ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB029

BURN-OFF WITH ASYMMETRIC INTERACTION POINTS

R. Tomás, I. Efthymiopoulos and G. Iadarola, CERN, Geneva, Switzerland.

Abstract

CERN's Large Hadron Collider (LHC) can host above 2700 proton bunches per ring providing collisions in the ATLAS, CMS, LHCb and ALICE interaction points. ATLAS and CMS, at IP1 and IP5, are placed symmetrically so that they feature the same colliding bunch pairs. This is not the case for LHCb, at IP8, hence introducing undesired bunch-by-bunch variations of the bunch intensity as the physics fill evolves. We present first analytical derivations, numerical simulations and experimental data in different bunch train collision configurations.

INTRODUCTION

LHCb is planning to increase its luminosity from $0.2{\times}10^{34}$ cm^{-2}s^{-1} to $1.5{\times}10^{34}$ cm^{-2}s^{-1} in the HL-LHC era [1] when the ATLAS and CMS luminosity is foreseen to increase to $5{\times}10^{34}$ cm^{-2}s^{-1}. Simulated luminosities along the physics fill are shown in Fig. 1 and corresponding bunch intensities [2] are shown in Fig. 2 for the nominal HL-LHC case and the proposed LHCb upgrade. The increased burn-off produces *a priori* a small impact on the integrated luminositiy in IP1/5 of about 2%, but introduces bunch-by-bunch variations that could limit performance of the physics detectors.

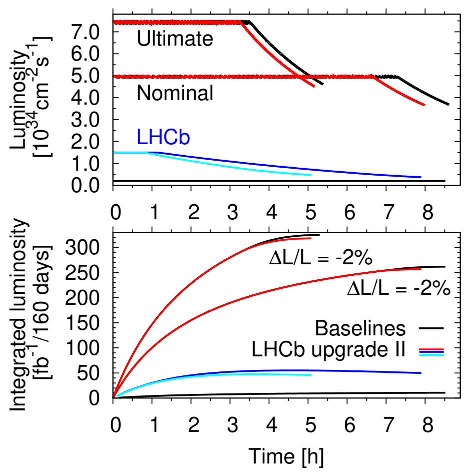

Figure 1: Instantaneous (top) and integrated (bottom) luminosities in black for the HL-LHC baseline and in colours for the LHCb upgrade (red for IP1&5 and blue for LHCb).

Figure 3 shows possible IP8 collision configurations between bunch pairs colliding in IP1&5. Simulating these configurations, and taking into account that IP8 burn-off is significantly smaller than the combined IP1&5 burn-off, shows that it is sufficient to consider the effective configurations shown in Fig. 4. This figure also shows the number of bunches pertaining to the 4 different cases for the standard and BCMS filling schemes.

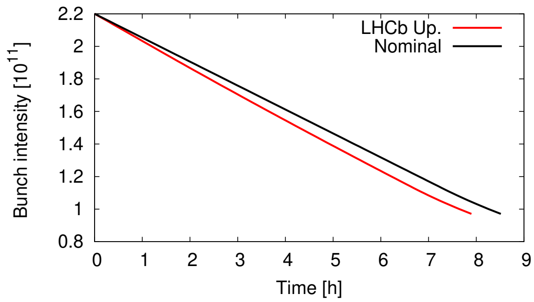

Figure 2: Bunch intensity versus time throughout the fill for bunches colliding in IP1/5 and IP8.

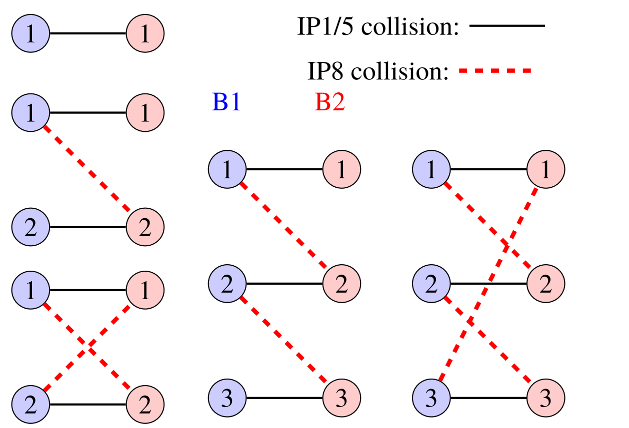

Figure 3: The 5 possible IP8 collision configurations for one, two and three bunch pairs colliding in IP1/5, ordered from top to bottom and left to right.

