LHC COLLIMATOR CONTROLS FOR A SAFE LHC OPERATION

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Abstract

The Large Hadron Collider (LHC) collimation system is designed to protect the machine against beam losses and consists of 108 collimators, 100 of which are movable, located along the 27 km long ring and in the transfer lines. The cleaning performance and machine protection role of the system depend critically on accurate jaw positioning. A fully redundant control system has been developed to ensure that the collimators dynamically follow optimum settings in all phases of the LHC operational cycle. Jaw positions and collimator gaps are interlocked against dump limits defined redundantly as functions of time, beam energy and the β^* functions, which describe the focusing property of the beams. In this paper, the architectural choices that guarantee a safe LHC operation are presented. Hardware and software implementations that ensure the required performance are described.

INTRODUCTION

The nominal beam stored energy at the Large Hadron Collider (LHC) will exceed 350 MJ, to be compared with the quench limit of super-conducting magnets of a few mJ per cm^3 and the damage limit of metal of a few hundred kJ per cm^3. The collimation system, based on 108 collimators located around the ring, protects the machine against beam losses and cleans the beam halos [1].

Each collimator has two jaws controlled by four stepping motors to precisely adjust jaw position and angle with respect to the beam. Stepping motors have been used to ensure high reproducibility of settings. Linear Variable Differential Transformer (LVDT) sensors and resolvers have been installed to monitor the position of the axes of the collimators in real-time (RT) at 100 Hz. The collimator jaws follow motion profiles expressed as functions of time, which is a unique feature for collimation systems in particle accelerators. Different sets of functions are optimized for the different LHC operational phases. Resolvers are used to detect losses of motor steps whereas LVDT readings are compared redundantly with safety limits. Limits a defined as functions of time, of beam energy and of β^* functions that express the focusing property of the beams. If the measured axis position violates any of these limits, which are always active in parallel, the low level control system requests an immediate abort of the circulating beams.

The control system of the collimators is responsible for the motion control, synchronization and survey of about 400 axes (see Tab. 1). It is characterized by challenging requirements [2] such as timing synchronization in the motion axes at the microsecond level; motion repeatability of a few micrometers and accuracy in the monitoring of the profile in execution. High reliability is ensured through architectural choices and redundancy implemented to ensure machine safety. In the next section the architecture of the LHC collimator control system is described. The redundant strategy implemented on the collimator axes monitoring and survey through interlock limit functions is then presented. An analysis of the additional interlock conditions is presented in the last section.

Table 1: Main System Parameters. The number of settings in the second part of the table is calculated for the 2011 operational cycle, with squeeze to $\beta^* = 1$m in IP1 and IP5. Energy– and β^*–limits are common to all machine cycles (same values resident in the hardware). The two dump protection collimator are not included in this list.

Parameters	Number
Movable collimators in the ring	85
Transfer line collimators	13
Stepping motors	392
Resolvers	392
Position/gap measurements	584
Interlocked position sensors	584
Motor settings versus time	1760
Threshold settings versus time	3054
Threshold settings versus energy	196
Threshold settings versus β^*	384

COLLIMATOR CONTROLS

The Control Architecture

In Fig. 1 the general layout of the LHC collimator control system (LCCS) is presented [3]. Starting from the bottom we can identify the following layers: i) Low level front-ends based on two National Instruments PXI systems for the motion control and survey ii) the collimator middle ware based on a gateway that concentrates all the data accesses from the top level application via a standard CERN middle ware server [4] and establishes peer to peer connections with the collimators' low level control systems through the Data Interchange Management protocol (DIM) [5]; iii) the Central Control Application (CCA) [6] is responsible for generating and orchestrating the settings for the whole system and for sending them to the middle ware referring to the collimators' FESA class [7]. The CCA is fully integrated into the LHC Software Architecture (LSA) environment [8].

