EXTERNAL POST-OPERATIONAL CHECKS FOR THE LHC BEAM DUMPING SYSTEM

N. Magnin, V. Baggiolini, E. Carlier, B. Goddard, R. Gorbonosov, D. Khasbulatov, J. Uythoven, M. Zerlauth, CERN, Geneva, Switzerland

Abstract

The LHC Beam Dumping System (LBDS) is a critical part of the LHC machine protection system. After every LHC beam dump action the various signals and transient data recordings of the beam dumping control systems and beam instrumentation measurements are automatically analysed by the eXternal Post-Operational Checks (XPOC) system to verify the correct execution of the dump action and the integrity of the related equipment. This software system complements the LHC machine protection hardware, and has to ascertain that the beam dumping system is 'as good as new' before the start of the next operational cycle. This is the only way by which the stringent reliability requirements can be met.

The XPOC system has been developed within the framework of the LHC "Post-Mortem" system, allowing highly dependable data acquisition, data archiving, live analysis of acquired data and replay of previously recorded events. It is composed of various analysis modules, each one dedicated to the analysis of measurements coming from specific equipment.

This paper describes the global architecture of the XPOC system and gives examples of the analyses performed by some of the most important analysis modules. It explains the integration of the XPOC into the LHC control infrastructure along with its integration into the decision chain to allow proceeding with beam operation. Finally, it discusses the operational experience with the XPOC system acquired during the first years of LHC operation, and illustrates examples of internal system faults or abnormal beam dump executions which it has detected.

INTRODUCTION

The LHC Beam Dumping System (LBDS) must insure the loss-free extraction of the two circulating beams over one LHC revolution, at a programmed dump at the end of a physics run, or in case of emergency.

LBDS Kicker System

The LBDS kicker system consists of 15 horizontal extraction kickers (MKD), 15 vertically deflecting septum magnets (MSD) to deflect the beam into the extraction channel, and 4 horizontal and 6 vertical dilution kickers (MKB) to dilute the beam before it reaches the absorber block (TDE) situated around 1 km away from the extraction point in the LHC ring [1].

LBDS Kicker Control System

During LHC operation, the kicker generator voltages must follow the beam energy, which can vary from 450 GeV at injection up to 7 TeV at collision energy. Moreover, the LBDS triggers must always be issued synchronously with the 3 μs beam-free abort gap that allows the magnetic field of MKDs to reach their nominal strength. To guarantee faultless operation, various fail-safe or fault-tolerant (redundant) control sub-systems have been put in place (SCSS, BETS, TSDS, FAAS) [2]. Each of these sub-systems has an Internal Post-Operation Check (IPOC) system which verifies the correct operation during the latest beam dump action. We can mention the following IPOC systems:

- The IPOC FAAS [3] systems acquire the MKD and MKB current waveforms, analyse them, and save them into the Post Mortem Data Collection storage [4].
- The Trigger Synchronisation Unit (TSU) IPOC systems [5] acquire the waveforms of the main LBDS synchronisation signals as well as all redundant trigger signals. These waveforms are analysed to check the correct synchronisation of all signals, and to ascertain that all redundant signal paths were operational. The TSU IPOC systems will save their analysis results into the Post Mortem Data Collection storage.

Beam Instrumentation

Various beam instruments are deployed at LBDS for diagnosis purpose [1]:

- Beam Loss Monitors (BLM) in the dump line and the extraction area;
- Beam Current Transformers (BCT) on the LHC ring and in the injection and extraction channels;
- Beam screen (BTV) in front of the TDE;
- Beam Position Monitors (BPM) in the extraction channels;
- Beam Synchrotron Radiation monitor for beam abort gap population (BSRA).

All beam instrumentation equipment provide their post operation data, consisting of history buffers of states and measurements at the moment of the beam dump action.

XPOC System

After each dump action, the sanity of the LBDS is verified by the XPOC system through an in-depth analysis of the LBDS performance. The XPOC analysis server will process all the post operation data stored by the various LBDS control sub-systems or beam instrumentation equipment, to make sure that all LBDS equipment performed correctly, and that the beam was extracted as expected, in a manner to ascertain that the beam dumping system is ‘as good as new’ for the next operational cycle.

