OPERATIONAL EXPERIENCE WITH A PLC BASED POSITIONING SYSTEM FOR A LHC EXTRACTION PROTECTION ELEMENT

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Abstract

The LHC Beam Dumping System (LBDS) nominally dumps the beam synchronously with the passage of the particle free beam abort gap at the beam dump extraction kickers. In the case of an asynchronous beam dump, an absorber element protects the machine aperture. This is a single sided collimator (TCDQ), positioned close to the beam, which has to follow the beam position and beam size during the energy ramp.

The TCDQ positioning control is implemented within a SIEMENS S7-300 Programmable Logic Controller (PLC). A positioning accuracy better than 30 µm is achieved through a PID based servo algorithm. Errors due to a wrong position of the absorber w.r.t. the beam energy and size generates interlock conditions to the LHC machine protection system. Additionally, the correct position of the TCDQ w.r.t. the beam position in the extraction region is cross-checked after each dump by the LBDS eXternal Post Operational Check (XPOC).

This paper presents the experience gained during LHC Run 1 and describes improvements that will be applied during the LHC shutdown 2013 – 2014.

INTRODUCTION

The LHC beam dumping system includes a single-sided mobile collimator installed in front of the superconducting magnets Q4 for machine protection in case of a beam dump incorrectly synchronised with the particle-free abort gap (Fig. 1).

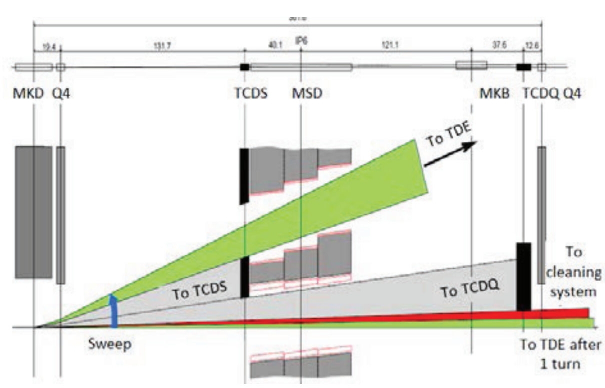

Figure 1: Schematic and functional layout of TCDS and TCDQ absorber elements.

The TCDQ is initially positioned at 8σ from the nominal beam orbit. It is moved inwards during the energy ramp in order to follow the adiabatic damping of the beam emittance. Its positioning system has to move synchronously the upstream and downstream corner of the jaws, to keep the position relative to the beam stable and to perform any displacement synchronously with all other collimators around the machine. The jaw position is acquired and analyzed in real-time and a beam dump is automatically executed in case of an internal or external failure.

The system is supervised from the control room where operators can move the TCDQ jaw by means of dedicated applications. These applications allow to control the positioning of the TCDQ jaw either to discrete settings or through functions (i.e. during the energy ramp). A sequencer is used to automatically displace the jaw of the TCDQ from parking to injection position and to launch the ramp function.

POSITIONING SYSTEM

Architecture

The TCDQ positioning system consists of two entities: the Motor Drive and Control (MDC) and the Position Readout and Survey (PRS).

The MDC controls the positioning system and its protection logic. The position is acquired by a linear potentiometer used as feedback in the positioning regulation loops. A set of mechanical switches determines the operational limits of the jaws. A second set of switches is used for the protection of the mechanical limits.

The PRS surveys the relative position of the jaw w.r.t. interlock limits defined by operational conditions (Fig. 2) and managed as Machine Critical Settings (MCS) [1]. The upstream and downstream positions of the jaw are acquired by Linear Variable Differential Transformer (LVDT). The PRS is connected to the LHC Beam Interlock System (BIS) in order to dump the beam in case of an incorrect position. The PRS monitors also the jaw temperature.

