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COMMISSIONING OF THE CONTROL SYSTEM FOR THE LHC BEAM DUMP KICKER SYSTEM

E. Carlier, A. Antoine, C. Chanavat, B. Goddard, V. Kain, N. Magnin, J. Uythoven, N.Voumard

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The beam dumping system of the Large Hadron Collider (LHC) provides a loss-free fast extraction of the circulating beams. It consists per ring of 15 extraction kickers, followed by 15 septum magnets, 10 dilution kickers and an external absorber. A dump request can occur at any moment during the operation of the collider, from injection energy up to collision energy. All kickers must fire synchronously with the beam abort gap to properly extract the whole beam in one single turn into the extraction channel. Incorrect operation of the extraction kickers can lead to beam losses and severe damage to the machine. The control system of the LHC beam dump kickers is based on a modular architecture composed of 4 different sub-systems, each with a specific function, in order to detect internal failures, to ensure a correct extraction trajectory over the whole LHC operational range, to synchronise and distribute dumps requests, and to analyse the transient signals recorded during the beam dumping process. The control architecture is presented and the different steps performed for its validation, from the individual sub-systems tests to the final commissioning with beam, are described.

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Abstract

The beam dumping system of the Large Hadron Collider (LHC) provides a loss-free fast extraction of the circulating beams. It consists per ring of 15 extraction kickers, followed by 15 septum magnets, 10 dilution kickers and an external absorber. A dump request can occur at any moment during the operation of the collider, from injection energy up to collision energy. All kickers must fire synchronously with the beam abort gap to properly extract the whole beam in one single turn into the extraction channel. Incorrect operation of the extraction kickers can lead to beam losses and severe damage to the machine. The control system of the LHC beam dump kickers is based on a modular architecture composed of 4 different sub-systems, each with a specific function, in order to detect internal failures, to ensure a correct extraction trajectory over the whole LHC operational range, to synchronise and distribute dumps requests, and to analyse the transient signals recorded during the beam dumping process. The control architecture is presented and the different steps performed for its validation, from the individual sub-systems tests to the final commissioning with beam, are described.

INTRODUCTION

The function of the LHC beam dumping system (LBDS) is to fast extract the circulating beam in a low-loss way from each ring of the collider and to transport it to an external absorber with the appropriate beam dilution in order to not overheat the absorber material. The LBDS is installed around the LHC long straight section 6 and consists, per ring, of 15 extraction kickers, 15 septum magnets, 10 dilution kickers, and finally an external dump, mounted in a separate cavern some hundred meters away from the LHC ring.

A beam dump request can occur at any moment during the operation of the collider, from the injection energy of 450 GeV up to the collision energy of 7 TeV. Each of the two sets of extraction kickers must operate synchronously with the 3 μs long beam abort gap foreseen for the rise of the kicker field, to deflect the beam safely away from the machine into the extraction channel, in one single turn of 89 μs.

Incorrect operation of the extraction kickers can lead to full or partial beam loss and thus to severe damage to the machine, to the experiments or to the beam dumping system itself. The extraction kickers are therefore one of the most critical components of the LBDS [1], in terms of potential impact but also in terms of complexity.

Consequently great attention has been paid to their design and to their commissioning with the aim to achieve a high level of reliability during their operation with beam.

KICKER SYSTEM CONTROL

The performance of the LBDS kicker systems is determined by three operational parameters: their state, their kick time and their kick strength. To reflect this the control architecture comprises three independent subsystems, each one dedicated to the control of one specific parameter: the state control and surveillance system (SCSS), the trigger synchronisation and distribution system (TSDS) and the beam energy tracking system (BETS). In addition, a fourth subsystem, the fast acquisition and analysis system (FAAS), has been implemented to check the waveforms of the pulsed signals.

The global status of the LBDS kicker system is determined by the sum of the individual status of all its subsystems. It can either be in a *ready* state when the system is in operation, in a *pulse* state during the execution of the dump or in a *not ready* state in case of internal failure.

