

# SEMI-EMPIRICAL MODEL FOR OPTIMISING FUTURE HEAVY-ION LUMINOSITY OF THE LHC

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## Abstract

The wide spectrum of intensities and emittances imprinted on the LHC Pb bunches during the accumulation of bunch trains in the injector chain result in a significant spread in the single bunch luminosities and lifetimes in collision. Based on the data collected in the 2011 Pb-Pb run, an empirical model is derived to predict the single-bunch peak luminosity depending on the bunch's position within the beam. In combination with this model, simulations of representative bunches are used to estimate the luminosity evolution for the complete ensemble of bunches. Several options are being considered to improve the injector performance and to increase the number of bunches in the LHC, leading to several potential injection scenarios, resulting in different peak and integrated luminosities. The most important options for after the long shutdown (LS) 1 and 2 are evaluated and compared.

## THE PEAK-LUMINOSITY MODEL

The main goal is to maximise the integrated luminosity,  $\mathcal{L}_{\text{int}}$ , for the experiments. It naturally increases with the time the beams are in collisions, i.e. the fill length, but also with the available peak luminosity,  $\mathcal{L}_{\text{peak}}$ , which is the sum of the single bunch luminosities at the start of collisions. In general the (peak) luminosity increases with the number of bunches per beam and the brightness ( $= N_b/\epsilon_n$ ) per bunch.

In contrast to the p-p operation, individual Pb bunches in the LHC have a wide spectrum of intensities,  $N_b$ , and emittances,  $\epsilon_n$ , imprinted during the accumulation of bunches from the PS in the SPS (red line) and bunch trains from the SPS in the LHC (green line), resulting in the typical structure of the bunch-by-bunch peak luminosities,  $\mathcal{L}_b$ , (black dots) shown in Fig. 1, as measured by the ATLAS experiment. A detailed analysis of those Pb bunch-by-bunch differences in the LHC can be found in [1].

The bunch degradation in the SPS is influenced by several effects of different strength (mainly IBS, space charge and RF noise). It is non-trivial to distinguish between them and extremely difficult to predict the amount of particle losses and beam blow up during the SPS cycle. Therefore, from a pragmatic point of view, it is desirable to find a description of what is observed in the LHC without relying on the detailed knowledge of the processes happening in the SPS.

### Peak Luminosity Degradation in the SPS & LHC

By inspection of Fig. 1 it can be seen that the leading bunches of each train give the smallest  $\mathcal{L}_b$ . Those were injected first from the PS into the SPS and thus had to suffer for the longest time from the strong dynamic effects at the SPS flat-bottom. On the other hand, the energy ramp is

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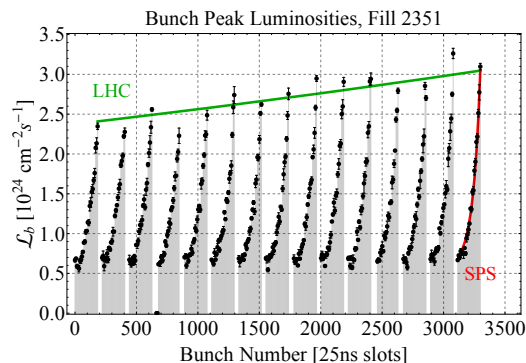


Figure 1: Peak bunch-by-bunch luminosities.

started right after the injection of the last bunch, hence this bunch spends almost no time at low energy in the SPS and does not have time to decay. In this manner, and with the assumption that all bunches produced in the PS are equal within statistics, the inverse order of the injections from the PS can be interpreted as the increasing amount of waiting time in the SPS. Therefore, the red curve in Fig. 1 represents the reduction with time of  $\mathcal{L}_b$  along a single train, caused by the length of the SPS injection procedure.