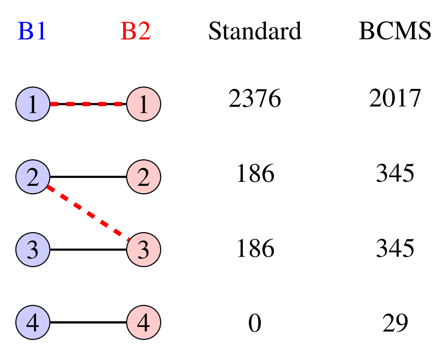

Figure 4: Number of the different type of collisions for the Standard and BCMS filling schemes.

BUNCH CHARGE EVOLUTION

Analytical equations for the bunch charge evolution in presence of luminosity burn-off at constant beam emittance can be found e.g. in [3]. These equations can be applied to configurations where only one colliding bunch pair is involved, as those of bunches 1 and 4 in Fig. 4. However, analytical equations do not exist for the s-shaped configu-

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ration corresponding to bunches 2 and 3 in the figure. In the following an analytical approximation is found for this configuration.

Following the s-shaped configuration in Fig. 4, let $n_1(t)$ be the bunch charge of the beam 1 and beam 2 bunches colliding in IP8 and $n_2(t)$ the bunch charge of the other 2 bunches. Note that we have assumed equal charges in symmetric bunches for simplicity. The luminosity burn-off removes particles according to the following differential equations,

$$\frac{dn_1}{dt} = -\sigma n_1 n_2 - \sigma_8 n_1^2 , \quad \frac{dn_2}{dt} = -\sigma n_1 n_2 ,$$

where σ and σ_8 are IP1&5 and IP8 specific luminosity times the effective cross section. Dividing these two equations and integrating the following relation between n_1 and n_2 is found,

$$n_1 = C n_2^{\frac{\sigma_8}{\sigma}} + \frac{n_2}{1 - \frac{\sigma_8}{\sigma}} ,$$

where C is constant over time. Making the approximation $\sigma_r = \frac{\sigma_8}{\sigma} \ll 1$ and defining $n_{z,0} = n_z(0)$, $n_r = \frac{n_{1,0}}{n_{2,0}}$ and $\chi = n_r(1 - \sigma_r) - 1$, gives:

$$\begin{aligned} n_1(t) &= n_2(t) n_r e^{\sigma n_{2,0} \chi t} , \\ n_2(t) &= n_{2,0} \frac{\chi}{n_r e^{\sigma n_{2,0} \chi t} - \sigma_r n_r - 1} . \end{aligned}$$

BUNCH-BY-BUNCH VARIATIONS IN HL-LHC

The analytical equations above are introduced in the simulation code used in [2] to step through the physics fill. Figures 5 and 6 show the bunch intensities and luminosities for the representative bunch pairs, also shown on the figures. Maximum bunch intensity deviations of 8% are observed between the pairs colliding only in IP1&5 and those effectively colliding also in IP8. Correspondingly, the maximum luminosity deviation reaches about 10% towards the end of the physics fill. It is important to recall that in the standard filling scheme there are no pairs colliding only in IP1&5, see Fig. 4. In this filling scheme, the maximum deviations are defined by the s-shaped collision schemes, reaching about 4% both for bunch intensity and luminosity. Figure 6 also shows the evolution of the rms values of the bunch-by-bunch luminosities both for the standard and BCMS filling schemes, reaching about 2% for both filling schemes.

