ONLINE LUMINOSITY OPTIMIZATION AT THE LHC

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Abstract

The online luminosity control of the LHC experiments consists of an automatic slow real-time feedback system controlled by a specific experiment software that communicates directly with an LHC application. The LHC application drives a set of corrector magnets to adjust the transversal beam overlap at the interaction point in order to keep the instantaneous luminosity aligned to the target luminosity provided by the experiment. This solution was proposed by the LHCb experiment and tested first in July 2010. It has been in routine operation during the first two years of physics luminosity data taking, 2011 and 2012, in LHCb. It was also adopted for the ALICE experiment during 2011. The experience provides an important basis for the potential future need of levelling the luminosity in all the LHC experiments. This paper describes the implementation of the LHC application controlling the luminosity at the experiments and the information exchanged that allows this automatic control.

INTRODUCTION

The four major LHC experiments have different objectives and different luminosity needs. Whereas CMS and ATLAS can work at the LHC design luminosity of 1×10^{34} $cm^{-2}s^{-1}$ with the beams colliding head on and with high pileup of more than 20 (number of proton-proton collisions per bunch crossing), the LHCb 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. As consequence, the LHCb experiment was initially designed to run at a luminosity of 2×10^{32} $cm^{-2}s^{-1}$ corresponding to an average pileup of about 0.4 [1]. The ALICE experiment is designed for ion physics but used proton collisions for calibrations and physics normalizations. In proton physics mode, the ALICE luminosity working point is between 5×10^{29} $cm^{-2}s^{-1}$ and 5×10^{30} $cm^{-2}s^{-1}$ with a pileup of less than 0.05 [2]. In particular for ALICE, there is also the potential risk of detector damage by high luminosity peaks and it may also be responsible for premature ageing of the detectors.

In order to run at two or four orders of magnitude lower than the LHC design luminosity, a beam defocusing at the LHCb and ALICE interaction point is required. The number of collisions is also optimized for the experiment needs.

A fundamental but extremely challenging turn point in the operational strategy 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. As the choice of beam focussing at the LHCb experiment had been chosen for low intensity, the average event pileup in LHCb quickly reached as high as 3 collisions per bunch crossing. Many LHCb systems performed extremely well in this exceptional high pileup environment [1]. 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 a real-time luminosity control based on adjusting the beam transversal overlap was proposed and tested in July 2010 at the LHCb interaction point. This concept 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.

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 controlling the transverse beam separation at the interaction point [2][3]. Initially when the bunch intensities are large and the emittances are small, the beam separation is kept large. As the intensity drops and the emittance grows during the fill, the beam separation is reduced successively to maintain a stable luminosity.

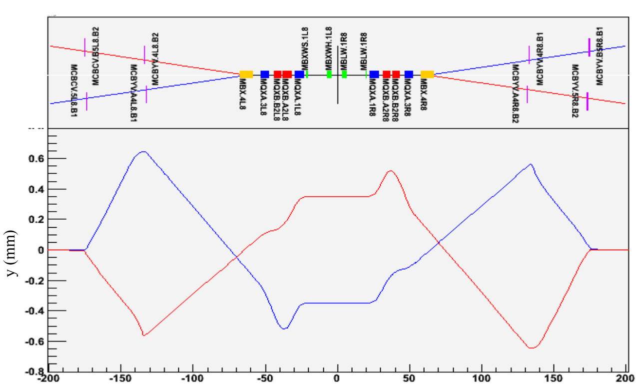

Figure 1: Beam 1 (blue) and Beam 2 (red) orbit for a beam-beam separation at IP8 of 700 μm in the vertical plane.

The beam separation at the interaction point is achieved by a set of four dipole correctors per beam and per plane (magenta symbols in Figure 1) which are located on the long straight sections of all the LHC experiments. The correctors provide a local bump as illustrated in Figure 1 in order to maintain the beams separated or colliding head

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on in the common vacuum chamber around the experiment. Each set of correctors per experiment can be independently adjusted to achieve fully head-on beams in ATLAS and CMS with optimized luminosity, and, at the same time, the same beams are colliding with a small separation in LHCb and ALICE. The maximum separation is defined by the beam clearance at the smallest aperture around the experiments which also depends on the configuration of the optics. Currently a maximum shift of up to six beam sigma is used.

LUMINOSITY CONTROL SOFTWARE

The Luminosity Control and Monitoring software is composed of two well differentiated parts as sketched in Figure 2.

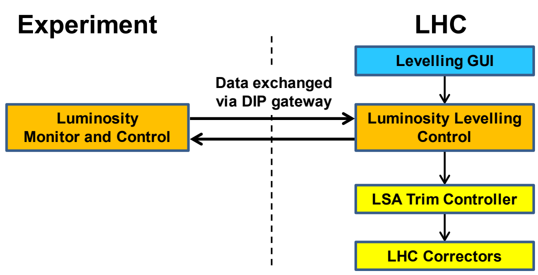

Figure 2: Luminosity Control Software diagram.