XPOC SYSTEM IMPLEMENTATION

The XPOC system has been programmed with Java 6, using the standard technologies selected for the CERN control application development like Swing, the Spring framework and the Controls Middleware (CMW) [6]. It mainly relies on the LHC Post Mortem Analysis Framework (PMA) [4] which provides:

- A powerful and reliable data collection system to store PM data buffers coming from all equipment;
- An event builder system to group collected PM data buffers into PM events;
- An analysis system which launches the various analysis modules for each PM event;
- Connections to other LHC control systems such as the Logging Database, the Software Interlock System and the LHC Sequencer;
- A Graphical User Interface application to display analysis results of the latest PM events, or to replay any past PM event.

The XPOC system has been deployed in the form of three parts: XPOC data collection server, XPOC analysis server, and XPOC-Viewer user interface application used for the monitoring and control of XPOC analysis server.

The two XPOC server processes run on the same computer HP ProLiant BL460c G7 equipped with two Intel Xeon(R) CPU X560@2.8GHz (with a total 24 of cores), 24 GB RAM, and running Scientific Linux CERN 5 (SLC5) operating system.

XPOC Data Collection Server

Several of the beam instrumentation devices do not use the standard PM data collection mechanism which would allow them to directly send their PM data buffers to the PM data collection server. Therefore, a special XPOC data collection server had to be developed, which uses the normal CMW subscription/notification mechanism to obtain the necessary data.

After each ‘beam dumped’ event received from the timing system, the XPOC data collection server starts to collect PM data buffers from a predefined list of equipment and sends them to the PM data collection server.

When all PM data buffers for a ‘beam dumped’ event have been collected, the XPOC data collection server builds an XPOC PM event with the predefined list of collected PM data buffers attached. Two types of PM events are generated: ‘XPOC-Beam1’ and ‘XPOC-Beam2’; dumps of LHC beam1 and beam2 will be handled separately.

XPOC Analysis Server

Once an XPOC PM event has been built, the XPOC analysis server starts a new analysis session and launches the execution of the equipment dedicated analysis modules in parallel threads, following their configured dependencies.

After execution of all analysis modules, the XPOC analysis server publishes all module result data to the LHC Logging Database.

The overall status of the XPOC analysis session is sent to the LHC Sequencer and Software Interlock System.

User Interface

The XPOC-Viewer application shows the latest ‘XPOC-Beam1’ and ‘XPOC-Beam2’ PM event analysis results, and allows the reset of SIS latches by authorized people.

A screenshot of XPOC-Viewer is shown in Figure 1

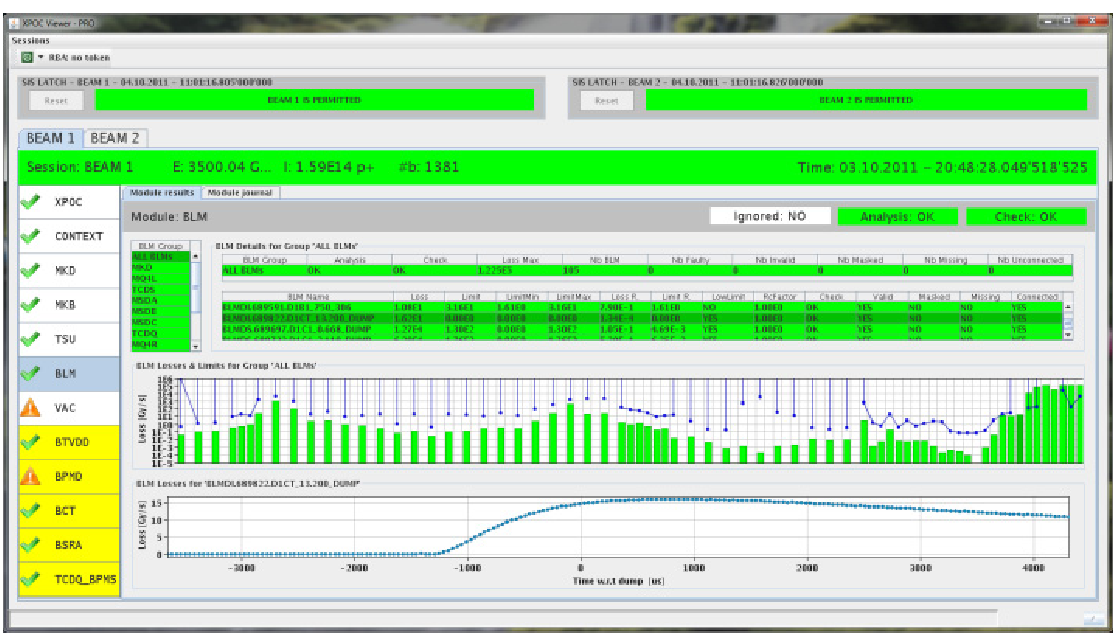

Figure 1: XPOC-Viewer application displaying status of XPOC SIS latches and BLM analysis module results.