EXPERIMENTAL OBSERVATIONS IN RUN 2

In Run 2, the LHCb luminosity was leveled to about 2% of that of the high-luminosity experiments ATLAS and CMS at the beginning of collisions. With time and the luminosity decay in Run 2, this ratio increases to about 15% after 10 hours in collisions. Thus, overall the impact of the burn-off due to collisions at LHCb in Run 2 is expected to be much smaller compared to HL-LHC conditions, where the LHCb luminosity would be up to 25% of ATLAS and CMS, and can

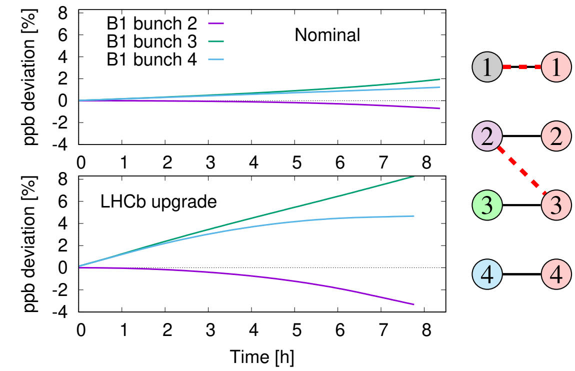

Figure 5: Relative bunch intensity for representative beam 1 bunches with respect to the pair colliding both in IP1&5 and IP8 versus time in the physics fill. Top: Nominal HL-LHC. Bottom: LHCb upgrade to luminosity of $1.5{\times}10^{34}\mathrm{cm^{-2}s^{-1}}$. Right: Collision schemes.

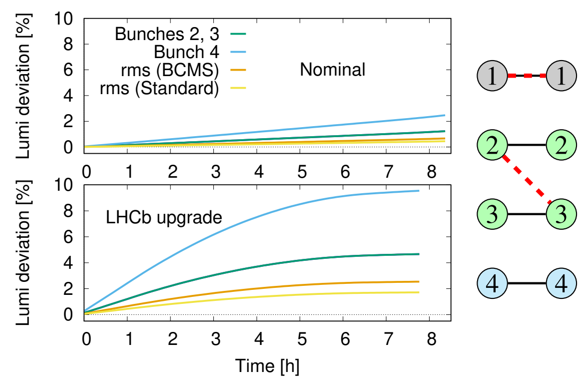

Figure 6: Relative IP1&5 luminosity for representative bunch pairs with respect to the pair colliding both in IP1&5 and IP8 versus time in the physics fill. Top: Nominal HL-LHC. Bottom: LHCb upgrade to luminosity of $1.5{\times}10^{34}\mathrm{cm^{-2}s^{-1}}$. Right: Collision schemes.

be detected only in long fills after some time in collisions. We analysed some selected fills lasting for more than 12 hours in collisions using the data from the measured bunch luminosity by the experiments, and the bunch intensity and emittance measured by the machine instrumentation. The time evolution of the mean and rms of the bunches are used as observables, considering different sets of bunches sensitive to the collisions at IP8.

Figure 7 shows the relative spread of bunch-by-bunch luminosity versus time for three bunch families: i) all colliding bunches in IP1 and IP5, ii) bunches colliding only in IP1-IP5, iii) a control set of bunches with similar collision pattern to those in ii) but also colliding in IP8. This control sample is important to allow separating the impact of the IP8 collisions to the beam burn-off and dynamics on top of other effects like beam-beam, beam-beam long-range interactions and electron cloud, that have a sizeable impact on the bunch fluctuations in Run 2 [4]. Finally the prediction of the luminosity model that includes all known effects is included for

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reference [5]. What is observed is that the bunches colliding

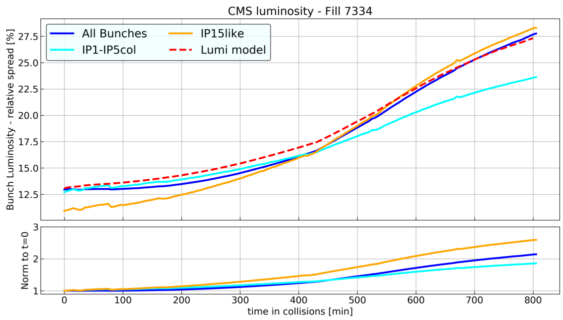

Figure 7: Evolution of the relative spread (rms) of the bunch-by-bunch luminosity for selected bunch families as explained in the text. In the bottom plot the data are normalized to t=0 point to demonstrate the relative increase.

only in IP1/IP5 exhibit a lower relative luminosity spread growth versus time in collisions, compared to those of the control sample. This clearly demonstrates that IP8 collisions increase the bunch-by-bunch luminosity variations, as expected from the discussion above regarding only burn-off considerations.