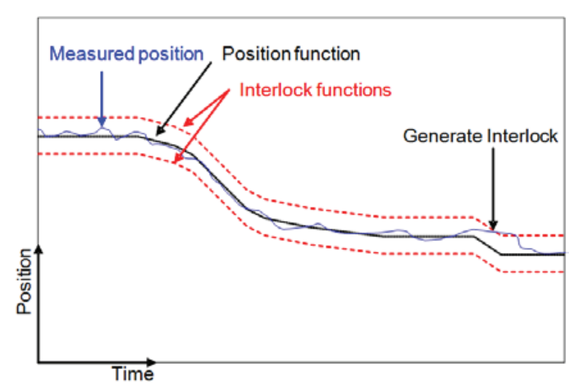

Figure 2: Interlock logic during a displacement monitoring.

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Hardware

The electronics of the positioning system is composed of a SIEMENS S7-300 PLC with a PROFINET network interfacing two deported I/O stations. Each TCDQ motorisation is equipped with a DC motor associated with a mechanical coupling, a reduction gear and a mechanical clutch. The DC motors are controlled by PARVEX DC servomotor drives. The positioning precision is achieved by a PID based speed regulation loop.

Integration within CERN Control Environment

The TCDQ is controlled and monitored from the CERN Control Centre (CCC) using the standard communication protocols developed at CERN, which are not available on SIEMENS hardware. So to interface the SIEMENS PLCs to the CERN Control Middleware (CMW), a ‘proxy’ computer was inserted which runs an implementation of a CERN standard Front-End Software Architecture (FESA) class. It communicates with the PLC on one side using SIEMENS proprietary protocols, and to the CERN control environment on the other side using CMW. This allows the remote control of the TCDQ by the ‘central collimator application’, the check of TCDQ references and limits against the values stored in the MCS database, the continuous publication of all the TCDQ data to the LHC Logging database, or the storage of the post operation data to the Post-Mortem Data Store after every beam dump.

Performance

The TCDQ positioning system must be able to control the upstream and downstream motorisation with a high positioning accuracy and a good reproducibility within a large operational range as summarised in Table 1 [2].

Table 1: Initial Requirements for TCDQ Positioning System

	Motorisation Settings	
Accuracy	±0.2 σ	±100 μm
Adjustment Level	±0.1 σ	±50 μm
Reproducibility	±0.2 σ	±100 μm
Operational displacement range	-15,+15 mm	
Angular range	-1,+1 mrad	
Angular precision	±10 μrad	

RELIABILITY

An external review of the TCDQ positioning system has been conducted in 2009 before the start of LHC run 1 [3] with the objective to determine the different possible failure scenarios of the positioning system and their likelihood, based on the IEC 61508 standard [4].

The review has shown that the failure rate of the TCDQ positioning system is 3.64E-05 for one year of operation and corresponds to a SIL4 safety level (Safety Integrity Level). However, three dominant single points of failure have been identified during the review:

- Failure of the timing distribution to transmit the start command to positioning system;
- Common mode failure of the PLC CPU to provide position controls and supervision;
- Failure of the Ethernet card to transmit set points to the PLC.

As a result, the PLC positioning system and the low-level software have been upgraded during the LHC Run 1 to limit the risk of failure. Most of these improvements were made through the implementation of additional diagnostics and surveillance functions.

OPERATIONAL EXPERIENCE

Commissioning Phase

A commissioning phase without and with beam has been carried out in 2009 and 2010 in order to check the status of the TCDQ positioning system and validate the provided protections [5]. The commissioning objectives were to:

- Test the beam based alignment procedure of the collimator jaws;
- Check the software interlocks on the TCDQ position with respect to the beam position (dump limit set at ±400 μm around nominal settings);
- Check the provided protection during asynchronous dumps.

During this phase, different tests have permitted to identify and solve several problems:

- An incorrect displacement polarity was detected and solved with the inversion of the polarity reference signals on the feedback potentiometers.
- First operations with beam have shown that a setting resolution of 100 μm was too coarse; it has been improved to 50 μm. Improvements in the acquisition chain (converter resolution, sampling rate) have permitted to improve the accuracy by a factor 2.
- Oscillations were observed during a displacement of the jaw with an angular offset between the upstream and downstream positioning systems. This has been traced back to an error in the position acquisition because the potentiometer and the LVDT were not placed on the same vertical measurement axis. Since no mechanical correction was possible, an improvement of the performance has been obtained after a reduction of the displacement speed by a factor 2.
- LVDT acquisition chains have shown to be less accurate than potentiometers. This is due to errors introduced by the double conversion (frequency-to-analogue conversion followed by an analogue-to-

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digital conversion) specific to the integration of LVDTs within the PLC environment.