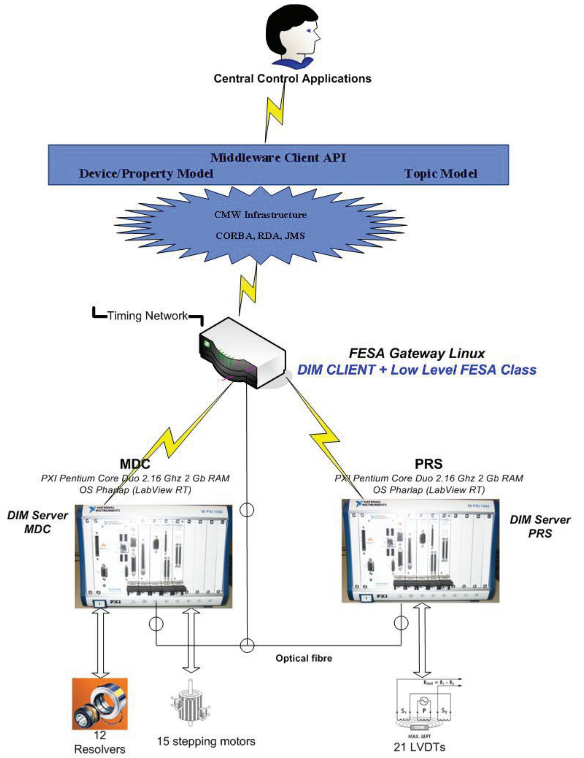

Figure 1: Architecture of the LHC collimator control system.

Low-level Control

Controls choice PXI platforms from National Instruments running LabView RT have been chosen as low level RT control system. Significant improvements of the PXI systems were applied to enhance their reliability and robustness [9]. The main changes are: i) Diskless controller equipped with the PXE network boot protocol; ii) Double core CPU to split the computational load; iii) Implementation of watch dog timers on the CPU and FPGA to detect stuck conditions on the host and bad working of the FPGA; iv) Monitoring of the system parameters (i.e. memory usage, CPU and chassis temperature, CPU load) to prevent operational anomalies (i.e. memory leakages). The control system's reliability was increased by splitting the functions of motion control and survey on two independent PXI systems: the Motor Drive Control (MDC), responsible for the generation of stepping pulses and for the resolver monitoring for up to three collimators, and the Position Readout and Survey (PRS), responsible for the synchronous monitoring of up to three collimators via the LVDTs.

Motor driver controller (MDC) The MDC receives motion commands (i.e. simple displacements or long motion profiles) from the top level through the FESA middle ware. It verifies the consistency of the requested settings against present status of the collimator, then checks for steps lost during execution in RT using one FPGA card per collimator. A specific software was developed for the step generation: in the host controller, the motion profiles are interpolated with a 5 μm step resolution to generate the set points; these are sent via a FIFO to the FPGA, where a step generation loop, operating at 1 MHz, produces the pulses for each collimator motor. Each motor's resolver is read synchronously with the generated steps at up to 400 Hz thanks to a custom reading solution based on CORDIC transformations [3]. The nominal speed for discrete movements is 400 steps/s, which corresponds to 2 mm/s.

Position readout system (PRS) The PRS is responsible to verify that the collimator jaw positions and gaps are within the safety thresholds and to trigger a beam abort otherwise. On each collimator, 6 LVDT sensors are installed to read the 4 axis position and the 2 upstream and downstream gaps. The LVDT position sensors for up to 3 collimators are read at a frequency of 100 Hz and with an accuracy of a few μm [2]. Two parallel 16 bit ADC cards sample the secondary voltages of the 7 LVDTs of each collimator. A sine fit algorithm, which is properly optimized for RT implementation, runs on the Host and estimates the amplitudes. A ratiometric technique is then used to obtain the position. The survey process also runs on the Host but the synchronization is ensured by timing signals generated on an FPGA card and passed via the PXI bus [3].

Collimator Middle-ware

A gateway is installed in each LHC point with collimators to supervise and synchronize all the systems of that point. The RT actions (e.g. MDC motion or PRS monitoring start) are triggered through pulses sent via optical fibers directly to the PXI FPGA cards. All the gateways are equipped with a CERN timing receiver and synchronized via the CERN timing network [10]. This provides not only the LHC timestamps, but also machine status information (i.e. beam energy, β^*) [11]. The information of energy and β^* are used to determine via special tables the gap limits to be sent to the PRS over the network at 1 Hz refresh rate. On the PRS specific watch dog timers have been implemented to detect network communication problems and use, in this case, the tightest limits. On each gateway a FESA server exposes each collimator's data to the operator applications via a device model with information organized in properties and data fields. On the other side, a DIM client running on the same gateway fetches data and sends commands to the DIM servers on the corresponding PXI (MDC and PRS).