On the side of the experiment, a luminosity monitoring and control system measures the luminosity with the help of dedicated detectors [4]. Based on the running conditions, the application computes the target luminosity and the control parameters. The luminosity and control parameters are sent to the LHC luminosity levelling control driver at the Cern Control Centre (CCC) over a dedicated Data Interchange Protocol (DIP) that is used for all software communication between the LHC and the experiments.

Typical parameters sent from the experiments are:

- **Target Luminosity** [$cm^{-2}s^{-1}$]
  LHCb proton typical target = 400 [10^{30} $cm^{-2}s^{-1}$]
  ALICE proton-Lead typical target = 100 [10^{27} $cm^{-2}s^{-1}$]
- **Instant Luminosity** [$cm^{-2}s^{-1}$]
- **Levelling Step Size** [σ] (optional)
  LHCb levelling step size during luminosity ramp = 0.2 σ (10.3 μm)
  LHCb levelling step size when stable luminosity = 0.03 σ (1.5 μm)
- **Data quality**
  If bad quality the levelling is not permitted
- **Levelling Request**
  If no request from the experiment the adjustment to the target is not permitted

On the LHC side, the luminosity levelling control driver is part of a more general JAVA luminosity control application that includes the luminosity scan optimization. The luminosity levelling control driver, which also includes a graphical interface for monitoring and control (Figure 3), runs a levelling algorithm that determines when the beam separation has to be adjusted to reach the target luminosity as received from the experiments.

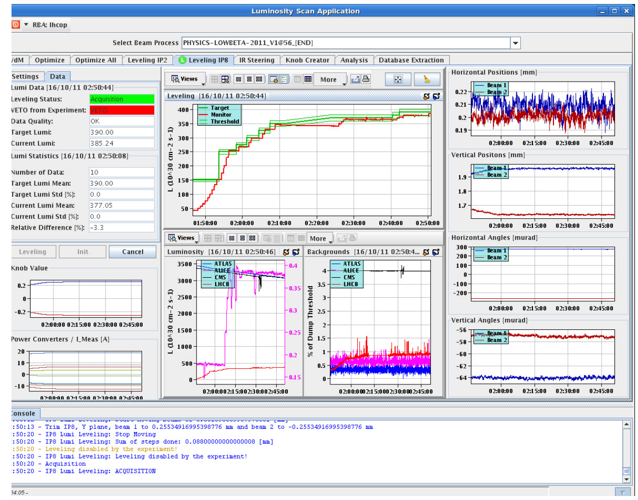

Figure 3: LHC Luminosity Control application.

The luminosity control application is client of the LHC Software Architecture (LSA), which provides a homogenous application software suite to operate most of CERN accelerators. In the LSA trim package all the LHC parameters are defined. The beam parameters are hierarchically linked (Figure 4) to the hardware parameters and the rules to compute their values are defined. The high level parameters (i.e. tune, beam position at IPs, chromaticity) are called knobs and they represent a property of the beam. The knobs values are trimmed in operation to optimize the beam and the changes are propagated to the hardware level (i.e. the currents for a set of magnets).

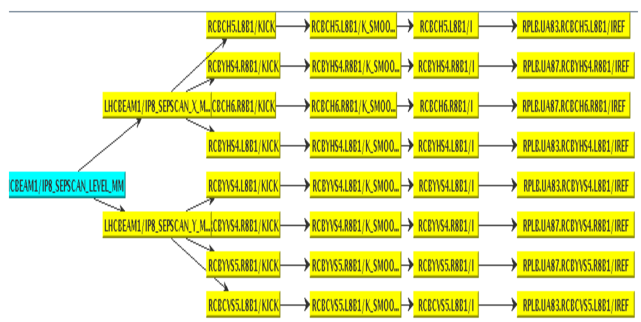

Figure 4: Example of LSA parameters hierarchy.

To optimize the luminosity, the luminosity control process computes the step size and instructs the LSA trim package to change the value of the knob that defines the beam position in horizontal or vertical plane. Four knobs per interaction point are defined in LSA, in units of millimetres, to move each beam in the horizontal or the vertical plane. Each time a new beam position is requested by the luminosity control, LSA computes the new currents for the four corrector magnets that are used to control the beam position and angle at the interaction point for a given beam and plane. Every setting modification is stored in the LSA database.

