ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB172

BUNCH LUMINOSITY VARIATIONS IN LHC RUN 2

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Abstract

The LHC is designed to collide intense bunches of protons circulating in opposite directions at the four experiments installed in its ring with tightly defined conditions, aimed to maximize the delivered integrated luminosity to the experiments. Not least of these conditions is the maximum level of bunch-to-bunch fluctuation in the luminosity, in particular when levelling at maximum acceptable event rate at the experiments. Analysis results of the bunch-to-bunch luminosity variations in LHC Run 2 are presented here. In particular, the observed correlations with the LHC filling pattern and the underlying sources that can enhance bunch-dependent losses or emittance blow-up from injection to collisions are discussed. In Run 2 conditions, bunch luminosity fluctuations remained below 10% at the start of collisions and gradually increased with time, however without affecting the experiments as the luminosity was not levelled. Projections for Run 3 and HL-LHC operation are discussed along with envisaged mitigation measures.

INTRODUCTION

The LHC is a high energy circular accelerator where two bunched beams of protons circulating in opposite directions collide at the center of the experiments located in four points around the ring. The machine operates an optimised set of parameters aiming to maximize the integrated luminosity delivered to the experiments. A limiting parameter for the machine operation is the total instantaneous luminosity that is related to the observed event rate in the experiment, and their capacity to record the interaction data. The instantaneous luminosity for the collision of two bunches is defined in the basic form as:

$$\mathscr{L}_{b,inst} = \frac{f N_1 N_2}{2\pi \sqrt{\beta^*_{1,2x}\,\beta^*_{1,2y}}\sqrt{\epsilon_{1x}+\epsilon_{1x}}\,\sqrt{\epsilon_{1y}+\epsilon_{2y}}} S, \tag{1}$$

with S a factor depending on the bunch length σ_s, spot size in the crossing plane $\sigma_\times$, and the crossing angle $\phi_\times$.

For Run 2, LHC was tuned to provide around 50 pile-up events at the start of collisions. Then the luminosity was left to decay in time with the intensity burn-off, and only re-tuning at regular intervals the basic parameters (β^*, $\phi_\times$) to stay close to optimal. The bunch structure of the machine produces bunch-to-bunch variations (**btb-variations**) in the delivered luminosity, which from Eq. (1) results:

$$\frac{\delta\mathscr{L}}{\mathscr{L}} = \sqrt{2\left(\frac{\delta N}{N}\right)^2 + \frac{1}{8}\left(\frac{\delta\epsilon_x}{\epsilon_x}\right)^2 + \frac{1}{8}\left(\frac{\delta\epsilon_y}{\epsilon_y}\right)^2}, \tag{2}$$

considering equivalence between the two beams and no correlations, graphically shown in Fig. 1, where the luminosity variation is plotted versus the transverse emittance spread, for different intensity variations. When operating at maximum acceptable pile-up, the optimal configuration is that the luminosity btb-variations stay around 10% to be in the shadow of variations in the pile-up statistics (15%).

In LHC btb-variations in the emittance or intensity can originate from different sources: i) during the beam production at the injector chain, ii) effects during injection at low-energy and in acceleration that can affect individual bunches or trains, iii) beam dynamic effects during stable beams that affect selected bunches, and last, iv) asymmetric burn off due to variable schedule of collisions in the four interaction points. The following sections highlight results on the luminosity btb-variations in LHC Run 2 illustrating the above effects.

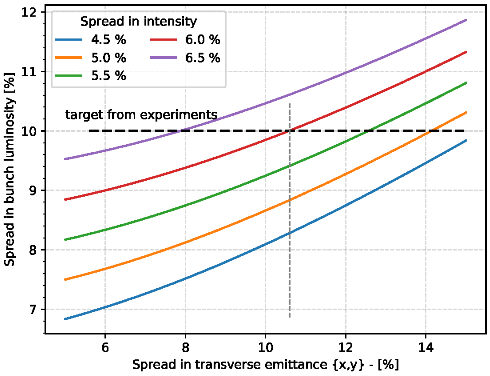

Figure 1: Bunch-to-bunch luminosity variation dependence on bunch emittance and intensity variations.

