THE LHCB ONLINE LUMINOSITY MONITORING AND CONTROL

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Abstract

The LHCb experiment searches for New Physics by precision measurements in heavy flavour physics. The optimization of the data taking conditions relies on accurate monitoring of the instantaneous luminosity, and many physics measurements rely on accurate knowledge of the integrated luminosity. Most of the measurements have potential systematic effects associated with pileup and changing running conditions. To cope with these while aiming at maximising the collected luminosity, a control of the LHCb luminosity was put in operation. It consists of an automatic real-time feedback system controlled from the LHCb online system which communicates directly with an LHC application which in turn adjusts the beam overlap at the interaction point. It was proposed and tested in July 2010 and has been in routine operation during 2011-2012. As a result, LHCb has been operating at well over four times the design pileup, and 95% of the integrated luminosity has been recorded within 3% of the desired luminosity.

INTRODUCTION

The LHCb experiment [1] is located at one of the four interaction points on the Large Hadron Collider (LHC) at CERN. The LHCb search strategy for new physics beyond the Standard Model is based on measuring precisely the effects of new physics in CP violation and in rare decays by exploiting the large production of $b\bar{b}$- and $c\bar{c}$-quark pairs at the LHC. The LHC accelerator was designed to deliver a luminosity of $10^{34}cm^{-2}s^{-1}$ in its first phase through a very large number of proton-proton interactions per bunch crossing. However, flavour precision physics relies on resolving properly the vertex structure and the entire final state decay chains. Event pileup significantly complicates the reconstruction and flavour tagging, and increases the combinatorial background. At higher event pileup, the increased detector occupancy also leads to excessive reconstruction times in the trigger and the offline processing. The systematic errors in a large number of analyses are sensitive to the consequences of varying event pileup, and varying detector performance and ageing rate. These effects are further aggravated by operating at a high luminosity. To maximize the integrated luminosity with bunch crossings containing only single interactions, the LHCb experiment was initially designed to take data at a luminosity of $2x10^{32}cm^{-2}s^{-1}$ with ~2600 bunches at 25ns spacing, corresponding to an average number of visible interactions per crossing of ~0.4. In order to run at two orders of magnitude lower luminosity than the LHC design, the LHCb interaction point required less beam focussing. A progressive trigger scheme was initially envisaged to ensure efficient data taking as a function of the luminosity decay in each fill with the consequence of complicating severely the physics analyses with changing trigger efficiencies on top of the intrinsic sub-detector performance and ageing variations.

As the number of bunches and the bunch intensity was expected to remain limited in the first year of LHC operation 2010, the same beam focussing as the Atlas and CMS experiment was applied at the LHCb interaction point. However, a fundamental but extremely challenging turn point in the operational strategy of LHCb came when the LHC commissioning changed strategy in June 2010 from commissioning many bunches with low intensity to rather commissioning first nominal intensity per bunch. The average event pileup in LHCb quickly reached as high as three. The sub-detectors and the readout system performed extremely well and the reconstruction was much more robust than anticipated in these conditions of high occupancy. This opened the possibility to operate LHCb at an instantaneous luminosity well beyond the design specifications [2]. In order to run in an environment with event pileup and at an instantaneous luminosity well above the design of LHCb, 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.

LUMINOSITY MONITORING

The need for event reconstruction to achieve high trigger efficiencies has driven the design of the LHCb trigger and the readout architecture. The main event filtering is performed on a very large processing farm based on commercial multi-core PCs by a software High-Level Trigger (HLT) with access to all detector information. Consequently, LHCb has opted for a relatively simple and inclusive first level trigger (L0), and full event readout to the event filter farm at 1 MHz.

