The LHCb Online Framework for Experiment Protection, and Global Operational Control and Monitoring

F. Alessio, R. Jacobsson
CERN, Switzerland

S. Schleich
TU Dortmund, Germany

E-mail: Federico.Alessio@cern.ch, Richard.Jacobsson@cern.ch

Abstract. The complexity and extreme parameters of the LHC, such as the stored energy, the collision frequency, the high risk of adverse background conditions and potentially damaging beam losses have demanded an unprecedented connectivity between the operation of the accelerator and the experiments at both hardware and software level.

LHCb has been at the forefront of developing a software framework and hardware which connects to all of the LHC communication interfaces for timing, control and monitoring of the machine and beam parameters, in addition to its own local systems for beam and background monitoring. The framework also includes failsafe connectivity with the beam interlock system.

The framework drives the global operation of the detector and is integrated into the readout control. It provides the shifters with the tools needed to take fast and well-guided decisions to run the LHCb experiment safely and efficiently. In particular, it has allowed the detector to be operated with only two shifters already at the LHC pilot run. The requirements include reliability and clarity for the shifters, and the possibility to retrieve the past conditions for offline analysis. All essential parameters are archived and an interactive analysis tool has been developed which provides overviews of the experimental performance and which allows post-analysis of any anomaly in the operation.

This paper describes the architecture and the many functions, including the basis of the automation of the LHCb operational procedure and detector controls, and the information exchange between LHCb and the LHC, and finally the shifter and expert tools for monitoring the experimental conditions.

1. Introduction

Past physics experiments have never been as tightly connected to the accelerator as the LHC experiments to the LHC machine. This is largely due to the unprecedented LHC stored energy, which will ultimately reach the enormous value of ~360 MJ per beam in the machine. Each LHC experiment therefore needs to protect itself against any failure of the machine, and needs to monitor, understand, and optimize the experimental conditions in order to increase its efficiency and performance. High level of operational communications and interconnectivity, including high level of redundancy, and strict operational procedures are thus needed in order to ensure safe operation while maintaining high data taking efficiency. Moreover, each experiment at the LHC has to cope with high interaction rates

1 To whom any correspondence should be addressed.
and large event sizes, requiring a fast and reliable centralized readout, storage and transfer to offline processing, as well as fast feedback from the Data Quality checking.

Moreover, in view of the very long data-taking life, one of the main goals of the LHCb experiment has been to ensure 24h smooth and efficient operation over many years with few people and non-experts on shift.

In this paper we will describe the LHCb online framework for global operational control and experiment protection which is aimed at satisfying all of these aspects. The paper begins with the specific requirements. It then describes the system architecture and the involved systems and functions, and finally concludes with the data analysis framework for the optimization of the experiment conditions.

2. System Requirements

2.1 LHCb Particularities

LHCb is an experiment dedicated to studying B decays and CP violation effects. As such, the experimental challenge is defined by being a forward precision detector at a proton collider. The consequence is that LHCb has several additional specificities as compared to the other General Purpose Detectors (ATLAS and CMS):

- The LHCb experiment is located at Point 8 in the direct line of sight of the injection line of the counter clockwise proton beam. Since a nominal injection at the LHC consists of ~2.4 MJ of beam over 10 μs, it requires extremely high level of reliability. However, equally important, it requires detailed local monitoring and injection interlocks controlled by LHCb. Due to large number of parameters and elements involved, beam losses associated with injection may already be very complex and very difficult to disentangle.

- The detector is equipped with several sensitive and fragile sub-detectors which are based on silicon technology and which are located very close to the beam line. In particular, the Vertex Locator (VELO) is a movable device and requires special procedures. Once the beams are stable and colliding, the VELO silicon sensors are moved as close as 5mm to the beam for data taking.

- The Front-End electronics of several detectors are located very close to the beam line requiring that the low voltage is OFF during the injection phase. The sub-detector high voltages are also all OFF during the injection and are powered gradually during the beam energy ramp and preparation for collisions. This implies that the voltages must be controlled in a safe manner according to the mode of the LHC machine.