VARIATIONS AT INJECTION

In a typical physics fill of Run 2, LHC receives 20 injections of bunch trains per beam. These bunch trains originate from Linac pulses going through a complex handling in the injector chain, where the individual bunches are formed. For example, initial pulses are merged and then split to form series of bunches with the correct time spacing (25 ns) and intensity [1]. Thus, variations in the parameters (intensity and emittance for example) between the initial pulses would leave their trace in the generated bunch trains. Losses or other dynamic effects in the injectors can cause variations between the pulses following the cascade mode of the production process.

The distribution of bunch intensity and transverse emittance using data from of all physics fills of 2018 is shown in Fig. 2. Overall the variations in both the intensity and emittance remain below 5%, which demonstrates the performance capabilities of the injector chain.

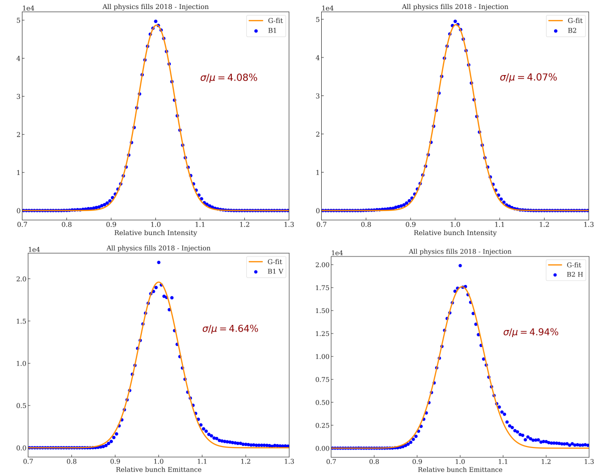

Figure 2: Distribution of the relative bunch intensity (top) and transverse emittance (bottom) at injection from 263 fills with more than 2500 bunches in 2018. Left: beam 1, right: beam 2. The bunch data are normalized to the mean of all bunches per fill.

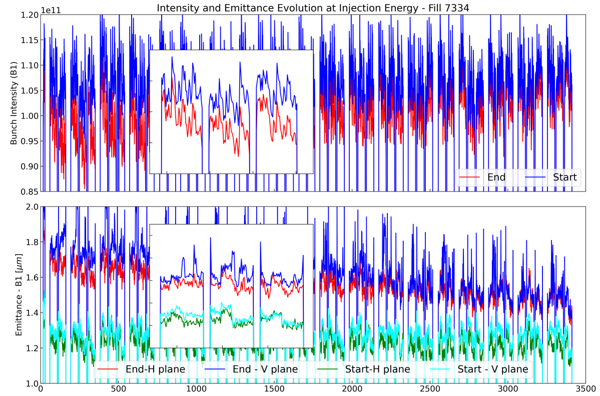

Figure 3: Typical intensity and emittance per bunch distributions at FB for an LHC fill. The Start corresponds to measurements done the moment each bunch is injected, and End to measurements done at the end of the injection processes. The low bunch numbers are injected first. The insets are zoomed distributions in a set of bunch trains corresponding to a complete injection from SPS to LHC.

Once inside the LHC, the beams remain at the injection energy of 450 GeV (flat-bottom FB) during the whole injection process, which for the bunches injected first, corresponds to approx 30 minutes. The presence of noise, IBS or other beam dynamic effects would thus affect differently the bunches.

Figure 3 shows a typical spectrum of the bunch intensity and emittance measured at FB. The bunch intensity evolution clearly depends on the time spent at FB, and the bunch position within the train (see inset), a typical effect of the e-cloud that dominates the btb-variations [2]. Instead, the emittance data exhibits the variation between bunches within the train (see inset) originating from different production batches in the injectors. Table 1 summarizes the evolution of the RMS distribution for bunch intensity and emittance during injection and acceleration up to the start of collisions. With the exception of B2 emittance measurements in particular for the horizontal plane that could be attributed to measurement device errors for some fills, the values stay within the target parameters of Fig. 1.