The exact functional description of the decay curve is unknown, however, the empirical approach of an exponential decay

$$\sqrt{\mathcal{L}_b (SPS)} = a \exp[-bx] + c \quad (1)$$

seems to fit the data well and was adopted. Since the model is built on the ATLAS (or equivalent CMS) luminosity data, only equal bunches ( $N_b = N_{b1} = N_{b2}$ ,  $\epsilon_n = \epsilon_{n1} = \epsilon_{n2}$ ) are colliding and  $\sqrt{\mathcal{L}_b} \propto N_b/\sqrt{\epsilon_n}$ . We chose to fit the square root of the bunch luminosities in order to gain a closer relation to the bunch brightness.

A similar, but less pronounced, slope is imprinted on the LHC flat-bottom train-by-train (green line in Fig. 1). By grouping bunches from equivalent PS injections between trains, which had spent the same time in SPS, a comparable interpretation of the  $\mathcal{L}_b$  reduction with time caused by the length of the LHC injection plateau can be made.

The decay in the SPS is much stronger compared to the one arising in the LHC, because of the lower energy in the SPS. Therefore, the degradation in the LHC can be seen as a modulation of the SPS effect and it is sufficient to fit Eq. (1) with  $c = 0$ :

$$\sqrt{\mathcal{L}_b (LHC)} = A \exp[-Bx]. \quad (2)$$

### The Full Model

$\mathcal{L}_b$  of a colliding bunch pair strongly depends on the position of the bunches inside the train ( $n_{bu}$ ) and of the train

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inside the beam ( $n_{tr}$ ). To obtain an analytical equation describing the peak values of the (square root of the) luminosity for each bunch as a function of its position in the beam, the LHC decay in Eq. (2) has to be normalised (divided by  $A$ ), to act only as a modulation, and multiplied with Eq. (1):

$$\sqrt{\mathcal{L}_b} = F_{Nb} \exp[-\bar{B} n_{tr}] (\bar{a} \exp[-\bar{b} n_{bu}] + \bar{c}). \quad (3)$$

To allow for a potential intensity improvement compared to the 2011 data, a linear intensity scaling,  $F_{Nb}$ , was introduced. It has to be underlined, that this intensity scaling can only be an approximation. In particular, the shape of Eq. (1) will change with the bunch conditions delivered from the PS due to the underlying dynamic effects, which are strongly dependent on the bunch brightnesses.

Fits were done to the last train's luminosity data in each suitable fill from 2011. A general description is obtained by using the averages of the fitting constants  $\bar{a}$ ,  $\bar{b}$  and  $\bar{c}$  in Eq. (3).

Bunches in the tail of the trains show a faster decay in the LHC compared to head bunches, mainly because of their different intensities. Individual decay curves would be required to describe the effect in full detail. However, since it is desired to find a single equation describing all bunches, a PS batch with average beam parameters from the core of the train is chosen for the fit. The averages of the fit parameters  $\bar{A}$  and  $\bar{B}$  of all suitable fills from 2011 give the general description of the LHC degradation used in Eq. (3).

Comparisons of the results from Eq. (3) with data show an agreement of a few percent for many fills of the 2011 run. This is a satisfying agreement, considering the model is based on an average over many fills.

## MODELLING THE TOTAL LUMINOSITY EVOLUTION

Ultrapерipheral electromagnetic interactions cause the initial luminosity to decay (burn-off) rapidly in heavy-ion collisions [2]. The beam and luminosity evolution of a single bunch pair during collisions can be predicted with the Collider Time Evolution (CTE) program [3]. Due to the large bunch-by-bunch differences, bunches at the head of a train will evolve differently from bunches sitting in the core or tail. Therefore, a simulation should be done for all individual bunches separately depending on their beam parameters. The sum over all bunches would then give the total beam and luminosity evolution. To save simulation resources and time, an interpolation method was devised:

The evolution of a set of typical bunches covering the expected spectrum of bunch properties at the desired collision energy is simulated with CTE. The simulated luminosity decay for each of these bunches is parametrised by an exponential fit. Finally, the resulting fit parameters are interpolated linearly as a function of  $\mathcal{L}_b$ . From those interpolations, luminosity decay curves can be extracted for individual bunches with a given peak luminosity.