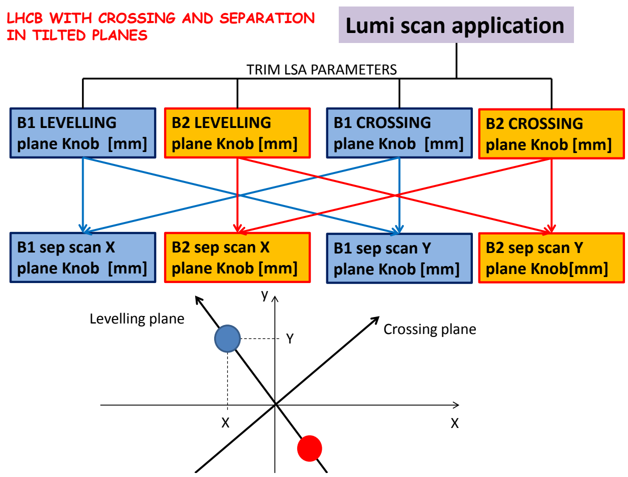

Figure 5: Levelling knobs with LHCb tilted plane.

In 2012, the collisions in LHCb were established with a so-called ‘tilted’ crossing angle scheme [5] in order to operate with the same size of the crossing angle for the two polarities of the LHCb spectrometer magnet. The LSA parameter space had to be adapted accordingly. The higher level knobs were created as a linear combination of the horizontal and vertical knobs to move the beams in the tilted crossing and levelling planes (Figures 4 and 5) [6].

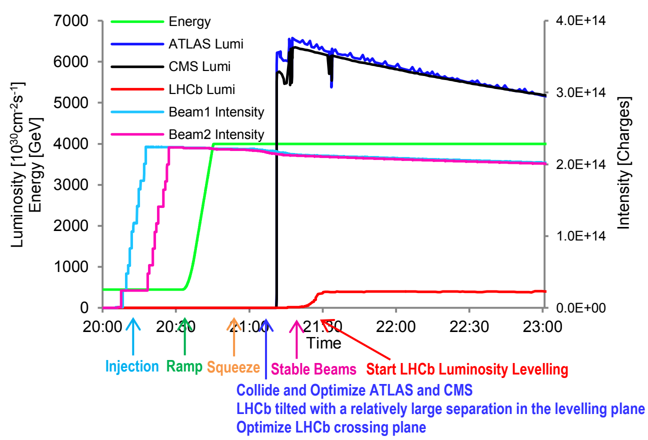

Figure 6: LHC cycle from injection to stable beams.

Figure 6 shows the complete operational procedure during the preparatory phase and the collision phase of a physics fill. After both beams are injected into the LHC machine, the beams are ramped up to the nominal collision energy. At this point the beams are squeezed, brought into collision and the luminosity is optimized in ATLAS and CMS. At the LHCb interaction point, the beams are tilted and the beam overlap is optimized in the crossing plane while the beams are kept at a relatively large separation in the levelling plane in order to be able to perform a controlled ramp of the luminosity.

Once “Stable Beams” is declared, the levelling algorithm (Figure 7) is continuously running and comparing independently the LHCb and the ALICE instantaneous luminosity with the target. The levelling controller does an averaging over several measurements from each experiment and checks the stability of the values and the quality of the measurements as flagged by the experiment. If the luminosity is in the range defined by the experiment or the experiment does not require a luminosity adjustment, the measurement loop continues. Otherwise the application generates an audible voice message to warn the LHC operator that a luminosity adjustment is required. Once the operational conditions are evaluated (luminosities, backgrounds, beam intensities, beam losses, orbit, etc.) and the parameters that will be applied are checked, the LHC operator starts the levelling. In this case the driver application will instruct the accelerator control system to move the two beams in the levelling plane by a predefined step size. In normal operation, the step size is taken from the parameters sent by the experiment. At this point the luminosity levelling controller does as before an averaging over several luminosity measurements and checks the stability and quality of the measurements. If the luminosity is in the range defined by the experiment, the algorithm goes back to the measurement loop. Otherwise, if the levelling request is still present, a new step is applied. In case the luminosity difference between the target and the instantaneous luminosity is increased, the algorithm can require that the step is undone and inverted. The beams are moved iteratively in steps until the luminosity is within the limits defined by the experiment. When approaching the target, the levelling step is reduced automatically by the algorithm to avoid a luminosity overshoot.

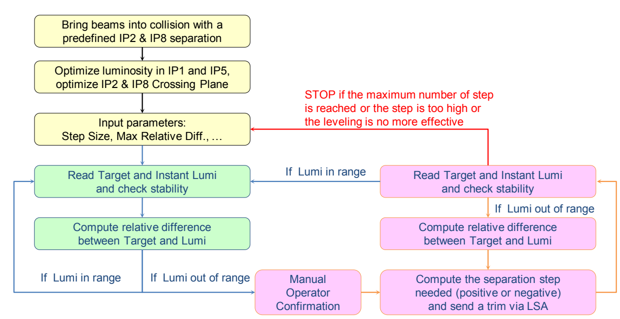

Figure 7: Block diagram of the levelling algorithm.