When in the *ready* state, a continuous surveillance implemented through a redundant fail-safe logic protects the system against internal failures. In case of a failure, a synchronous internal self-trigger is issued in order to dump the beam. On the contrary, during the *pulse* state, no reaction to failure of the dump action itself is possible. In order to protect the system against possible failures, a redundant fault tolerant logic is used with in-depth post operational checks to verify the correct operation of all the redundant circuits during the last dump action.

Surveillance

The surveillance of the LBDS kicker systems is based on a fail-safe multi-master programmable logic controller (PLC) architecture for the SCSS and on LynxOS VME front-ends with dedicated hardware and their embedded software for the BETS and the TSDS.

When in a *ready* state, the surveillance checks all the critical signals which can affect the safety of the system in case of failure like the charging voltage of the kicker high voltage generators with respect to the beam energy, the correct locking of the trigger synchronisation with the beam revolution frequency, the low-level interlock conditions, and the status of the high voltage switches. The surveillance thresholds have been adjusted in such a way that even if they are reached the dump action will still be correctly executed.

Internal post operational checks

The aim of the internal post operation checks (IPOC) is to verify that the beam dump hardware operated correctly during the last dump action. This verification requires acquisition of all transient signals during the dump action within the SCSS, TSDS, BETS and FAAS subsystems.

The acquired signals are analysed and correlated with each other in order to determine how well the sub-systems carried out their task during the dump action and to ensure that no damage was caused on components of the dump system itself. To ensure this, a high precision data acquisition and analysis of the 50 magnet current pulse shapes is performed within the FAAS by a set of CompactPCI crates running LINUX and housing National Instruments PXI-5122 digitisers with 14 bit resolution and 100 MS/s sampling rate.

The LBDS will be declared ready for the next dump by the IPOC if, and only if, it can be confirmed that all the hardware has operated correctly during the last dump action and if it can be expected that all hardware, including all redundant components, will be able to respond correctly to the next dump request.

External post operational checks

The aim of the external post operation checks (XPOC) is to verify that the executed beam dump was performed without faults, by analysing and correlating hardware signals form equipment and beam measurements.

In addition to a fully redundant analysis of the extraction and dilution kicker current waveforms with individual references and tighter tolerance limits, the XPOC system also analyses the measurements taken by the beam instrumentation during the dump action:

- The beam position in the extraction channel;
- The beam image of the screen just in front of the dump block;
- The beam intensities in the dump channel and in the machine;
- The beam losses in the extraction channel and at the collimators distributed over the machine;
- The beam population in the abort gap;
- The vacuum pressure in the extraction channel.

COMMISSIONING

During its life cycle, the control of the kicker systems will be sensitive to different types of failures (infant, random, design, systematic, wear-out…) which will affect directly the reliability of the complete LBDS system.

In order to reduce the impact of these different failures, a strategy (Table 1) to fully test, validate and commission the LBDS before normal operation with beam has been implemented.

Table 1: Commissioning strategy

Failure	**Protection**
Design	• Reliability, Availability, Maintainability and Safety (RAMS) studies • Failure Mode, Effect and Criticality Analysis (FMECA) studies • Reviews
Infant	• Individual system test • Reliability run • Dry run
Random	• Surveillance • IPOC & XPOC
Wear-out	• XPOC

Reviews

In order to confirm the design choices and to check their correct implementation, a series of technical reviews has been performed.

Firstly, the conceptual design of the LBDS has been reviewed in the frame of the LHC machine protection system review. The outcome of this general review was a clear recommendation to organise more detailed reviews of the most critical systems like the LBDS.

In accordance with this recommendation, all the LBDS kicker control subsystems (SCSS, TSDS, BETS, FAAS, IPOC, XPOC) have been reviewed in details in the frame of a technical audit lasting one full week. The auditors concluded that the design and the implementation of the LBDS kicker controls is sound, complete, straightforward and, in particular, conform to the requirement of a high inherent level of safety, reliability and availability. Nevertheless, a list of recommendations for the different subsystems has been established, some needs for clarification of interdependencies definition between equipment have been identified, and a strong recommendation for the organisation of parallel peer-reviews of VHDL and PLC code has been made.