## LUMINOSITY ESTIMATES

### Post LS1 - Optimising the SPS Train Length

Already in the 2013 p-Pb run [4] the Pb bunch intensity injected into the LHC was increased by about 30% compared to 2011. Together with a reduction in  $\beta^*$  and the beam energy increase to 6.5Z TeV,  $\mathcal{L}_{peak}$  can be expected to reach  $2.8 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ , a factor 2.8 above design.

As a result of an optics change in the SPS [5] the minimum spacing between PS batches is increased to 225 ns, compared to 200 ns in 2011. On the other hand, a batch compression to 100 ns (it was 200 ns) spacing between bunches in one PS batch could be performed. These modifications would allow a Pb filling scheme with an alternating bunch spacing of 100/225 ns and increase the number of bunches per beam.

The derivation of the model above has shown that the longer the bunches stay in the SPS, the more brightness they lose. Thus, there is an optimum number of PS batches per train, providing the highest  $\mathcal{L}_{peak}$  for a given bunch spacing. Figure 2 shows that the maximum of the total peak luminosity (calculated with Eq. (3))

$$\mathcal{L}_{peak} = 3.7 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1} \quad (4)$$

is reached with 7 PS injections, i.e., 14 bunches per train, and 29 trains per beam.

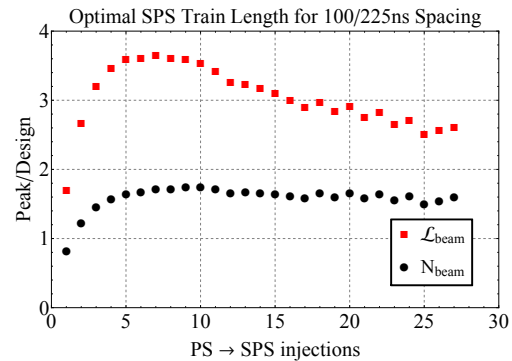


Figure 2: Optimisation of the SPS train length.

### Post LS2 - Injector Scenarios

Under the scope of the LIU (LHC Injector Upgrade) project [6] several options are under study to upgrade the heavy-ion injector complex. The impact of the most important upgrades on the Pb-Pb luminosity will be addressed in the following: the intensity increase in LEIR, the batch compression, bunch splitting or slip stacking in the PS (defining the bunch spacing within batches) and the choice of the SPS kicker rise-time (defining the PS batch spacing).

The potential peak (top) and integrated (bottom) luminosity after a 5 h fill at 7Z TeV is shown in Fig. 3 as a function of the SPS kicker rise-time for 4 PS batch scenarios: the baseline (red squares) assumes 2 bunches with 2013 intensities spaced by 100 ns. From that, further upgrades are considered: batch compression to 50 ns and/or 40% more

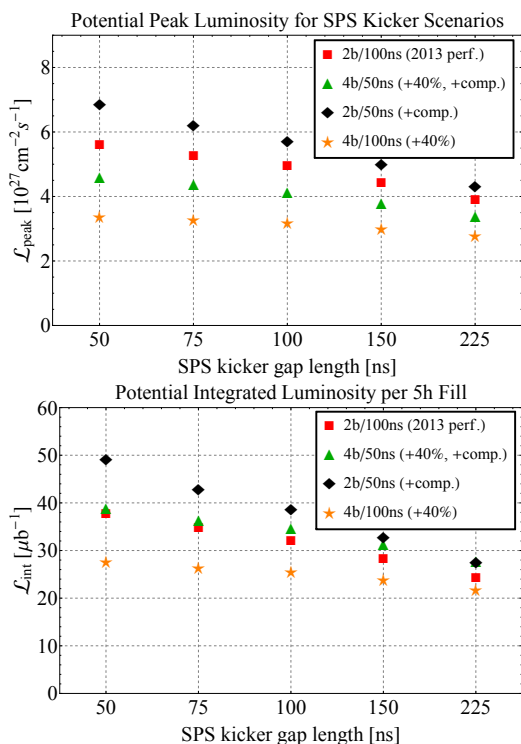


Figure 3: Expected peak and integrated luminosity for a 5h fill for different filling scheme scenarios.

