MEASURED PERFORMANCE OF THE LHC COLLIMATORS LOW LEVEL CONTROL SYSTEM

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Abstract

The LHC Collimator low level control system (LLCS) is responsible for the control of more than 500 stepper motor axes and the monitoring of more than 700 LVDT (linear variable differential transformer) positioning sensors. It is characterized by challenging requirements such as sub-ms axes synchronization over 30 minute long motion profiles, few tens of μm positioning accuracy and 100 Hz monitoring frequency of all the positioning sensors. The National Instruments PXI platform has been adopted as the real-time low level hardware. In this paper we briefly describe the control architecture and the low level custom solution implemented on the FPGA then we provide a detailed performance review of the entire system. In particular we present the excellent synchronization of several hundred motors over a profile of about 30 minutes, simulating the nominal energy ramp of the LHC, and show that the position error is well below the specified 20 microns.

INTRODUCTION

The LHC will be protected against uncontrolled beam losses by the collimation system, which is made of more than 100 collimators, each equipped with two moveable jaws of different materials [1]. This system has to control the position and angle of the jaws with an accuracy of a few microns, and monitors the current position error at a rate of up to 100 Hz, triggering a fast beam dump in case of problems. We choose stepping motors (two per collimator jaw) to have an accurate open loop positioning, while LVDTs and resolvers monitor the axes. During an energy ramp all the collimators` jaws (about 400 motion axes) approach synchronously the beam according to motion profiles of about 30 minutes that have to be executed within tolerance windows, which depend on the energy and the position (i.e. 20 μm at nominal energy) with a maximum jitter of 10 ms. over the entire profile duration. On the other hand, axes of the same jaw have to be synchronized at us level in order to avoid mechanical vibrations in the block's material (i.e., graphite). Cable length between electronics and sensors-motors is another project challenge. In fact, because of the high radiation level close to the collimators, the conditioning and control electronics is located in safe alcoves up to 800 m away.

THE CONTROL ARCHITECTURE

In Fig.1 the general layout of the LLCS [2] is presented. Starting from the bottom we can identify the following modules: i) ***the Motor Drive Control (MDC)*** is the PXI system responsible for the generation of stepping pulses

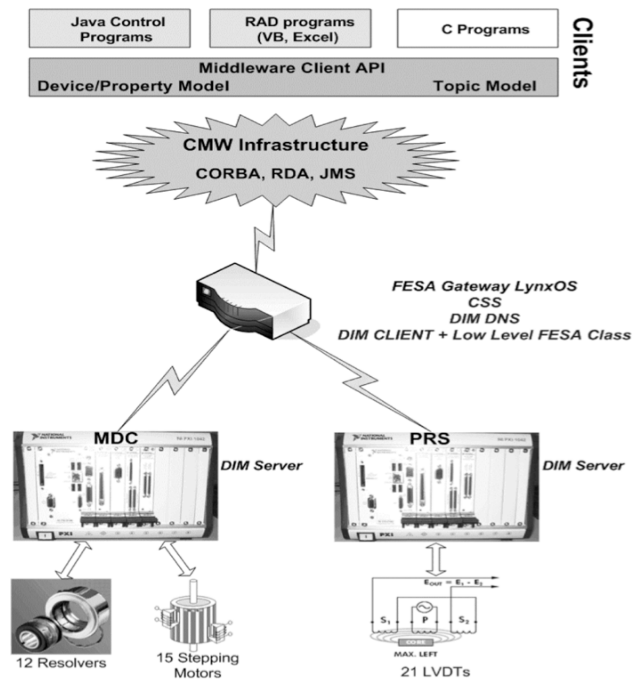

Figure 1: LLCS control architecture layout.

and the resolvers' reading for up to three collimators.

It receives motion commands from the top level, verifies the consistency and checks for steps lost during the execution in Real Time using an FPGA card for each collimator. The National Instruments Softmotion module, which has been properly customized for this application, has been used for the steps' generation: the trajectory generation running on the host produces the set points, sent via a FIFO to the FPGA, where a steps generation loop, operating at 1 MHz, produces the pulses for each collimator axis. Each axis' resolver is read synchronously with the generated steps at up to 400 Hz thanks to a custom solution based on CORDIC transformations [2]; ii) ***the Position Readout and Survey (PRS)*** is responsible for the synchronous monitoring of up to three collimators via the LVDT reading. Two parallel 16 bit ADC cards sample the secondary voltages of the 7 LVDTs of a collimator. A Sine fit algorithm, which is properly optimized for a real-time implementation, runs on the host to estimate the amplitudes and a ratiometric technique has been used to obtain the position [3]. The survey process also runs on the host but the synchronization is ensured by timing signals generated on the FPGA and passed via the PXI bus [3]; iii) ***the Collimator Gateway*** concentrates all the data accesses from the top level application via a standard CERN middleware server [2] and establishes one to one connections with the collimators' low level control systems through the Data Interchange Management protocol (DIM) [5]. A gateway is installed in each LHC collimation point [1] to supervise all the systems of that point and synchronize different points. The real-time actions (e.g. MDC motion or PRS monitoring start) are triggered through pulses sent via optical fibre directly to the PXI FPGA cards. All the gateways are equipped with a timing receiver and synchronized together via the CERN timing network [5]. This provides, not only the LHC timestamps, but also machine status information (i.e. beam energy, machine cycle). On the low level side the 10 MHz backplane clock of all the PXIs of the same point are daisy chained and connected to an MDC master equipped with a timing card NI-6653 that generates a reference clock stable at 50 ppb; iv) ***the Central Control Application (CCA)*** [6, 7] is responsible for generating and orchestrating the settings for the whole system, for sending them all devices, for monitoring the aspects relevant for beam operation.