Despite the above instabilities, the TCDQ positioning system allowed a safe operation of the LHC and an adequate protection of the machine during the whole LHC Run 1.

Operation Phase

The first operation phase of LHC has permitted to improve the global performance of the TCDQ positioning system. Thanks to a high level of preventive maintenance, no fault interrupted the operation of the LHC. The required stability and reproducibility have been successfully achieved. The positioning performance has been improved by the optimisation of the PID loop and the addition of an automatic speed correction function between the upstream and downstream motors.

Nevertheless, several problems appeared since the last commissioning tests in 2010:

- An important mechanical clearance has appeared on the clutch inducing a speed regulation disturbance when the system converges to its final position as shown in Fig 3. This problem has appeared twice and has been solved in both cases by re-tightening the clutch.
- After a verification of the positioning system calibration during a technical stop, an alignment offset has been introduced in the system due to a human error. The error was detected by the PRS during the re-validation tests performed before beam injection. After a beam based alignment verification, a position offset of 2 mm (~3 σ) was found. Since any intervention would have required a long down time, the TCDQ settings were recalculated (over the full operational cycle) taking into account the measured offset.

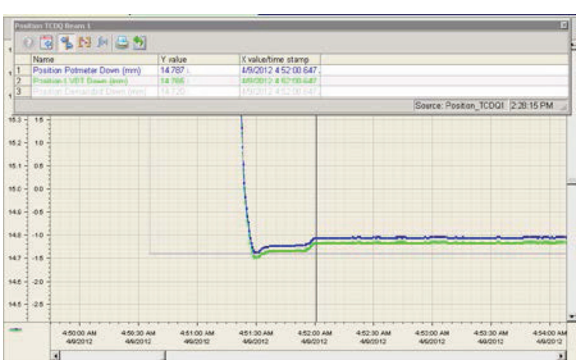

Figure 3: Mechanical clearance causing a displacement error after a stop of the motors.

A final positioning accuracy of ±30 µm has been reached, which is better than the last required performance (±50 µm). This precision was reached by upgrading the analogue to digital converter to a 16 bits resolution with a faster sampling rate and a significant improvement of the earth circuit. The cycle time of the PLC was also reduced with a new and faster CPU using a 100 Mbps PROFINET fieldbus (Ethernet) instead of a 3 Mbps PROFIBUS.

EXTERNAL POST OPERATIONAL CHECK

After every beam dump, the good behaviour of the LBDS is verified by the eXternal Post-Operational Check (XPOC) system [6], which analyses the post operation data collected from the various LBDS sub-systems or beam instrumentation equipment.

Among other things, it checks the TCDQ state and positions w.r.t. the beam position at the time of dump. The beam position corresponds to the measurement of a Beam Position Monitor (BPM) located at point 6, taken at the time of dump.

The TCDQ statuses and positions data are read from the PLC by the TCDQ FESA class, frozen at the time of dump and then pushed into the Post-Mortem Data Storage.

The TCDQ_BPMS XPOC analysis module first checks that no warnings or errors were issued by the TCDQ low-level control. Then it checks the jaw positions w.r.t. the reference values in MCS, but with tighter limits than the PRS. It check also the beam position measurement w.r.t. a reference orbit and a predefined tolerance, to make sure that the beam was at the expected position at the time of dump. Finally it computes the distance between the jaw and the beam, expressed in sigma of beam emittance, and checks against predefined references and limits that the TCDQ was well positioned.

