FINAL IMPLEMENTATION AND PERFORMANCE OF THE LHC COLLIMATOR CONTROL SYSTEM

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Abstract

The 2008 collimation system of the CERN Large Hadron Collider (LHC) included 80 movable collimators for a total of 316 degrees of freedom. Before beam operation, the final controls implementation was deployed and commissioned. The control system enabled remote control and appropriate diagnostics of the relevant parameters. The collimator motion is driven with time-functions, synchronized with other accelerator systems, which allows controlling the collimator jaw positions with a micrometer accuracy during all machine phases. The machine protection functionality of the system, which also relies on function-based tolerance windows, was also fully validated. The collimator control challenges are reviewed and the final system architecture is presented. The results of the remote system commissioning and the overall performance are discussed.

INTRODUCTION: LAYOUT AND DESIGN

The 2008 LHC collimation system [1] included 78 movable devices with 2 jaws, each moved by 2 stepping motors, and 2 one-sided beam dump protection devices (TCDQ). This is a distributed system, with elements in seven out of eight LHC straight sections (Fig. 1). The list of key parameters for this system is given in Table 1. The collimators have different designs, orientations (horizontal, vertical or skew) and roles for cleaning and protection [2]: (1) primary (TCP) and secondary (TCSG) collimators, and shower absorbers (TCLA) are located in the momentum (IP3) and betatron (IP7) cleaning insertions; (2) tertiary collimators (TCT) protect the super-conducting triplet quadrupoles in all experimental regions (IP1, 2, 5, 8); (3) injection protection devices in the ring (TDI, TCLI, TCDD) and in the transfer lines (TCDI) protect the machine in case of injection errors; (4) dump elements (TCSG, TCDQ) to protect against asynchronous or unclean beam dumps in IP6. Twenty additional collimators are being installed for the 2009 beam operation to complete the Phase I system [1].

The tightest settings of 6 sigmas for the TCPs correspond to gaps of about 3 mm at 7 TeV, which requires position accuracy of about 20 μm. In order to maintain optimum settings during energy ramp or optics changes (such as the betatron squeeze), the jaw positions have to be expressed with functions of time [3]. The PXI technology by National Instruments was used as the low-level control platform [4].

In order to ensure that the jaw positions will stay within safe operational windows, a complex system of threshold functions has been implemented. Each motor axis is redundantly surveyed by one resolver and one LVDT (linear variable displacement transformer). Two additional LVDTs measure upstream and downstream gaps, for a total of 10 sensors per collimator. The LVDTs provide precise measurements that are used for jaw position interlocking. Four limit functions (inner and outer dump and warning limits) can be defined for each LVDT, for a total of 24 functions. The comparison of measured positions against thresholds is performed at 100 Hz by a PXI unit independent of the one that controls the motors. Limit functions for the maximum gap values versus beam energy (which is available from the LHC timing network) can also be defined. This additional protection mechanism will catch the failure that the start of time functions is not triggered at the start of energy ramp: a beam dump is eventually requested if the collimator gaps are not scaled down as needed by smaller beams.

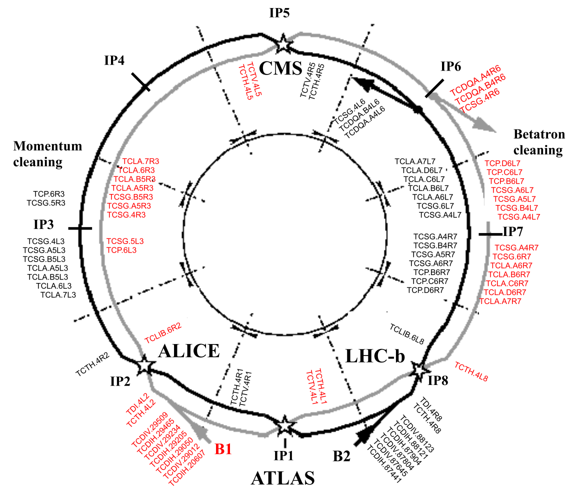

Figure 1: Layout of the 2008 LHC collimation system.

Table 1: Main System Parameters

Parameters	2008	2009
Number of movable collimators	80	100
Degrees of freedom	316	396
Position sensors	788	998
Interlocked position sensors	472	592
Motor settings versus time	316	396
Threshold settings versus time	1896	2376
Threshold settings versus energy	154	194

TOP-LEVEL IMPLEMENTATION

The applications required for collimator control and monitoring [3, 5] were developed within the standard framework of the LHC Software Application (LSA) [6, 7]. The main task of this software is to generate and orchestrate the settings for the whole system and to send them

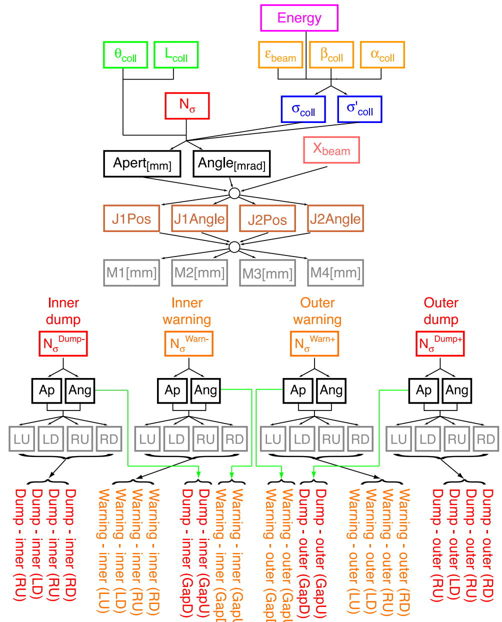

Figure 2: Parameter space of collimator settings.