Table 1: Evolution the Bunch Intensity and Emittance Distribution RMS during Injection and Acceleration. The Bunches of All Physics Fills of 2018 Are Used

	beam	Injection	Collisions
Intensity	B1	4.09	4.46
	B2	4.08	4.26
Emittance	B1-H	4.80	6.59
	B1-V	4.64	7.42
	B2-H	4.97	13.28
	B2-V	5.11	9.52

VARIATIONS IN COLLISIONS

Figure 4 shows the distribution of the bunch luminosity as measured by ATLAS and CMS at the start of collisions. The btb-variations is ~ 10%, that is slightly higher but still compatible with the estimate in Fig. 1 using the measurements of the machine parameters shown in Table 1 and considering simplifications for absence of tails and correlations.

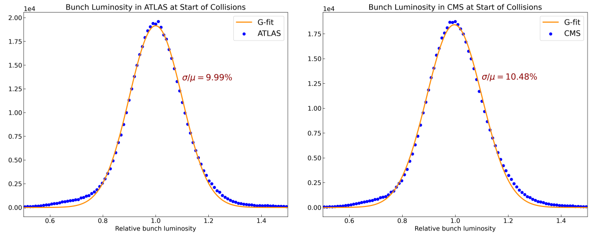

Figure 4: Distribution of the relative bunch luminosity as measured at the start of collisions in ATLAS and CMS, using data from 159 physics fills in 2018 with more than 2500 bunches. The bunch luminosity is normalized to the mean of all bunches per fill.

This difference can be attributed to imprecise measurements and absolute scale calibration in the beam emittance measurement resulting approx. 15% higher mean luminosity compared to that measured by the experiments [3].

Figure 5 shows the bunch luminosity measured by ATLAS at different times in collisions, revealing some interesting underlying features: First, an overall variation with bunch number is visible from the start up to four hours in collisions, reflecting the variations at FB, correlated to the time the bunches spend at injection. Second, a variation within the bunches of the injection trains with a sub-structure appearing (see also Fig. 6), due to the combined effects of burn-off, beam-beam interactions, and electron cloud that affect differently the bunches leading to variable intensity losses and emittance blow-up [4].

During operations, the luminosity to the experiments is optimised or levelled to the total or to the average bunch

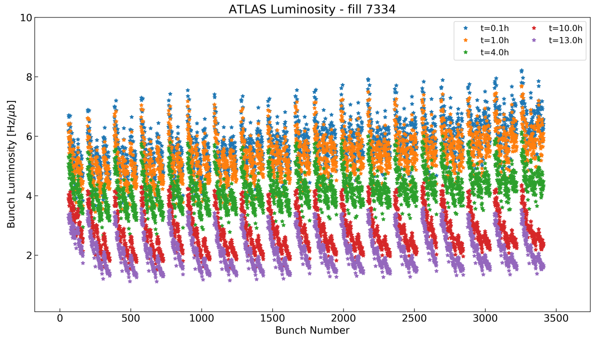

Figure 5: Bunch luminosity distributions as measured by ATLAS at various times during collisions, for a typical long physics fill with more than 2500 bunches and 14 hours in collisions.

luminosity (or pile-up), with the btb-variations having a distinct impact in each case that needs to be considered. For example, the number of bunches with > 10% luminosity than the average increases from 20 to 30% in ten hours in collisions, while their contribution to the total luminosity increases from 25 to above 40%.

To better understand the impact of the various beam dynamic effects that contribute to the development of btb-variations,different bunch families are studied: i) the 1st bunch in each injection from SPS, that has minimal number of beam-beam long-range (BBLR) interaction and is not affected by e-cloud, ii) the 1st bunch in each of the following trains that has a higher number of BBLR interactions, and some impact of e-cloud, iii) the 12th bunch in the trains that has the average BBLR interactions and is affected by higher e-cloud, iv) the 15th bunch in the trains that have maximum BBLR interactions and e-cloud, and v) the last bunch in each train with the same low number of BBLR as ii) but is fully affected by e-cloud. Their distinct behaviour is clearly demonstrated in Fig. 6.