The physics motivation and the readout architecture put strong requirements on a flexible readout and trigger control with minimal dead-time and accurate event accounting. For a large number of analyses, an accurate measure of the integrated recorded luminosity is required. These features are integrated into the LHCb Timing and Fast Control (TFC) system [3] and its associated control system. The TFC system performs the LHCb readout control and event management by managing real-time the timing, synchronization and control of the trigger and the entire dataflow from the front-end electronics up to the event filter farm. It is entirely based on custom-made electronics, all of which are implemented with large FPGAs. The master of the TFC system is the readout supervisor ODIN. It is interfaced directly to the L0 trigger hardware and receives several types of physics decisions. It sequences internally the LHC bunch crossing scheme, which is loaded automatically into ODIN during the filling process of the LHC. Using this information, ODIN

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generates random triggers and a wide variety of auto-triggers for calibration and test purposes. The correctness of the filling scheme is checked against a system of local beam pickups [4]. An event data bank is prepared and transmitted by ODIN for every accepted L0 trigger with information about the identity, time and source of the event. The ODIN data bank also allows supplying real-time information about the state of the detectors and the LHC, and special information to flag partial data sets. The information is used for routing and filtering purposes in the HLT, in the monitoring farm, and in the offline processing and analysis. All sources of dead-time in the LHCb readout system are managed by ODIN. It allows ODIN to produce a large part of the precise accounting of run statistics, technical and physics trigger dead-time, and data taking performance.

The online instantaneous luminosity and accounting of the integrated luminosity are determined by a mechanism which is different from the one of the offline accounting of integrated luminosity. Both mechanisms are implemented in ODIN. The offline luminosity is determined with the help of random sampling of trigger-unbiased beam-beam crossings. In order to perform subtraction of background induced by single beam interactions and background from environmental effects, a smaller random rate of beam-1-only, beam-2-only, and empty crossings are also recorded. The luminosity events are stripped down to contain only a limited amount of information from a small set of detectors with observables which have distributions proportional to instantaneous luminosity, and their acceptance is forced in the High-Level Trigger. The events are mixed into the stream of accepted physics events and are analysed offline [5]. The offline luminosity takes automatically into account all sources of dead-time since they are applied in ODIN exactly in the same way to the physics triggers as to the randomly sampled luminosity triggers. This offline luminosity technique allows extracting the equivalent integrated luminosity for any data set.

The luminosity random trigger is based on an advanced cellular automaton pseudo-random generator [6]. In order to destroy the correlations between the states of adjacent cells, each unit cell contains an internal memory for intermediate storage of the output of the preceding cell. The address for writing and reading is based on the output bits of the cell itself after a delay together with a counter. The outputs of the cell is computed by XOR logic of the inputs of the preceding cell together with the output of the memory and self-feedback. A non-linear combination of cross-connections between the adjacent cells is used to further improve the quality of the random sequence. The construct allows producing a sequence with an extremely long periodicity and which shows no evidence of the high correlations observed in classical random generators based for instance on Linear Feedback Shift Registers. The hardware implementation in ODIN produces simultaneously two uncorrelated 32-bit random numbers at bunch crossing rate. Programmable trigger thresholds allow independently adjusting the random trigger output rates at a resolution of $40\text{MHz}/(2^{32}-1) \sim 0.01$ Hz. One of the random generators is used for the luminosity trigger while the other is used to produce an uncorrelated no-bias physics trigger on solely beam-beam crossings.

The online determination of the instantaneous luminosity is based on the method of counting triggers satisfying a simple detector criterion, which corresponds to a minimum bias physics condition with minimal acceptance for beam-induced background. Assuming Poisson statistics and a background free environment, the probability of zero interactions $P_0 = e^{-\mu}$ allows obtaining the average number of interactions per crossing by $\mu = -\ln(1-\rho/(f_{rev}*n_{bb}))$, where ρ is the minimum bias trigger rate, f_{rev} is the revolution frequency of the LHC beams, n_{bb} is the number of beam-beam crossings in the LHC filling scheme. The instantaneous luminosity follows as $L = \mu*f_{rev}*n_{bb}/(\sigma*\varepsilon_{det})$, where σ is the minimum bias cross-section and ε_{det} is the combined detector efficiency and acceptance. ODIN uses a minimum bias trigger based on transverse energy as the main source for the determination of the instantaneous luminosity, and counts the trigger rate on beam-beam crossings, beam-1-only crossings, beam-2-only crossings, and empty crossings. The average number of interactions per beam-beam crossing is corrected for the rate of background triggers measured in beam-1-only and beam-2-only crossings. A minimum bias muon trigger and a no-primary-vertex flag from the LHCb pileup system is used for cross-checking and as a check of the long-term stability. The luminosity counting is performed on the raw trigger rates before any dead-time is introduced in order to obtain the true instantaneous luminosity which is subsequently used for the optimization of the operating conditions.

