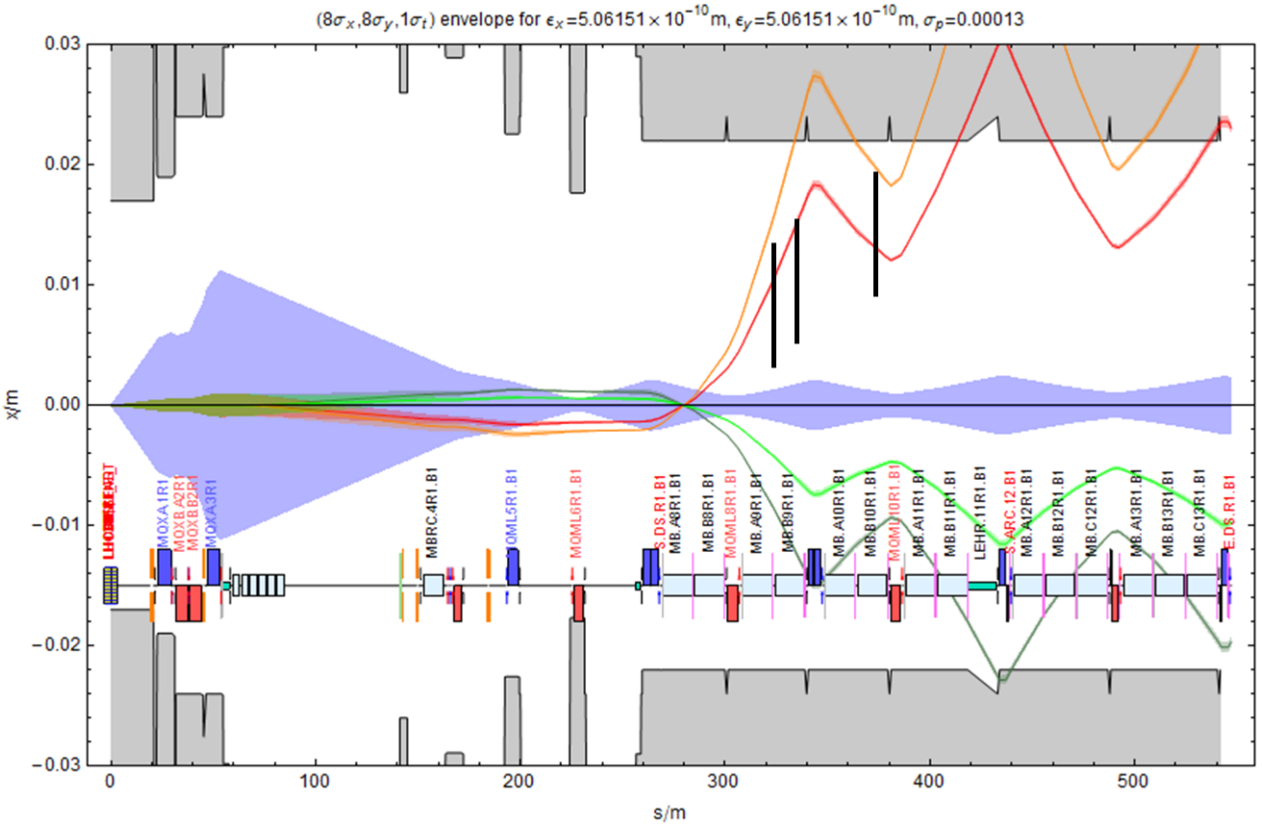

Figure 23: Secondary beams from the ATLAS collision point and possible DS Collimator locations, shown as black lines, on the right of IP1. The situation around CMS is similar.

expected to improve cooling.

CONCLUSIONS

In Run 2, Pb-Pb and p-Pb luminosities should already exceed the LHC design and the prospects of reaching the LHC design goal of $1\,\mathrm{nb}^{-1}$ in Pb-Pb are very good. A levelling strategy to meet the requirements of ALICE has been proposed.

With the current baseline upgrades foreseen from the injectors, the peak luminosity will increase further in Run 3 and beyond. Further gains from injectors should nevertheless be pursued as a priority to achieve the HL-LHC goal of $10\,\mathrm{nb}^{-1}$. These could include injection schemes for more, and brighter, bunches (50 ns spacing), means to reduce the intensity decay of bunches in the SPS.

The potential p-Pb performance depends critically on resolution of BPM problems, above all to avoid beam dumps due to single low-intensity Pb bunches.

Dispersion suppressor collimators are foreseen to be installed around ALICE in LS2; operating experience in 2015 will clarify the gain to be expected from them.

Following the success at RHIC, we also recommend initiating a fast track to stochastic cooling implementation. First simulations have shown very promising results but some key problems remain to be solved.

ACKNOWLEDGEMENTS

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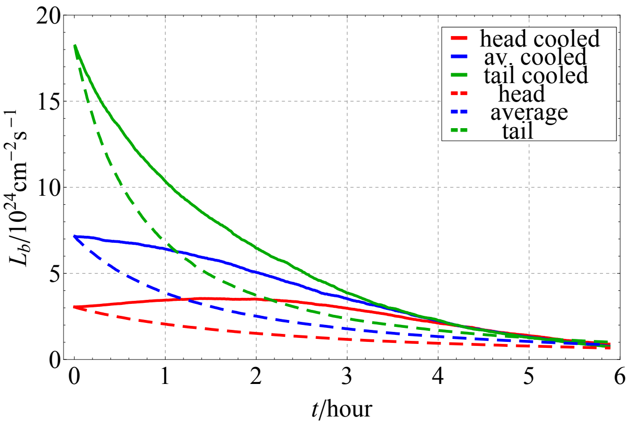

Figure 25: Evolution of bunch-pair luminosity with three experiments in collisions for three typical bunches in a train, with (solid curves) and without (dashed curves) the effect of stochastic cooling in all three planes. Bunch parameters are similar to the examples shown in the paper [42], except that luminosity burn-off is stronger with three experiments taking collisions. The bunch parameters are different from those shown in Figure 5.

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