POSITION LIMITS AND INTERLOCKS

Operation Cycle for Collimators

The sequence of the relevant phases through which the LHC is driven to establish collisions for physics data taking is referred to as the operational cycle. This includes the injection of high intensity beams, the energy ramp, the betatron squeeze – when the focusing properties of the lattice are changed to reduce the β functions at the collision

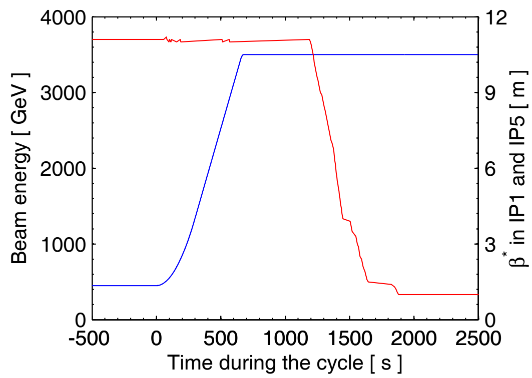

Figure 2: Beam energy (blue, left axis) and β^* in IP1 and IP5 (red, right axis) as a function of time during the LHC cycle. Time zero represent the start of the energy ramp.

points – the establishment of collisions, the physics data taking and the pre-cycle. Due to the large LHC stored energy (more than 20 MJ already at injection), beam collimation is needed in all phases. Appropriate redundancy of interlocks has been built into the system in order to ensure that the critical phases like the energy ramp and squeeze are performed with collimators at the correct positions. For this purpose, the concepts of energy– and β^*–limit functions have been built into the system in addition to standard limits as a function of time.

The beam energy and the β^* functions in a high-luminosity experiment are shown as a function of time during an LHC cycle in Fig. 2. Not shown in Fig. 2 is the pre-cycle without beam when the injection conditions are restored after a beam dump at high energy. Correspondingly, the collimators are moved as shown in Fig. 3. As representative examples, one primary collimator (TCP) of the betatron cleaning insertion and a tertiary collimator (TCT) that protects ATLAS, are shown. The measured collimator gaps and the different types of interlock limits are given as a function of time. Only dump limits, and not the warning limits, are shown.

Limit Functions Versus Time

Most accelerator systems are driven with functions of a pre-defined time duration only during energy ramp, betatron squeeze and collision preparation. The function duration is determined by the property of the power converters. A specific feature of the LHC collimators is that their jaws can be moved with pre-defined functions of time. This feature is necessary to allow the optimum settings to be maintained throughout the operational cycle, when the beam energy or the machine's optics change [12]. Correspondingly, limit functions versus time are also defined for each motor axis and for a gap. Inner and outer limits, with additional operational warning levels are defined for each degree of freedom, for a total of 24 limits functions for collimator, with a clear redundancy, since the degrees of freedom are only 4, one for each motor of the collimator.

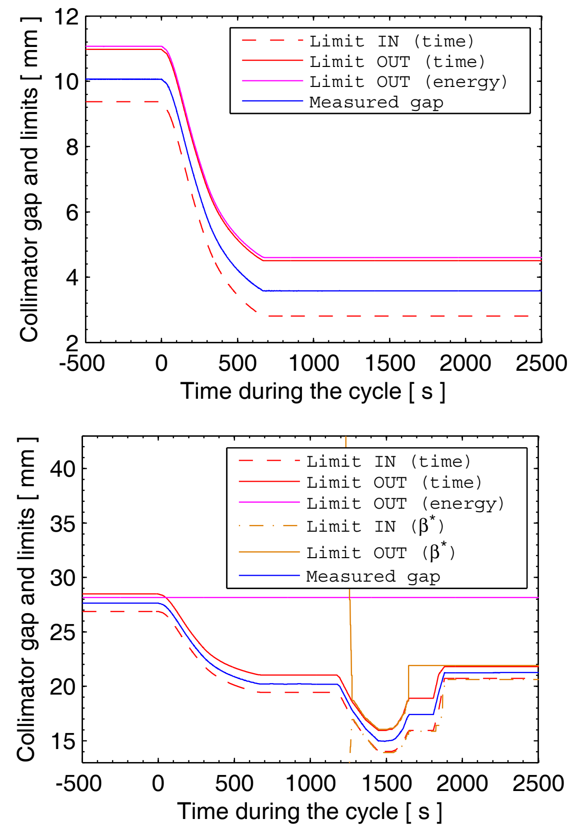

Figure 3: Gap and interlock limits versus time for a primary collimator of the betatron cleaning insertion (top) and for a tertiary collimator in IP1 (bottom) during a complete operational cycle (see Fig. 2).