XPOC ANALYSIS MODULES

Modules Dependencies

The list of all XPOC analysis modules is visible in the left column of Figure 1. The "CONTEXT" analysis module, which is a dependency for all other analysis modules, is executed first. Then the execution of all other analysis modules is launched in parallel, and finally the "XPOC" analysis module is executed to perform the overall analysis and give the final XPOC analysis session result.

CONTEXT Module

The aim of this module is to compute the "dumped beam intensity" and the "dumped beam filling pattern" present in the machine at the time of dump, as well as to determine the precise "dump timestamp". This information will be used by the other XPOC analysis modules to validate their input PM data buffers based on their timestamp, and to determine limits and thresholds to check data analysis results against.

The timestamp is taken from the LBDS trigger timestamp with a precision of about 100 ns (1 ns resolution). If no TSU data are available, the timestamp is taken from the PM event, which is less accurate (1 ms resolution).

The beam intensity calculation is based on three pieces of information:

- The history buffer of 30 s of the circulating beam intensity, with a sampling rate of 20 ms;
- The timestamp of the latest injection in the LHC;
- The beam intensity of the latest injection in LHC.

The circulating beam intensity is determined by performing an average over a few samples from the history buffer just before the dump action. Then the timestamp of the latest injection in LHC is compared to the dump timestamp to check if the dump took place just after injection. If a difference less than 20 ms is detected, the beam intensity of the latest injection in LHC is added to the circulating beam intensity, and the injected bunch pattern is added to the circulating beam pattern.

TSU Module

This module makes sure that the TSU cards and the trigger distribution systems functioned as expected, by checking that:

- Both TSU cards have properly detected the dump request and issued a synchronous dump trigger in less than one LHC revolution;
- The TSU IPOC has successfully checked the presence and the correct synchronisation of all LBDS synchronisation and redundant trigger signals.

MKD and MKB Modules

These two modules analyse the current waveforms in the dump kicker magnets (MKDs) and dilution kicker magnets (MKBs), recorded by the six IPOC FAAS [3]. The analysis consists of finding the critical points on the waveform to determine its characteristic values, like delay, rise time, strength, and check that these values are within predefined limits determined during the LBDS kicker calibration measurements [3].

BLM Module

This module performs the analysis of losses recorded by some BLM installed near LBDS equipment and near collimators all around the LHC. It uses the loss history buffer (+/- 3ms around the dump event) provided by every BLM device to determine their maximum loss at the moment of the dump action. It then computes loss limits based on beam energy and beam intensity provided by the "Context" analysis module. As there are quite a lot of BLM devices, they are grouped by family to easily manage their limits and write out to logging the maximum loss value per family. Each family has a reference BLM with defined ratios of loss versus energy and loss versus intensity, which allows the calculation of loss limit for a given dump action. All other BLMs in the same family have a constant loss limit ratio with respect to their family reference BLM. These limit ratios are determined by analysing the logged BLM XPOC analysis results for many 'normal' dumps at various energies and intensities. The measured losses are compared to the limits for each BLM to make sure that they all are within the computed limits.

Other Modules

Some modules are still under evaluation, so they are ignored by the final XPOC check module (their names are displayed in yellow in Figure 1). They are normally executed, and their results are displayed and logged as they provide very useful information for the understanding of the dump actions, and for long term measurement correlations.

As example, the "BTVDD**"** module analyses the Beam TV (BTV) images, taken on a screen placed a few meters in front of the TDE, to make sure that the beam reached the target at the expected position, and that the dilution was performed properly. The image is processed digitally to generate the skeleton of the beam sweep on the target. The skeleton position is then checked against the reference beam position computed based on the circulating beam filling pattern and average MKD and MKB kicker waveform.

The **"**BSRA" module checks that the beam population in the abort gap at the moment of the dump is below predefined limits.

INTEGRATION INTO THE LHC CONTROL SYSTEM

LHC Sequencer

Before injecting any beam into the LHC, the LHC Sequencer application executes a predefined list of tasks which will check the status of various devices and perform their initialisation. Checks include:

- The timestamp of the latest XPOC analysis session is compared to the timestamp of the latest LBDS trigger, to make sure that the latest dump action was properly analysed;
- The result of the latest XPOC session to make sure that no errors were detected during execution of the previous beam dump action.