- The LHCb experiment timing, readout control and event management are centrally managed and rely heavily on the LHC accelerator configuration and mode.

- The particular acceptance of the LHCb detector makes it particularly exposed to adverse background conditions which may induce ageing effects.

2.2 Experiment Conditions

The LHCb experiment is exposed to a very complex multi-source background [1]. Figure 1 illustrates the background phase space together with the consequences of different levels and structure of the background. The wide background spectrum imposes different requirements on the levels of measures and the reaction times:

1. Protection of the experiment against beam incidents due to e.g. equipment failures requires extremely fast reaction times of $O(\mu s)$ in order to dump the beam as quickly as possible ($< 2$-3 beam revolutions). Information must be collected with fine time granularity in order to understand the origin of the beam loss.

2. Rapid degradation in the beam quality may lead to high levels of background causing detector trips, Single-Event Upsets, and long-term detector damage in terms of fast ageing, and requires proper monitoring and reaction times of $O(s)$. Feedback must quickly give sufficient
information to correct the problem, in particular since the conditions may otherwise rapidly develop into the situation described in the first point.

3. Abnormal beam halo or vacuum related problems may lead to increased trigger rates, poor data quality and accumulated detector radiation doses. The immediate consequence is poor operational efficiency but the complexity of this type of background generally requires more profound offline analysis to optimize away. All relevant parameters must therefore be archived. However, online monitoring is also essential since background at this level may hint to a hidden malfunctioning, which may manifest itself later.

The LHCb experimental condition in terms of background is effectively a complex function of the machine settings and the beam parameters. Reducing the background to increase the data taking efficiency and quality, while optimizing the luminosity-to-background ratio, requires the understanding of these relations.

![Diagram](image)

**Figure 1:** The LHCb experiment condition in terms of background is effectively a complex function of the machine settings and the beam parameters. Depending on the amount and time structure of the background it has different consequences for the experiment as shown in the figure.

3. **Framework Architecture**

In order to satisfy the requirements in Section 2 and optimize the experimental conditions, a very large interconnectivity between the LHC machine and the LHCb experiment is needed. Figure 2 shows an overview of the framework architecture and the data flow. The framework involves both software and hardware systems and interconnectivity depending on the level of reliability required. The architecture contains units to

- protect the experiment through fast beam extraction,
- automate and secure the operational procedures,
- control the readout and manage the events for physics, luminosity and calibrations,
- monitor, diagnose, and provide direct online feedback to the LHC control room and the LHCb control room,
- and finally archive all machine, beam, and detector parameters for offline analysis.

Although several connections and logic are based purely on hardware for reliability reason, the core of the framework consists of a control system developed using the PVSS SCADA tool from ETM [2]. It performs the readout of the monitoring hardware, the global data exchange between the various sub-components and LHC, and runs the control logic. Together with the control system for the timing and readout control, it controls the configuration of all the components below. The system runs on a power redundant Linux machine and has shown that it can cope with the required high load of data. The beam, background and luminosity monitoring are all performed by several devices each, some of which belong to LHC and some of which belong to LHCb [3] [4] [5].
3.1 Experiment protection and safety

The LHCb experiment can separately inhibit injection of both beams via a failsafe hardware interlock. This is used in order to assure that the injection phase only takes place while LHCb is in the proper safe state for injection. Since the powering of the detector begins immediately after the injection phase, the injection inhibit signal is also used to prevent further beam transfers between SPS and LHC during the entire duration of the preparation for physics and data taking. The injection inhibit signal is also associated with the background monitors in a way that it can pause the injection without dumping the circulating beam if the injections are abnormal. Moreover, each beam transfer as signalled by an injection pulse via a hardware link triggers the readout of an injection quality summary from the LHCb background monitors. It is transmitted automatically to the LHC control room for information and to raise an alarm to request investigation in case of improper transfers.

