THE LHCB ONLINE LUMINOSITY CONTROL AND MONITORING

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Abstract

The online luminosity control consists of an automatic slow real-time feedback system controlled by specific LHCb software, which communicates directly with a LHC software application. The LHC application drives a set of corrector magnets to adjust the transversal beam overlap at the LHCb interaction point in order to keep the instantaneous luminosity aligned to the target luminosity provided by the experiment. It was proposed and tested first in July 2010, and it has been in routine operation during the first two years of physics luminosity data taking, 2011 and 2012. This paper describes the operational performance of the LHCb experiment and the LHC accelerator during the luminosity control of the experiment, the accounting of the recorded luminosity and dead time of the detector, and analyses the beam stability during the adjustment of the transverse beam overlap at the interaction point.

INTRODUCTION

The LHCb experiment was initially designed to run at a luminosity of $2{\cdot}10^{32}\text{cm}^{-2}\text{s}^{-1}$ corresponding to an average pileup (number of proton-proton collisions per bunch crossing) of ~0.4 since flavour precision physics relies on resolving properly the vertex structure and event pileup significantly complicates this task. The increased detector occupancy also leads to excessive reconstruction times in the High-Level Trigger. In order to run at two orders of magnitude lower luminosity than the LHC design, a beam defocusing at the interaction point is required, therefore the β* in IR8 is bigger compared to IR1 or IR5.

However, a fundamental but extremely challenging turn point in the operational strategy of LHCb came when the LHC changed approach in June 2010 from commissioning many bunches with low intensity to rather commissioning nominal (and above) intensity per bunch. The average event pileup in LHCb quickly reached as high as three. Many LHCb systems performed extremely well in this exceptional high pileup environment. Nevertheless, the High-Level Trigger and the offline reconstruction suffered from excessively long processing times and a solution had to be found.

LUMINOSITY CONTROL BY TRANSVERSE BEAM SEPARATION

The concept of an LHCb-driven real-time luminosity control based on adjusting the beam transversal overlap at the LHCb interaction point was proposed and tested in July 2010. This became a direct tool to maximize the LHCb physics yield since the optimal pileup and luminosity were always under control, stable fill after fill and over months allowing the same trigger configuration to be maintained. Many of the LHCb physics analyses are very sensitive to changing pileup or, in order words, to changing running conditions and ageing, and therefore benefitted from an important reduction of the systematic errors. Figure 1 shows the evolution of the LHCb operating conditions between 2010 and up to mid-October 2012 in terms of the number of colliding bunches at the LHCb interaction point, the rate of visible crossings to be dealt with by the trigger, the average event pileup per visible bunch crossing, and the instantaneous luminosity. Largely thanks to the luminosity control, most of the LHCb data was recorded at an instantaneous luminosity of $4\text{x}10^{32}\ \text{cm}^{-2}\text{s}^{-1}$, which is equivalent to an average event pileup of visible interactions of 1.7 as compared to the design value of 0.4.

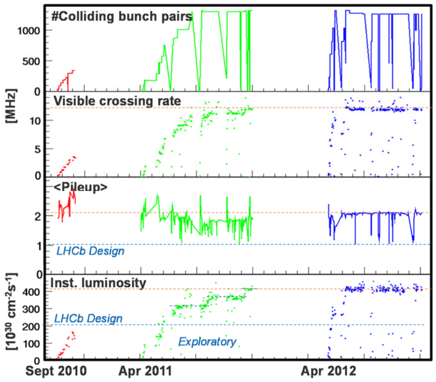

Figure 1: LHCb operating conditions between 2010 and 2012 in terms of the number of colliding bunches, the rate of visible bunch crossings which is seen by the first level trigger, the average event pileup per visible crossing, and the instantaneous luminosity.

Aligning the detector instantaneous luminosity to a given target luminosity all along the fill duration or until the instantaneous luminosity reaches the natural luminosity decay, can be achieved in different ways. The easiest implementation, given the current LHC operational scenario, consists of a variation of the transverse beam separation at the interaction point, one of the terms in the luminosity formula. If Gaussian distributions for the beam density distribution functions and equal bunch lengths for both beams are assumed, the luminosity formula is given by[$]:

$$L = \frac{N_1 N_2 f_{rev} N_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}} F \left(e^{-\frac{(y_2-y_1)^2}{2(\sigma_{y1}^2+\sigma_{y2}^2)}} \right) \qquad (1)$$

where N_i is the number of particles per bunch for beam i, f_{rev} is the bunch revolution frequency, N_b is the number of bunches in the beam, σ_{ix} and σ_{iy} are the transverse beam sizes. F is the geometrical reduction factor due to the crossing angle. The exponential part is a pure transverse beam separation contribution. If the offset is in the

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[$] Other terms appear in the luminosity formula but they are not relevant for the current discussion.

vertical plane [1], beam 1 is displaced by y_1 and beam 2 is displaced by y_2 with respect to their reference orbits. If the beam offset increases, the exponential decreases and thus L decreases (assuming all the other parameters stay constant), and vice versa, providing the luminosity levelling. The number of pileup events (μ) is calculated dividing the luminosity by $N_b \cdot f_{rev}$ and multiplying by the proton-proton inelastic cross section. Controlling the luminosity is, thus, equivalent to controlling the pileup.