The computation and the integration of the instantaneous luminosity, both with and without dead-time corrections, are performed in a special luminosity monitoring task in the LHCb control system in order to produce the integrated luminosity delivered by the machine and the precise luminosity recorded for physics. The online integrated luminosity for 2011 and 2012 was well within 1% of the most accurate determination of the offline integrated luminosity.

LUMINOSITY CONTROL

The LHCb luminosity control is aimed at stabilizing the data taking conditions and maximizing the efficiency of the luminosity integration by constantly operating the detector at its optimal instantaneous luminosity. This is often referred to as “luminosity levelling”. The optimal luminosity is a compromise between the physics priorities, the signal selection efficiencies related to the reconstruction capabilities, and technical limitations related to detector performance, the readout system, and the offline processing. Since the maximum luminosity may be temporarily limited below the optimal value due to technical issues, background conditions, or special data taking configurations, the luminosity should be remotely

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controllable real-time. LHCb has several technical design constraints which introduce limits on the luminosity:

- Complete event readout rate to the event filter farm limited at 1.1 MHz.
- The readout board output bandwidth limits average pileup at 1 MHz to about 2.7 (2012).
- The readout network bandwidth was limited to 70 Gigabyte/s in 2012.
- HLT CPU time/event at 1 MHz was limited to about 30ms in 2011, and 40ms in 2012.

The corresponding luminosity limits will depend on the particular trigger configuration. The detector stability may introduce another limit. The luminosity control concept has allowed exploring the LHCb detector stability beyond its initial design in a safe manner by progressively increasing an assumed safe limit during the LHC Run 1.

The easiest technique of controlling the luminosity locally at an interaction point consists of adjusting the transversal overlap of the two beams with the help of corrector magnets on each side of the experiment. Thus, by running with over-focused beams and begin the collision phase with a large beam separation, and then progressively decrease the overlap, this method allows ramping the luminosity to the desired value at the start of the collision phase in a controlled way, and allows maintaining the luminosity virtually constant by compensating for the emittance growth and intensity loss by a slow reduction of the separation.

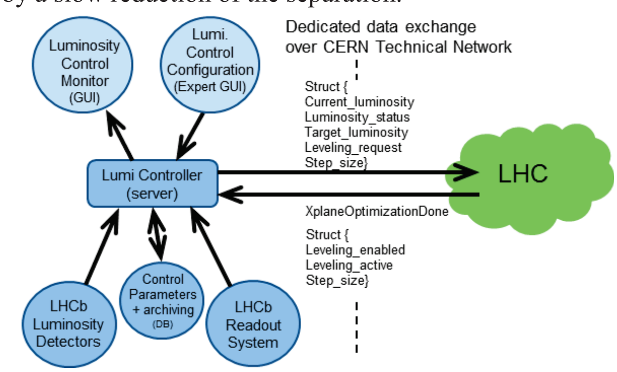

Figure 1: Block diagram of the LHCb luminosity control.