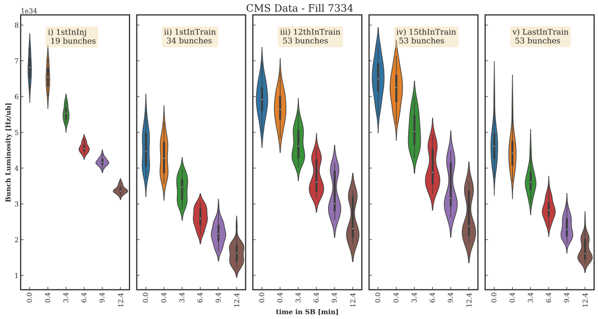

Figure 6: Evolution of bunch luminosity distribution with time in stable beams (SB) collisions, for five selected bunch families as explained in the text.

Figure 7 shows the evolution of the relative bunch luminosity RMS with time in collisions. Considering all bunches, the RMS shows an increase from 12% to approx. 25% after ten hours in collisions. We observe two groups of bunch families: iii) and iv) and ii) with v), that follow the same evolution, which indicates that it is the combined effect of BBLR and e-cloud that drastically affects the bunches, a hypothesis that needs to be further studied. The bunch families iii) and iv) have the major impact to the increase of the spread while the spread for the bunches of family i) is reduced with time, as expected.

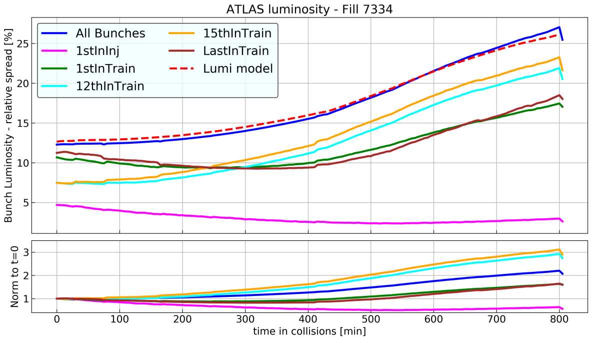

Figure 7: Evolution of relative bunch luminosity rms in collisions considering the different bunch families. Bottom: the same data but normalized to t=0 point. The results of the luminosity model using the measured bunch intensities as input are shown for reference [5].

RUN 3 AND HL-LHC

In the baseline of Run 3, the same beam types and filling scheme as for Run 2 will be used. However, with the increased bunch intensity and brightness delivered from the injectors, an initial period of levelling of several hours is foreseen to maintain the pile-up to the same levels as in Run 2 [6]. Thus, for the machine side, btb-variation results as of Run 2 are to be expected. The impact of btb-variations needs to be considered driven by the requirements of the trigger and capability to register events. The impact of additional contributions from IBS at FB and btb-variations from the bunch length is under study and will be reported in a future publication.

For HL-LHC, the requirement for the btb-variations becomes tighter to always remain in the shadow of the natural pile-up fluctuations (~ 8.5% at 140 pile-up events). However, the foreseen coating of the vacuum chambers is expected to mitigate the impact of the e-cloud, thus the expected behaviour would be hopefully closer to family i) of Fig. 7, which is well within the specifications.

SUMMARY AND OUTLOOK

We report on a study of the btb-variations in luminosity from LHC Run 2 data. At the start of collisions, the variations remained in the shadow to those from pile-up. An important growth of the rms bunch quantities (emittance and intensity) was observed at injection energy and further during collisions, leading to an overall growth in the btb-variations in luminosity. Further studies focusing on selected bunch families are ongoing to fully understand the underlying mechanisms and refine the luminosity model for Run 3 and HL-LHC.

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