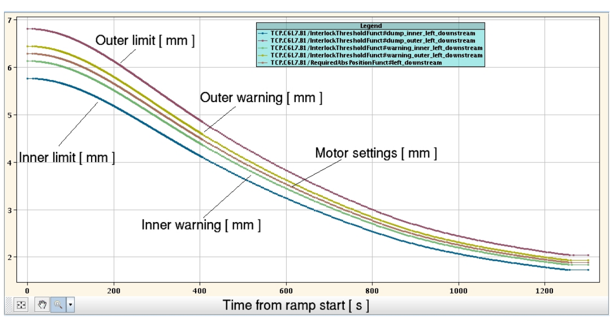

Figure 3: Position and threshold settings of one motor axis.

to the hardware for the appropriate machine context (ramp, squeeze, ...). In order to respect the strict setting hierarchy of the various collimators in the ring, settings have to be expressed in normalized beam size units [3]. The various parameters needed to achieve that, and the variable dependencies are shown in Fig. 2: collimator gaps, average jaw positions, jaw angles, and single motor positions can be calculated at all beam energies from the local optics and orbit at each collimator. Four 2D arrays for the motors of one collimators can be calculated simply by defining one function for the normalized aperture in sigma units (N_σ in Fig. 2). All the interlock thresholds are calculated in N_σ units in a similar way. An example for one motor axis is given in Fig. 3. The local beam sizes and the orbit at each collimator will be determined beam-based procedures and stored in the settings database.

REMOTE COMMISSIONING RESULTS

A summary of the main figures of merit that characterize the performance achieved during the tests without beam is given in Table 2. The collimation system was tested remotely through the nominal operational use cases. A few examples of performed tests are given here. In Figure 4

Table 2: Main System Parameters and Performance

Parameters	
Position sensor resolution (16 bit)	0.04 μm
Motor step size	5 μm
Positioning error/accuracy[1]	40 μm (axes)
	60 μm (gaps)
Fill-to-fill reproducibility	$\leq$ 20 μm
Position/status readout rate	1 Hz
Interlock check rate	100 Hz
Time response: load functions[2]	$\leq$ 30 s
load thresholds[2]	$\approx$ 120 s
low-level synchr.	100 μs
top-level response[3]	$\leq$ 10 ms
Number of logging variables (1 Hz)	15000
Data flow (2008 system)	1.6 GB/day
Data volume for permanent storage	160 MB/day

(top) the first synchronized energy ramp of 75 collimators is shown. To increase the statistics, collimators that will not move during the ramp, such as the injection protection devices, were also 'ramped' by scaling the gaps with the beam energy. To assess the absolute precision accuracy, this test was also done by using the same function for all collimators (bottom of Fig. 4). The synchronization of different insertions is achieved by a hardware timing event that triggers the execution of pre-loaded functions. Timing events are also used for the synchronization with other systems such as radio-frequency and power converted.

Nominal ramp cycles have been performed continuously for several days for all the 28 collimators in IP7. An example is shown in Fig.5 for one motor axis. The collimators showed an excellent reproducibility of settings and came back systematically to the same position within less than 20 micrometres, with the exception of 2 isolated cases out of 168 LVDT monitored in this test. The distribution of errors with respect to the average end-of-ramp position is illustrated in Fig. 5. Other tests showed that the absolute positioning error with respect to the requested positions can be up to 2–4 times larger than the 20 μm reproducibility.

PROTECTION FUNCTIONALITY

Automated sequences that hit inner and outer limits of each interlocked position sensor were prepared to validate the protection functionality of the system. An example for one motor axis is shown in Fig. 6 (top). The test consists in requesting positions outside the operator-defined limits and in verifying that (1) the motor stops with the expected error; (2) the hardware interlock is activated. All collimators were checked systematically. A few problems were found (mainly cabling errors that have been fixed) but the over-

[1] The RMS values of the difference between requested position and LVDT measurements are of $\approx$ 15 μm (300 axes, 150 gaps). Isolated sensors show error above what is quoted in the table.
[2] Limited by the PC gateway where 28 collimators were connected.
[3] Dominated by delays in the Ethernet network.