As the ultimate protection, the LHCb experiment has several failsafe links to the beam interlock system. It allows dumping the beams within two turns in case excessive beam losses or malfunctioning are detected which are too fast to be corrected. The main interlock input from LHCb is the LHCb Beam Condition Monitors (BCM [3]). The BCM is based on diamond detectors installed around the beam pipe inside and immediately upstream of the LHCb detector. The dump logic is based on a set of running sums with thresholds estimated from simulation and experience with beam. Due to the failsafe implementation of the readout electronics, the BCM is also used as driver of the injection interlock. The whole system is monitored by the LHCCOM system which acts on the injection inhibit depending on the information from the detector control system.

The LHCb Vertex Locator detector may only move to its data taking position once the physics conditions have been established and the beams are stable and colliding. In order for this procedure to be safe, a Movable Device Allowed and a Stable Beams flags are transmitted via the failsafe General Machine Timing system (GMT [6]) directly to the LHCCOM system, and to the VELO interlock logic and motion control. These flags can only be set in a particular mode of operation of the LHC (commonly referred to as Stable Beams). Once the flags are set, the global detector control system will initiate the VELO closure. Inversely, it will open the VELO automatically if safety conditions are not met anymore. A direct hardware link will also dump the beams in case the VELO is closed and the flags are unset in any of the mode of operation of the LHC. In order to avoid dumping the beams...
abruptly, a procedure to move from a safe state to an unsafe state (flags unset) has been defined and it is described in the next section.

3.2 Global operational procedure
The operation of the experiment is strictly connected to the LHC machine operations. The LHC machine operational phases are defined by so called “Beam Modes” and “Machine Modes”. In order to simplify the operations of the LHCb experiment, the 19 LHC beam modes have been mapped onto eight LHCb states in which the configuration of the LHCb detector is different. In this way, the sub-detector voltages and the beam, background and luminosity monitoring are controlled as functions of the LHC modes. Similarly, the configuration and control of the LHCb readout and trigger also relies on the LHC machine mode and the sub-detector states.

There are two situations in which the LHC moves from a safe mode to an unsafe mode for the experiments, i.e. the transition from the no-beam mode to the injection mode, and the transition from the stable beam mode to the adjust mode in which the machine manipulates the beams for machine development purposes. In order to make these transitions safe for the experiments, they are preceded by a software handshake via the data exchange network. The handshake consists of a ‘warning’ issued by the machine followed by the declaration of a ‘ready’ by the experiments once the experiment has been configured for the unsafe mode. Lifting the injection inhibit is associated with the injection handshake.

All of this forms the basis of the automation in the overall LHCb Experiment Control System. This automated implementation ensures a high reliability, shifter friendliness and reduces the action of the shifters to monitoring and confirming actions.

3.3 Global real-time control
In order to cope with the very high interaction rate of ~1 MHz, the typical event size of ~60kB/event, and the very complex detector and trigger, a centralized and highly reliable synchronous real-time readout control and event management are required [7]. This system also produces all the special non-biased triggers in order to analyze and determine the luminosity offline, and the necessary commands and triggers to monitor the long-term detector stability and aging due to radiations. Moreover, the system compiles and transmits a data bank which contains information about the identity of the event, such as the UTC timestamp, run number, event number, orbit number, crossing number, LHC crossing type, event type, trigger information etc. The data bank is appended to the event during the event building.

For these reasons the readout control is directly connected to the LHC accelerator via several interfaces to receive the LHC clocks, machine timing, and the various LHC parameters. It is also interfaced with the LHCb beam monitors to receive the beam current measurements per crossing. Its central position and access to information also allow the system to produce efficiently and reliably the run statistics, data taking performance parameters, and the online luminosity.