The luminosity control scheme (Figure 1) is based on an automatic slow real-time feedback system between an LHCb luminosity control manager and an LHC luminosity levelling driver [7]. The LHCb luminosity control manager is integrated in the control framework of the LHCb readout control, which is part of the overall Experiment Control System. This control framework [8] also manages all information exchange with the LHC and drives the global operation of the LHCb detector based on a defined set of operational modes of the LHC machine and handshake protocols between the LHC and the experiments. The LHC luminosity driver is integrated in the LHC control system as part of a wider application for the luminosity scans and luminosity optimization. It has direct access to the current setting of a set of corrector magnets in the LHCb intersection region. The exchange of information between the two applications employs a special software protocol which is used for bi-directional exchange between the LHC and the experiments of non-safety critical operational parameters and monitoring quantities over the CERN Technical Network.

The LHCb luminosity control manager consists of a finite state machine which is driven by the LHC operational modes and which monitors the instantaneous luminosity and compares it to the optimal target luminosity. The target luminosity is derived real-time from a comparison of the desired nominal luminosity and computations of the maximum luminosities from monitoring the different technical constraints listed above. Since the physics performance mainly defines a limit in event pileup, this luminosity limit is automatically calculated from the number of bunches in the LHC filling scheme. The most limiting value, which should only be different from the desired luminosity under exceptional circumstances, is used as the target luminosity. The desired nominal luminosity is taken from an array of values stored as a function of the operational modes of the machine. The array also includes a controlled luminosity ramp up at the beginning of each collision period. The luminosity is controlled in an iterative manner by transmitting the instantaneous luminosity and the target luminosity every six seconds to the LHC application together with a step size for the movement of the beams and a "levelling request". An adaptive step size is used to control the change in luminosity for each step in the iterative procedure. The instantaneous luminosity is averaged over six seconds to smoothen out variations, and the value is validated by several quality criteria. An associated status flag allows qualifying the value. At the limit of the readout and the trigger capacity, luminosity variations either introduce dead-time if the luminosity exceeds the optimal value, or leads to inefficient luminosity integration. The iterative procedure aims at maintaining the instantaneous luminosity within a 3% band of the target luminosity. This variation is also well within what is acceptable by any systematic sensitivity.

All parameters of the luminosity control are displayed in the LHCb control room as status information, but the procedure requires no actions from the people on shift.

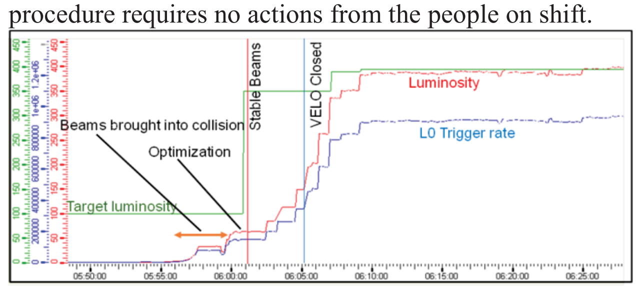

Figure 2: Luminosity control procedure at the beginning of a physics fill.

OPERATIONAL EXPERIENCE

Figure 2 illustrates the luminosity control procedure during the preparation for collisions and the first part of the collision phase. While the beams are brought into collision and optimized in all LHC interaction points, the

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optimization at the LHCb interaction point is only performed in the crossing plane. At this time, the beams are maintained at large separation in the orthogonal plane in order to prevent large accidental luminosity overshoots and allow a controlled ramp-up of the luminosity. The luminosity ramp-up consists of a small number of intermediate target luminosities with adaptive step sizes. The ramp-up allowed smoothing out some conditioning problems of the LHCb sub-detectors at high initial luminosity, and checking the trigger conditions. The LHCb VELO detector is moved to its data taking position in parallel to the luminosity ramp. During coasting beams, the luminosity is maintained virtually constant by controlling the separation to compensate against the natural luminosity decay and other effects such as orbit drifts and orbit corrections.