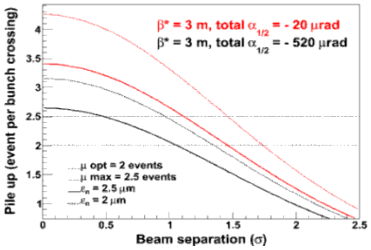

Figure 2: Pileup evolution as a function of the beam separation at IP8 for the two LHCb dipole polarities.

Figure 2 shows the pileup as a function of the beam separation for β* = 3 m, 2 and 2.5 µmrad normalized emittance. The two LHCb running scenarios are represented; the black curve corresponds to half crossing angle of -520 µrad (LHCb dipole negative polarity[%]). The red curve to -20 µrad (LHCb dipole positive polarity). As can be deduced from Fig.2, the beams cannot collide head on at IP8, but they have to be separated to keep the pileup below 2 or 2.5 events by ~ 1σ for dipole negative polarity and ~ 1.5σ for dipole positive polarity, before declaring stable beams. The required separation is smaller for LHCb dipole negative polarity because the crossing angle is bigger and this already contributes to a reduction of the luminosity and therefore the pileup.

The beam separation at the interaction point is achieved by a set of four dipole correctors per beam and per plane, magenta symbols in Fig. 3, providing a local bump as illustrated in Fig. 3.

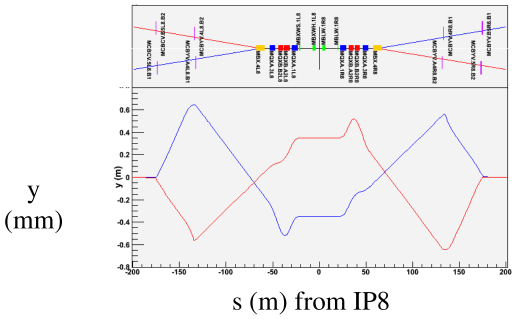

Figure 3: Beam 2/1 (red/blue) orbit for a beam separation at IP8 of ±350 µm in the vertical plane.

LUMINOSITY CONTROL SOFTWARE

The Luminosity Control and Monitoring software is composed of two well differentiated parts as sketched in Fig. 4.

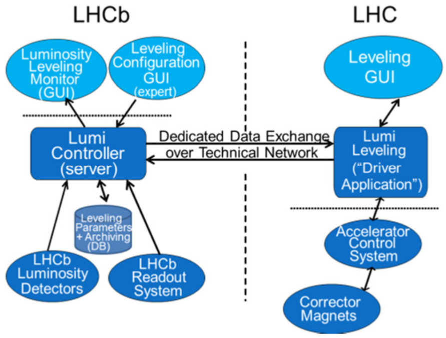

Figure 4: Luminosity Control Software diagram.

On the detector side the *Lumi Controller Server* gets the luminosity from the *LHCb Luminosity Detectors*; the online accounting of run statistics, luminosity, pileup, and dead time from the *LHCb ReadOut System*, and the *Levelling Parameters* from the *database*. The online luminosity is estimated based on a minimum bias transverse energy threshold from the calorimeter system, from the muon detectors and the Vertex Locator Pileup system. Based on the running conditions, the target luminosity is calculated and, together with the Levelling Parameters, the information is sent to the LHC *Lumi Levelling* driver application at the Cern Control Centre over a dedicated data exchange protocol. A *Levelling Configuration GUI* allows the configuration of the levelling parameters when needed, and a *Luminosity Levelling Monitor GUI* displays, in the LHCb Control Room, the relevant parameters. On the LHC side, the driver application runs a "levelling algorithm" that determines when and by how much the beam separation has to be modified to reach the target luminosity. Once Stable Beams are declared and the beam position is optimized in the crossing angle plane, the levelling algorithm is continuously running comparing the LHCb instantaneous luminosity with the target. If the difference is above or below the target by more than a predefined tolerance given by the experiment, the driver application instructs the accelerator control system to modify the beam separation to follow the target.

Table 1: LHCb Performance over the Last Two Years

Year	Lumi on tape (fb^{-1})	Pileup	Detector efficiency	Dead Time
2011	1.1	1.5	91%	3.8%
2012	2	1.6	94%	2.4%

The result can be seen in Fig. 5. The green curve is the target luminosity which is increased in several steps as soon the crossing angle optimization is done. The red curve shows the increase of the luminosity (equivalently pileup) as the beam separation decreases. The cruising luminosity, $4 \cdot 10^{32}$ $cm^{-2}s^{-1}$ (twice the design value), is reached once the LHCb VErtex LOcator detector is set at its final position. Then the luminosity is maintained along the fill, Fig. 6-a, until the luminosity level potential is

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[%] The LHCb dipole field is downwards and the clockwise rotating beam crosses from the outside of the ring to the inside.

exhausted and the beams are colliding head on in IP8. From then onwards the luminosity decays exponentially as in IP1 and IP5. Table 1 summarizes the achieved performance of LHCb for which the Luminosity Monitoring and Control System has played a central role.