Discrete Limits

Outside cycle phases driven by functions, the collimators remain idle at constant settings and discrete changes ("trims") are possible. In these cases, discrete collimator limits are used. These limits are computed from the functions: for example, the injection settings correspond to the ramp function's first point, and the limits during physics are given by the collision function's last points. Discrete limits apply for the motor axes and gaps, for a total of 12 dump limits and 12 warning limits per collimator.

Energy Limits

The limits as a function of energy were conceived to ensure that the collimator gaps follow the reduction of beam size during the energy ramp. Maximum allowed gap values versus energy are defined for each gap LVDT. The same concept is used for injection protection collimators – even if the are not "ramped" – to ensure that injection is not possible is collimator gaps are larger than safe limits [13].

β^* Limits

Additional inner and outer limits as a function of β^* are checked for upstream and downstream gap measurements (4 limits per collimator) in order to make sure that the ter-

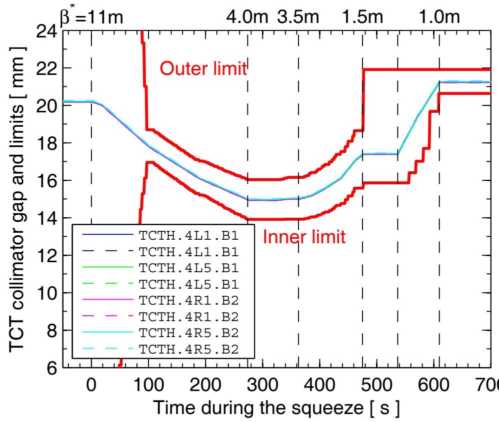

Figure 4: Measured gap position and β^*–limits of 2 tertiary collimators in IP1 and IP5 versus time during a betatron squeeze down to 1 m.

tiary collimators in the experimental region move as required while the optics is changed. The β^* information is distributed for each interaction point (IP) separately. Each collimator can be configured to use as input the β^* in any IP or the minimum of the 4 IPs. An example for 2 TCTs in IP1 and IP5 is given in Fig. 4.

Strategy for Motor Blockage

The controllers of each motor axis are blocked upon reaching the discrete or functional limits versus time in order to avoid that a collimator jaw runs into the circulating beam in the extremely unlikely case that the beam abort was not triggered by the violation of the inner position limits. This blockage mechanism also reduces the risks of mechanical damage in case of erroneous manipulations, like setting of tilt angles above the mechanical limit of 2 mrad or requested position beyond the mechanical end stops that could be reached in case of end switch failures.

Unlike the time-dependent limits, the limits as a function of energy and β^* do not block the motors. This allows the jaws to reach the open parking positions during the recycle without beam. In this phase, the energy limits generate an interlock that prevents injection of unsafe beams until the collimators are moved to safe injection settings. At every operational cycle, it is also verified that all the connections between the collimators and the beam interlock system are operational.

COLLIMATOR STATUS INTERLOCKS

In addition to the position interlocks, the PRS unit can also dump the beams in a number of cases when the machine protection role of the system cannot be ensured:

- Reboots of the low-level systems;
- Power cuts that affect the PRS PXI;
- Set of “Local” mode that allows expert checks and sensor calibrations;
- Stuck conditions detected on the PRS CPU through watch dog timer verified on the PRS FPGA.

CONCLUSIONS

In this paper the LHC Collimator control system has been presented focussing on design, architectural choices and control strategies that guarantee a safe LHC operation. In all operational cases, a highly redundant survey of collimator position ensures that the system is at the required safe settings. This strategy has been successfully validated by 2 years of LHC operation with high intensity beams.

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