If any of these sequencer tasks detects a problem regarding the XPOC analysis, the Engineer-In-Charge (EIC) is responsible for contacting an expert. The task that failed can be 'skipped' by the EIC, so it is not completely fail-safe; it is more informative.

LHC Software Interlock System

If an error is detected by the XPOC analysis server, the injection of beam in the LHC is inhibited using the Software Interlock System (SIS) by means of a so called "SIS latch". The SIS latch must be reset to proceed with beam operation. This is done using the XPOC-Viewer application, which provides two SIS-Latch reset buttons (visible on top of Figure 1), and is protected using the Role-Based Access Control (RBAC) mechanism [6]. The roles required to reset the XPOC SIS latch depend on the XPOC modules that failed. This is to make sure that the concerned expert has been contacted to check the problem before proceeding with injection in the LHC.

OPERATIONAL EXPERIENCES

The majority of XPOC analysis errors encountered so far were not related to LBDS problems, but to missing PM data buffers, mostly due to beam instrumentation equipment problems or CMW communication problems. Work is ongoing to have the very reliable data collection mechanism of the PMA framework implemented in all equipment used by the XPOC system. Nevertheless many interesting problems were detected by the XPOC system and some of them are briefly described below.

Problem with MKD Generators

MKD XPOC analysis errors occurred during operation with beam in 2008. After analysis of the long term trends of XPOC MKD logged analysis results, it appeared that some MKD characteristics were degrading. The problem was identified as a bad connection of a trigger cable [3].

Inject & Dump Synchronisation Error

During tests in Inject & Dump mode after a technical stop, the BTVDD XPOC analysis module failed at each dump action because the position of the pilot beam on BTVDD was much too high. The problem was traced back to a wrong LBDS control system parameter value for the Inject & Dump mode which was introduced during the technical stop. This resulted in the LBDS pulsing one LHC revolution too early (before beam injection), so the pilot beam (bunch #1) was not extracted at the beginning of the LBDS kicker pulses but at the end, and the extracted beam trajectory was not as expected. This problem was not seen by any other XPOC module, because all kickers pulsed properly, triggers were correctly synchronised with the beam revolution frequency, and no losses were detected by the BLM devices.

Losses Detected During Dump Action

When performing a beam dump, the BLM XPOC module often detects losses around protection equipment (absorbers and collimators). Recent analysis of the logged BLM and BSRA XPOC data showed a good correlation between the number of particles present in the beam abort gap at the time of dump and the losses measured on protection equipment. This correlation was the same for both beams. This is expected as all particles present in the abort gap during dump execution will be swept over all the LBDS protection equipment and the systems are identical for both beams. By combining these two measurements the XPOC system provided an easy way to confirm the rather complicated abort gap population measurement.

CONCLUSION

The XPOC system has proven its efficiency in detecting unexpected behaviour during execution of beam dump actions. It allowed the anticipation of some LBDS hardware problems before any system failure occurred, using the trends of logged XPOC analysis results. The LBDS stringent reliability specifications can only be met by the XPOC system guaranteeing that the latest dump was correctly executed, including all redundant parts. For this reason the reset of the XPOC SIS latch, which can only be done by experts having the required RBAC roles, is taken very seriously in daily operation of the LHC.

REFERENCES

[1] B. Goddard et al., "Initial results from beam commissioning of the LHC beam dump system", *Particle Accelerator Conference*, Vancouver, Canada, 2009.

[2] E. Carlier et al., "Design Aspect Related to the Reliability of the Control Architecture of the LHC Beam Dump Kicker Systems", *ICALEPCS*, Gyeongju, Korea, 2003.

[3] J. Uythoven et al., "Experience with the LHC beam dump post-operational checks system", *Particle Accelerator Conference*, Vancouver, Canada, 2009.

[4] M. Zerlauth et al., "The LHC Post Mortem Analysis Framework", *ICALEPCS*, Kobe, Japan, 2009.

[5] A. Antoine et al., "First Operational Experience of the LHC Trigger Synchronisation Unit", *ICALEPCS 2011*, Grenoble, France, 2011.

[6] K. Kostro et al., "Role-based authorization in equipment access at CERN", *ICALPECS*, Knoxville, Tennessee, USA, 2007.