3.4 Information exchange
A large fraction of the logic above, and the displays and tools used by the accelerator operators and the experiment shifters require a large exchange of data between the accelerator and the experiments. For all non-critical information, this is performed by a common data exchange software [8] which is integrated into the LHCCOM system. In total, including the local monitoring, the LHCCOM system receives as input more than ~20000 parameters. This includes the LHCb experiment conditions, LHC machine settings and safety conditions. The data exchange allows the experiment to follow closely the operation of the machine and to take actions accordingly. Alarms are also associated to particular conditions which require immediate action from the shifters. Inversely, it allows the machine operators to know the states of the experiments and to improve the experimental conditions. Information is also shown live on web pages and can be accessed from anywhere.

The information is in many cases used in feedback systems. For example, the machine control software for the luminosity optimization scans is semiautomatic and receives directly the online
luminosity parameters and the profiles of the luminous region from LHCb via the LHCCOM system. Another example is the van der Meer scans for luminosity calibration, during which the LHCb readout control receives real-time the scan step information via the LHCCOM system and inserts the information directly in the event data bank. Moreover, LHCb will also need luminosity levelling for 2011. This will be implemented by driving machine control software for the beam separation at the LHCb interaction point based on the transmission of the current luminosity and the desired luminosity.

4. Analysis of Experiment Conditions

The gathering and exchange of information play an extremely important role in the described framework. This data is analyzed online, processed and displayed in the LHCb control room via dedicated screens. However, in order to understand the sources of inefficiencies and to improve the beam characteristics and machine settings, it is necessary to analyse the information both online and offline. Thus, the data is also recorded in an experiment condition archive and can be interactively analyzed offline via a dedicated analysis tool whose aim is to provide graphical representations of the data and correlations (Figure 3). The analysis framework also automatically produces daily the LHCb Run Summary and updates the LHCb operations web pages with luminosity and performance plots. A large fraction of the data that LHCb transmits to LHC is also stored in the LHC Logging Database for offline analysis.

Figure 3: Overview of the data flow for the archiving, publication and analysis of the experimental conditions. The LHCCOM project gathers the information from the direct measurements, processes the information, and makes it available to the shifter displays and the expert analysis framework.

5. Conclusion

In this paper a complete online framework for the protection and global operation of the LHCb experiment has been described. It is connected to a very large number of systems in both LHC and LHCb. It involves both hardware and software implementations devoted to covering every level of safety of the experiment and improving the global efficiency and performance of the experiment. The framework has been operational since the first LHC beams, and has demonstrated an extremely high level of reliability. Homogeneity and scalability of the system played an important role in structuring the controls of the experiment. Already during the first months of operation at the LHC, the LHCb experiment was controlled by only two people on shift, operating the whole detector from two consoles. This was possible thanks to a large development of understandable high-level tools for diagnostics, alarms and data monitoring, which in turn also allowing easy training of non-expert shifters. The experiment condition analysis framework contributed heavily in the commissioning of
the accelerator and LHCb experiment thanks to its flexibility and storage of information, and it is used on a daily basis for the LHCb optimization.

6. References
[1] G. Corti et al, Simulation of Machine Induced Background in the LHCb Experiment: Methodology and Implementation, LHCb-PROC-2010-072
[2] ETM-PVSS website, http://www.pvss.com
[3] Ch. Ilgner et al, The Beam Conditions Monitors of the LHCb Experiment, submitted to IEEE TNS-00807-2009
[4] F. Alessio, Z. Guzik, R. Jacobsson, LHCb global timing and monitor of the LHC filling scheme, LHCb-PUB-2011-004
[5] F. Alessio et al, The Beam Loss Scintillator system for background monitoring at the LHCb experiment, Proceedings of RuPac2010
[6] R. Schmidt, Safe LHC parameters generation and transmission, LHC-CI-ES-0004, CERN EDMS 810607
[7] R. Jacobsson, Building Integrated Control Systems for Electronics Boards, IEEE TNS, vol. 55, no 1, February 2008
[8] E. Tsesmelis, Data to be exchanged between the LHC machine and the experiments, CERN EDMS 701510