FURTHER IMPROVEMENTS

Mechanical Modifications

Several upgrades are being put in place for the TCDQ in view of the LHC operation at 7 TeV after the long shutdown 2013 – 2014:

- Originally composed by two 3 m long graphite blocks and housed in 2 vacuum tanks, the TCDQ will be upgraded to three blocks, each 3 m long, of Carbon Fibre reinforced Carbon (CFC) as shown in Fig. 4. In case of an asynchronous beam dump at 7 TeV this longer and more robust jaw will allow diluting the wrongly kicked bunches without being damaged [7].
- The mechanical clutch will be blocked and its function will be replaced by a detection system, which monitors the current flow in the motor controller.
- All LVDTs will be replaced by potentiometers and an additional potentiometer per axis will be installed and connected to the Beam Energy Tracking System (BETS) [8] for a redundant check of the TCDQ position during the energy ramp.
- All potentiometers will be mechanically mounted on the same vertical axis in order to avoid any

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discrepancy between the different measurement points.

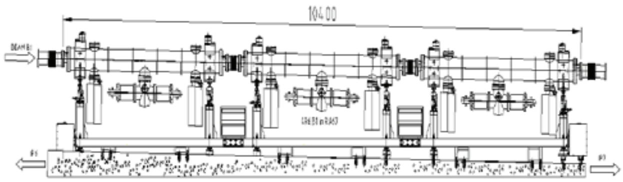

Figure 4: New TCDQ with three tanks.

Control System Modifications

As a consequence of the review held in 2009 the main improvement at the control level will be the dissociation of the MDC and PRS modules into two separate functional entities, each one based on an independent PLC, as shown in Fig. 5.

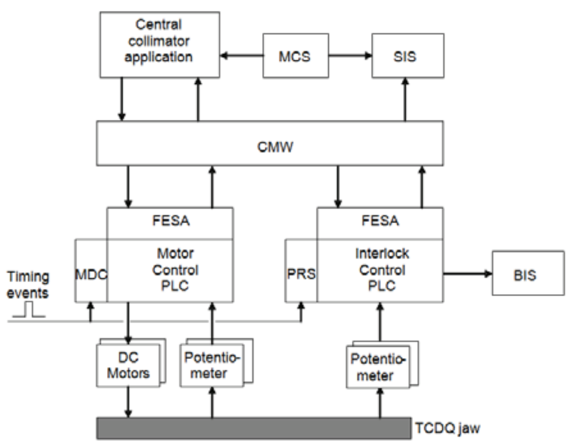

Figure 5: Architecture of MDC & PRS software.

The first PLC will treat the motion control. The MDC software will be modified at the low-level but its functionalities will be preserved in order to remain valid after the acceptance tests which were passed during the last run. The speed regulation loop will be disabled in the PARVEX controller and replaced by a current regulation which will permit a torque regulation and protection of the motor. Additionally, the speed regulation will be implemented in the MDC with the speed feedback received by the servo motor.

The second PLC will be dedicated to the protection logic. The PRS software will be unchanged at the low-level. The PRS FESA class will evolve into a new version which will remain compatible with the central collimator application and the MCS.

The MDC and PRS hardware will be modified to generate the potentiometer reference voltages by means of 16 bits digital-to-analogue converters with a line sensing functionality. This will compensate the losses in the reference lines and increase the positioning accuracy. Their software will also be improved in order to capture the Post-Mortem Data Storage buffers at the PLC level instead of at the FESA level.

The energy distribution in the TCDQ absorber blocks when operated at 7 TeV with high intensity beams could deteriorate the CFC. Each block will be equipped with 2 additional temperature sensors (PT100) to monitor any abnormal heating distribution during operation.

A camera will allow monitoring remotely the position on the dial gauges during the calibration sequences. This will limit exposure of technicians and engineers to radiation, in agreement with the “As Low As Reasonably Achievable” principle (ALARA).

CONCLUSION

The experience gained with the TCDQ positioning system during LHC Run 1 has permitted to improve its positioning performance by a factor 3 and highlighted possible weak points in the design.

For LHC Run 2, several upgrades will be made on the positioning system in order to improve its reliability and maintainability. The dissociation of the MDC and PRS functions into two fully independent entities will increase the TCDQ reliability thanks through improved “safety by design” approach resulting in a well-defined separation between control and surveillance functions.

Furthermore the implementation of an additional surveillance of the TCDQ jaw position within the BETS will provide a redundant protection against possible malfunction and possible human error.

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