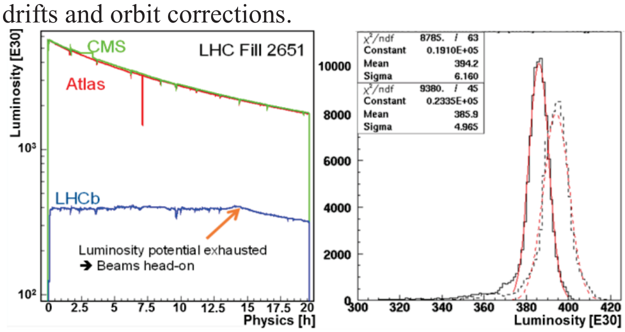

Figure 3: The LHCb luminosity compared to the ATLAS and CMS luminosity in a long fill (left), and the LHCb luminosity distribution over 3.5 months (right).

Figure 3 left shows the luminosity in ATLAS, CMS and LHCb during an entire LHC fill. In this particular case, the beams reached head-on collisions in LHCb after 14h. From there on the luminosity follows the same luminosity decay as in ATLAS and CMS with the only difference of a factor of five coming from the difference in focussing. The beam focussing in LHCb is chosen such that a levelling lifetime of more than 12h can be reached.

Figure 3 right shows the distribution of the delivered and recorded luminosity during 3.5 months of operation in 2012 at a target luminosity of $4x10^{32}$ $cm^{-2}s^{-1}$. The difference between the two distributions corresponds to a 2.1% design dead-time in the 2012 readout configuration. The 1.5% lower average luminosity than the target is due to the fact that the leveling is triggered at a luminosity of $L<97\%*L_{target}$ but is terminated when arriving in the band $L_{target}<L<103\%*L_{target}$. This is chosen to avoid luminosity over-shoots leading to increased dead-time.

Figure 4 shows the evolution of the LHCb running 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 event pileup per visible bunch crossing, and the instantaneous luminosity. The choice of the target luminosity from year to year was largely driven by the exploration of the LHCb trigger and reconstruction capabilities, and the detector performance and ageing. No hard limit in the detector stability has been encountered up to now.

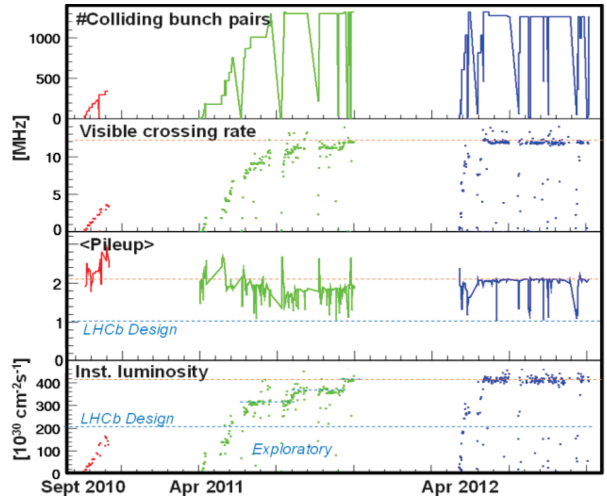

Figure 4: Evolution of the LHCb running conditions.

CONCLUSION

With the demonstration in early 2010 that the LHCb experiment could also successfully perform precision measurements with event pileup, the operational strategy evolved very rapidly in 2010 and matured at the beginning of 2011. Local luminosity control is one of the fundamental system developments which emerged in this period and which allowed LHCb to venture well beyond its design parameters and to extend the physics program. This system owes its success to an efficient and reliable monitoring of the instantaneous luminosity integrated into the LHCb readout control system and, for the first time, a high-level real-time feed-back control between the LHCb experiment and the LHC accelerator.

The luminosity control has been a direct tool to maximize the LHCb physics yield by allowing operating the experiment at extremely stable data taking conditions with more than 95% of the luminosity collected within 3% of the target, and a total integrated luminosity that is up to three times what would have been collected at the LHCb design conditions with the operation of LHC in Run 1. The stable conditions made it possible to maintain the same carefully optimized trigger configuration over months of running. Thus, calibration and ageing effects could be carefully monitored and well predicted, and managed on a continuous basis.

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