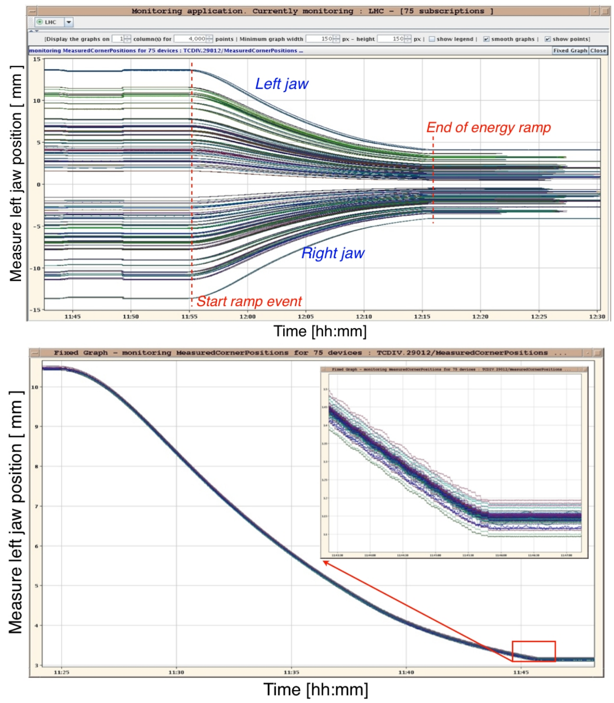

Figure 4: Jaw positions versus time during simulated LHC energy ramps to 5 TeV of 75 collimators.

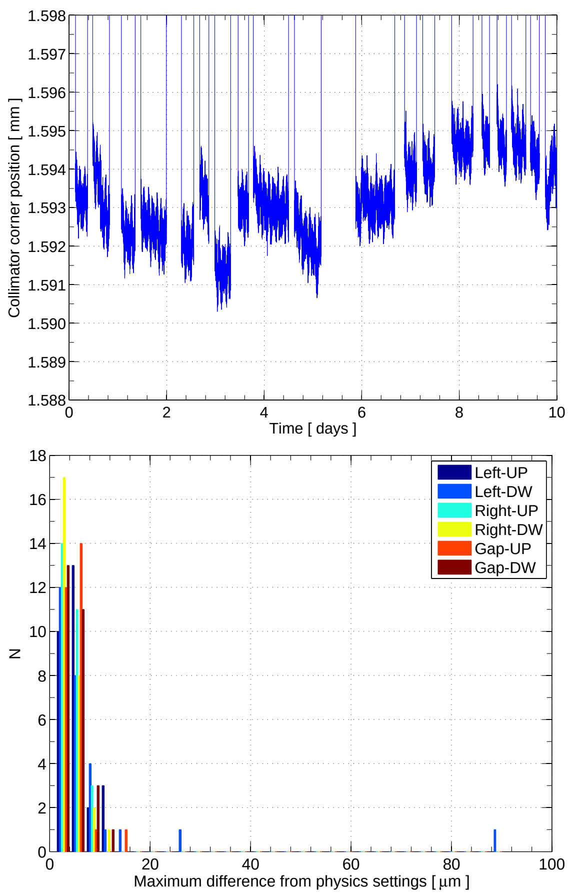

Figure 5: End-of-ramp settings versus time for one motor axis for 19 ramp cycles performed during 10 days (top) and distribution of errors with respect to average end-of-ramp settings for 168 LVDTs of 28 collimators in IR7 (bottom).

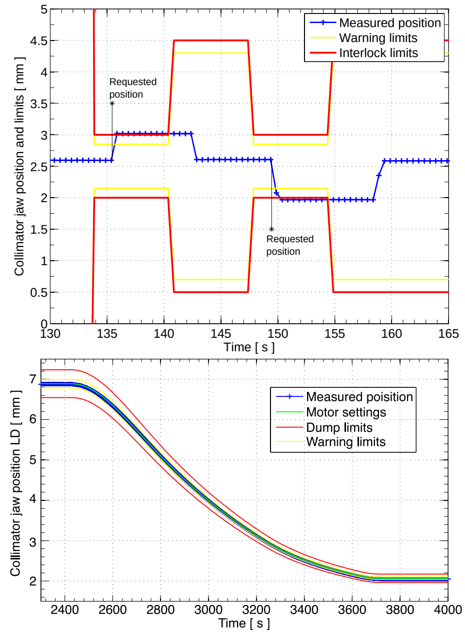

Figure 6: Example of interlock sequence (top) and 5 TeV ramp of motor settings and $\pm 0.5\ \sigma$ threshold functions.

all performance was very good. The system was validated as safe for high-intensity operation. An example of limit functions for a 5 TeV ramp test is given in Fig. 6 (bottom).

CONCLUSIONS

The control system of the LHC collimators provides the functionality required to handle high-intensity beams. A precise jaw positioning can be insured during all the operation phases and the occurrence of unsafe conditions is minimized by a highly-redundant position survey system, designed to make sure that all the critical degrees of freedom stay within safe operational windows. The remote commissioning without beam showed that the system works basically as specified but the final validation will be performed with beam in 2009.

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