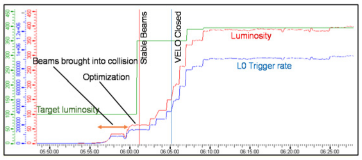

Figure 5: Top: evolution of the target and instantaneous luminosity during the first minutes after the beams are brought into collisions and stable beams declared. The LHCb luminosity is ramped up in several steps.

BEAM DYNAMICS EFFECTS DURING LUMINOSITY LEVELING

Though luminosity levelling by beam separation does not induce any beam instability by itself, it can prompt instabilities when some beam conditions are present.

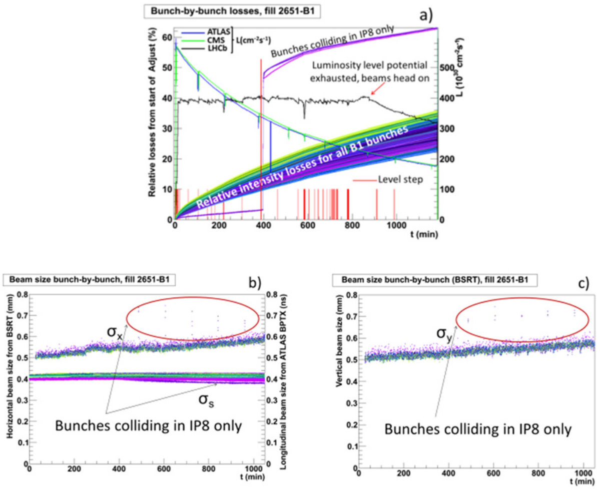

Figure 6: a) Relative bunch intensity losses and instantaneous luminosities in ATLAS, CMS and LHCb. b) Longitudinal bunch size from the ATLAS BPTX and horizontal bunch size from the Synchrotron light monitor (BSRT). c) Vertical bunch size from the BSRT. All plots show the parameter evolution as a function of time from the moment the beams are in collisions for fill 2651 and for the 1380 bunches of beam 1. The beam profile measurements are not calibrated, however, only bunch-by-bunch variations and relative variations versus time are relevant for the current discussion.

For example, during the first part of 2012, a small number of bunches out of the 1380 bunches per beam were colliding exclusively in IP8, with separations of the order of one sigma. The beam-beam force is a function of the beam distance and it becomes very non-linear for separations $\geq 1\sigma$. The non-linearity of the beam-beam force stabilizes the bunch trains due to the Landau damping they generate. Bunches colliding only in IP8 suffer from a certain lack of damping from missing beam-beam interactions in IP1 and IP5 making them more sensitive to instabilities [2].

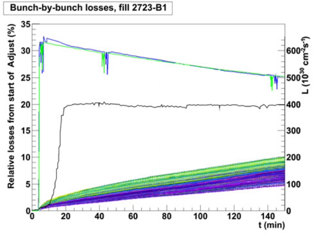

Figure 7: As in Fig. 6-a for fill 2723.

This can be seen in Figure 6-a for beam 1. Each red vertical line is a level step, i.e. the beam distance is decreased. After 400 minutes of stable beams, another levelling step is performed and the bunches, colliding in IP8 only, become unstable and lose 50% of their intensity. They are as well scraped longitudinally (Fig. 6-b) and blown up in the transverse plane (Fig. 6-b,c). The remainder bunches, colliding all in IP1 and 5 at least, are not affected. Several fills showed the same issue requiring the removal from the filling schema of any IP8 private bunches. Since then the fills were, in general, stable. An example is shown in Figure 7; the relative intensity losses for the entire beam 1 bunches are smoothly increasing due to luminosity burn up and kept, for the duration of that fill, below 10%. The bunch profile did not show any change due to instabilities despite the levelling being performed regularly in LHCb.

CONCLUSIONS

An LHCb-driven real-time luminosity control based on adjusting the beam transversal overlap at the LHCb interaction point through an LHC application became a direct tool to maximize the LHCb physics yield since the optimal pileup and luminosity were always under control, stable fill after fill and over months allowing the same trigger configuration to be maintained. Thanks to this experiment-accelerator system, LHCb has been able to run over the last two years with increasing performance up to twice its design value.

REFERENCES

[1] R. Alemany-Fernandez et al.,"Study and operational implementation of a tilted crossing angle in LHCb", TUPFI011, these proceedings.
[2] G. Arduini et al.,"Observations of instabilities in the LHC due to missing head-on beam-beam interactions" TUPFI032, these proceedings.