Table 1: Summary of Luminosity Estimates for After LS2

Scenario	$\mathcal{L}_{\text{peak}}$ [Hz/mb]	$\mathcal{L}_{\text{int}}$ [ $\mu\text{b}^{-1}$ ]	$\mathcal{L}_{\text{int/run}}$ [ $\text{nb}^{-1}$ ]	$10 \text{ nb}^{-1}$ [years]
200/200 ns	3.0	20	0.6	17
100/225 ns	3.9	25	0.8	13
100/100 ns	5.0	32	1.0	10
50/50 ns	4.6	39	1.2	9
50/100 ns	4.1	35	1.1	9

intensity out of LEIR. In the latter case the 2 bunches have to be split in 4 to mitigate the dynamic effects at low energy.

The total luminosity decreases with the SPS kicker gap. The longer the gap, the longer the trains and the fewer trains fit into the LHC. It is, however, important to notice, that the green triangles, describing the case of split bunches and 50 ns batch compression, give a lower  $\mathcal{L}_{\text{peak}}$  than the baseline case, but catch up in  $\mathcal{L}_{\text{int}}$ . This can be understood by looking at Fig. 4, where the instantaneous (top) and integrated (bottom) luminosity evolutions are displayed for those two cases as the blue dashed and red solid line, respectively, for a 100 ns SPS kicker. The instantaneous luminosity has a higher  $\mathcal{L}_{\text{peak}}$  but faster decay in the red case. The total beam intensity is distributed over more bunches for the blue line reducing the burn-off rate which results in a higher  $\mathcal{L}_{\text{int}}$ . This underlines that for the optimal Pb-Pb performance, both the achievable peak and integrated luminosity have to be considered in the choice of the filling scheme. Table 1 lists  $\mathcal{L}_{\text{peak}}$ ,  $\mathcal{L}_{\text{int}}$  after 5 h,  $\mathcal{L}_{\text{int}}$  per run and the number of years

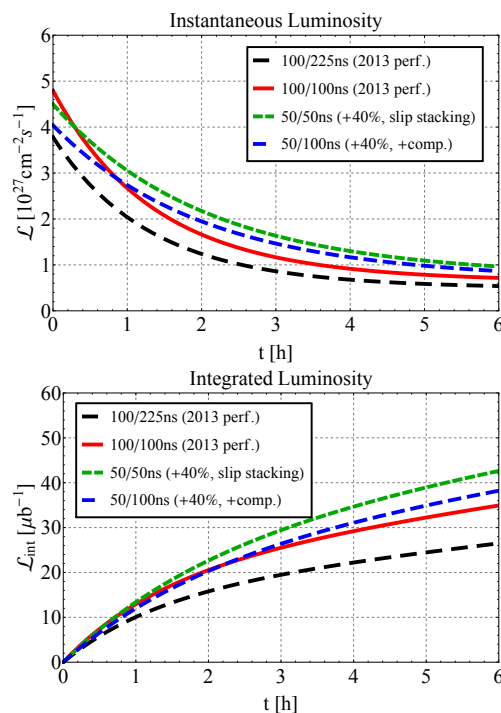


Figure 4: Expected instantaneous and integrated luminosity evolution for different filling scheme scenarios. Labelling: PS/SPS spacing in ns.

needed to integrate the goal of  $10 \text{ nb}^{-1}$  at 7Z TeV assuming 30 fills of 5 h each per run.

## CONCLUSIONS

The derived semi-empirical luminosity model for Pb-Pb collisions in the LHC has been used to make predictions for future runs after LS1 and 2, investigating several injector upgrade scenarios. The largest uncertainties of the model are the data based decay curves in the SPS and LHC. Those strongly depend on the dynamic effects at the injection plateaus, which are difficult to predict, especially in the SPS. Nevertheless, those curves could always be refitted in the run-up to a given Pb-Pb run to update the predictions and re-optimize the length of the SPS trains.

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