Since the information exchange with the experiment runs over a software network with limited reliability, the levelling algorithm enforces a number of protections. The levelling is automatically stopped if the predefined maximum number of steps has been reached, if the target luminosity is outside a safe range pre-specified by the experiments, or if the levelling is no more efficient (the beams are in a fully head-on configuration). In any case the levelling algorithm is stopped if one or both beams are no more present in the LHC machine or if the beam mode is not equal to “Stable Beams” or “Adjust”.

The result can be seen in Figure 8. The plot shows the instantaneous luminosities for ATLAS, CMS and LHCb for the physics fill 2651. While for LHCb luminosity is continuously levelled to the desired target value of $4x10^{32}$ $cm^{-2}s^{-1}$, the head-on luminosity in ATLAS and CMS decays naturally due to beam size growth and intensity decrease. After 15 hours in collision, the successive

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reduction in beam separation at the LHCb interaction point to maintain the constant luminosity reaches head-on. The luminosity then drops naturally as in ATLAS and CMS. The constant difference in head-on luminosity is due to less focussing in LHCb.

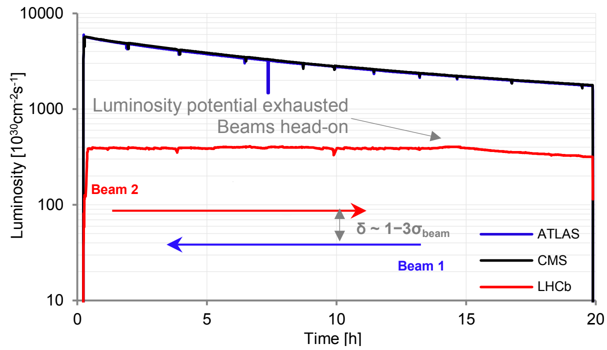

Figure 8: The ATLAS, CMS and LHCb instantaneous luminosity during fill 2651.

The overall luminosity control procedure and levelling have worked extremely well in routine operation during two years. Bunch stability with offset collisions has been monitored and analysed very carefully and apart from a case of strong instabilities associated with a small number of bunches with no head-on collisions in ATLAS and CMS, no other levelling related instabilities have affected the performance of the LHC [7]. A tiny cross-talk between the experiments has been observed requiring in some cases small re-optimizations of the ATLAS and CMS luminosity following strong changes to the LHCb luminosity.

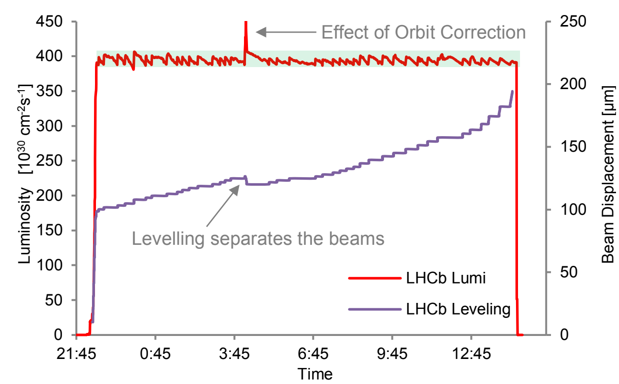

Figure 9: Example of luminosity spike in LHCb due to a manual global orbit correction.

A more serious effect is related to the occasionally large overall orbit corrections that have to be applied manually to compensate for drifts. In some cases, these have produced large luminosity spikes in LHCb and ALICE. Figure 9 shows an example of a luminosity spike due to an orbit correction. In this case, the levelling algorithm detects the increase in luminosity and adjusts automatically the beam overlap again to reach the target luminosity. In some other cases, the spikes have been large enough to require manual separation. A more integrated controls approach to the application for the orbit corrections and the luminosity scan application could be envisaged to perform these actions automatically.

CONCLUSIONS

The real-time luminosity control based on an iterative feedback loop between a luminosity control application in the experiment and a luminosity driver application in the LHC has become a direct tool for maximizing the physics yield of the LHCb experiment and the ALICE experiment. Currently, the luminosity control is based on the adjustment of the beam transversal overlap at the experiment's interaction points. The optimal pileup and luminosity were always under control, stable fill after fill and over months throughout 2011 and 2012. Thanks to this experiment-accelerator system, LHCb and ALICE have been able to run with increasing performance at a pileup of four times the design value. While several options are considered for the actual control of the luminosity, including a variable beam focussing, this very positive experience puts confidence into the possibility of dynamically controlling the luminosity for all experiments in the future, if needed [8].

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