The effects on the beam intensity and emittance are studied next. Figure 8 shows the evolution of the average emittance versus time in collisions for the three families described above. The emittance growth is slower for the bunches colliding at IP1 and IP5 only compared to those of the control sample and all bunches. The same effect is observed in the vertical plane, however less pronounced. These observations indicate that IP8 collisions introduce other beam dynamics effects on top of the burn-off.

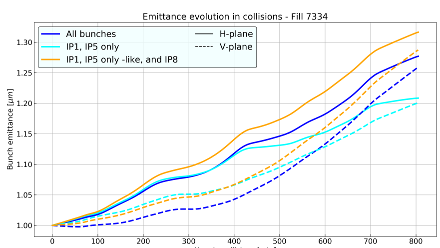

Figure 8: Evolution of the average bunch emittance from the transverse synchrotron light monitors (BSRT) for selected bunch families as explained in the text.

Figure 9 shows the average and rms bunch intensities for the families under consideration. The bunches colliding in IP8 lose more intensity and have an increased rms evolution with time in collisions. The relative increase of the intensity spread is similar to the increase in the luminosity spread with factors ranging from 2 to 3 at the end of the fill. Normally we would expect luminosity spread growth to be larger than intensity spread by about a factor 2. The fact that these are similar could imply correlations between intensity and emittance variations, again pointing towards rich beam dynamics phenomena.

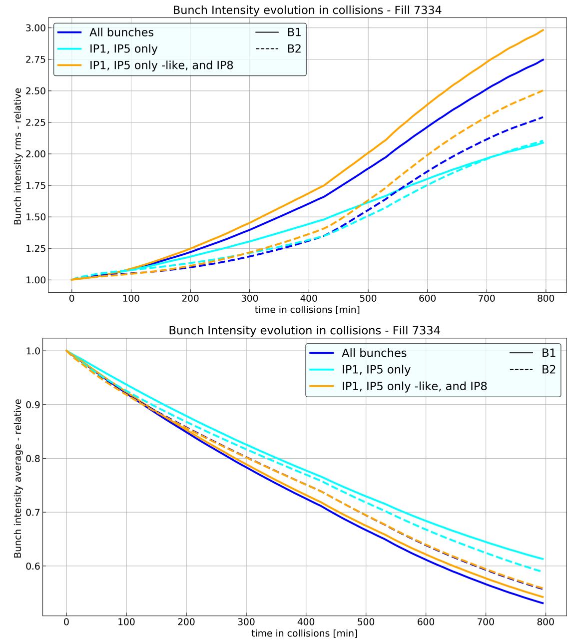

Figure 9: Evolution of the average (top) and rms (bottom) bunch intensity for selected bunch families as explained in the text.

The graphs shown correspond to a typical fill in 2018 when using the BCMS filling scheme. However, the same overall behaviour is observed in other fills of Run 2 with different filling scheme (8b4e) and LHCb spectrometer polarity.

SUMMARY AND OUTLOOK

Bunches colliding in LHCb experience an extra luminosity burn-off that results in increased bunch-by-bunch variations. This effect has been studied analytically, with simulations and via first experimental observations in Run 2. Ideal simulations for the HL-LHC suggest that the burn-off effect alone could generate about 2% rms luminosity variations, which is about a factor 5 below tolerance. Experimental observations in Run 2 confirm that IP8 collisions introduce bunch-by-bunch variations but suggest at the same time the existence of other mechanisms involving emittance growth possibly from beam-beam or e-cloud interactions. Further studies will be needed to gain understanding in this phenomena to better asses its potential impact in HL-LHC.

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