A follow-up of this audit has been organised one year later in order review the progress made in the implementation of the different recommendations. The auditors noted that the reliability runs have impressively shown the proper functioning of the IPOC and XPOC systems and that 60 % of the recommendations of the initial audit have been implemented, with the remaining ones being implemented during 2009. They confirmed their recommendation to perform a full review of FPGA code and to deploy FPGA test benches

Accordingly to this recommendation, a series of external reviews by industry of the most critical components of the different subsystems has been launched. The objectives are the validation of the correct implementation of the functional requirements, the verification of the pre-series performance, the identification of possible hardware and/or software anomalies, the recommendation for possible improvements and the proposal of guidelines of possible maintenance procedures for the embedded software.

Reliability runs

The main objectives of the reliability runs were to validate FMECA and RAMS studies for the LBDS kicker systems, to pass the burn-in period for all the hardware installed and to setup and optimise the IPOC and XPOC analyses [2]. For the reliability runs, the two LBDS have been operated in the LHC tunnel for an average effective running period of almost two months. During this period 750000 magnet current pulses, corresponding to more than 10 years of normal operation, have been executed and the resulting data successfully acquired and analysed by IPOC and XPOC [3].

The most important overall result from the reliability runs is that, for the LBDS kicker systems, no critical failures occurred which would have resulted in a non-acceptable beam dump. Nevertheless, different types of failures have been recorded either by the surveillance system (high voltage switch failures or fuse breakdowns in power trigger units) or by the IPOC and XPOC systems (flashover in a dilution magnet, spontaneous firing of one generator correctly followed by a re-triggering of the remaining generator, burn-in degradation of self-healing capacitor in the generator high voltage circuit or bad reconnection of a power trigger cable after an intervention).

Dry runs

Regular dry runs of the LBDS systems were carried out throughout 2008 until 10 September, overlapping with an intense phase of machine check-out during the last weeks before first beam. The main objective of this series of dry runs was to test and validate the integration of the LBDS control within the accelerator control system.

At this occasion, all LBDS interdependencies (beam interlock system, revolution frequency, access system, beam energy acquisition…) have been individually tested and commissioned. In addition, remote operation from the control room has been performed with a progressive boot-strapping of the application program layer including the validation of the sequencer, the fixed displays, the operator and expert applications, the management of critical settings, the Roles Based Access (RBAC), the analogue signal acquisition and viewer, the logging system, and other components.

Commissioning with beam

The main objective of the commissioning with beam [4] is to check that the expected performance of the LBDS is reached over the complete operational range.

In September 2008, the commissioning with beam has been started at 450 GeV and first beams have been successfully dumped either in inject & dump mode, in circulate & dump mode or upon request of the machine protection system.

Work has started on the commissioning of the beam instrumentation, the steering of the extraction trajectories, the fine-tuning of the kicker synchronisation and the validation of the XPOC analysis.

ISSUES

During the different commissioning phases of the LBDS kicker control, some weak points have been identified as a potential source of faults which can affect the reliability of the LBDS during exploitation. The principal points of concern are:

- Missing version management and code modification tracking tools within the SIEMENS S7 PLC software development framework;
- Dependence on changes in the accelerator control framework (common libraries) at the application and front-end level;
- Lack of remote low-level diagnostic for the redundant fault-tolerant systems;
- Maintenance, test and re-validation of software (application, front-end, embedded and PLC);
- Missing automated test procedures for re-validation of the complete system after hardware and/or software modifications.

CONCLUSIONS

The combination of fail-safe industrial components and the extensive use of redundant solutions, either in a fail-safe or in a fault-tolerant approach, result in a highly reliable control architecture. This high level of reliability is strengthened by the ability to declare the LBDS to be “as-good-as-new” after each dump action on the basis of the IPOC and XPOC results. During the LBDS commissioning, a series of reviews has validated the technical choices while reliability runs, dry runs and commissioning with beam have successfully demonstrated its correct functioning and confirmed its reliability level. Nevertheless, the maintenance of the LBDS control remains an issue in order to avoid the introduction of systematic failures during its life cycle.

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