The PXI systems reliability has been increased by replacing the Hard Drive with a SSD and basically implementing the system boot from a general PXE server. The host controller dual core processor helps to share the workload, moving all the communication tasks onto only one core.

THE MEASURED PERFORMANCE

MDC Timing Behaviour

The MDC timing behaviour can be characterized by the following parameters: i) *trigger response delay*, the time between the trigger reception and the generation of the first pulse for the stepping motor driver; ii) *trigger response jitter*, the variation of the trigger response delay in the execution of different motion profiles; iii) *profile stop jitter*, the variation of the profile execution time due to the drift of the FPGA clock.

The trigger response delay and jitter have been evaluated as the average and the standard deviation of the times measured on 30 repeated triggered displacements. A 30 minute long test profile has been considered in order to evaluate the standard deviation of the profile execution times. These latter have been measured as the time elapsed between the first and the last generated stepping pulse so as not to take into account the jitter on the start trigger. The measured parameters on an MDC master are summarized in Table 1.

The two axes of a single jaw are instead synchronized at the μs level since the steps generation for all the axes of the same collimator is performed in the same FPGA 1 MHz loop.

Table 1: MDC Performance Parameters

Trigger response delay	Trigger response jitter	Profile stop jitter
120 us	4 us	50 us

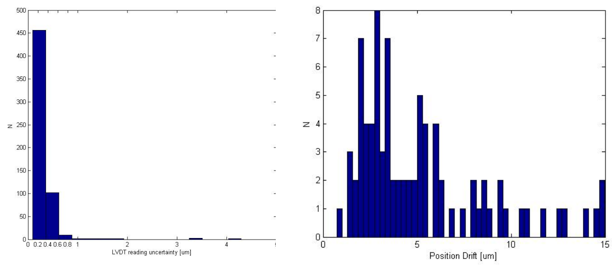

Figure 2: LVDT reading uncertainty in μm evaluated on 100 repeated readings (left) and drift distribution of 85 LVDTs in μm over 3 weeks (right).

PRS Reading Uncertainty

Our innovative digital approach based on the Sine fit algorithm ensures an excellent position reading uncertainty even with low SNR values [3]. In Fig.2 (left) we present the reading uncertainties distribution of the 648 LVDTs installed on the LHC collimators. These uncertainties have been evaluated from the standard deviations based on repeated readings. The reading uncertainty is, for most sensors, well below the μm level and only a small number of sensors reach a few μm.

The main cause of reading drift is the temperature of the LVDT itself. Thermal cycles performed on the PRS and LVDT showed that the reading drift produced by temperature excursion on the PRS only is negligible compared to that of the sensor [3]. According to the NI-6143 stability specifications [8] a maximum drift of a few μm over a year is expected on the LVDT reading. In Fig. 2 (right) a distribution of the LVDT sensors' drift over 1 month in the tunnel is shown.

Global System Characterization

The monitoring processes on different PRS have to be synchronized to within a few ms in order to avoid, at the maximum speed of 2 mm/s, large position errors between collimators controlled by different PXIs distributed along the 27 km-long LHC tunnel. We analyzed the PRS synchronization, measuring for each collimator the timestamps when the profile monitoring started and stopped.

On each PXI system a UTC timestamp counter has been implemented on the FPGA and synchronized with a precision of some hundreds of ns with the LHC timestamp received on each gateway. According to the stability specification of the precise master clock a timestamp drift of about 4 ms/day is expected. For the general system operation a synchronization accuracy of only some hundreds of ms is required so that, the timestamps' synchronization procedure can be repeated even yearly. Nevertheless, for the PRS synchronization analysis, the timestamps have been synchronized just before each test. In Fig.4 the distribution of the PXI timestamps' deviations with respect to the LHC timestamp just after a synchronization procedure is shown.

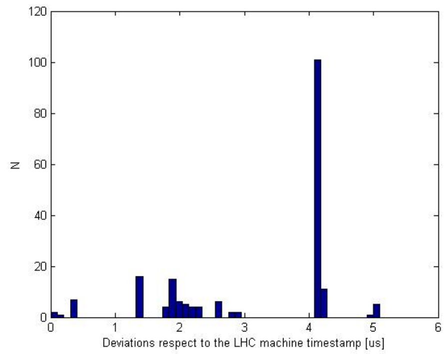

Figure 4: PXI systems timestamps deviations with respect to the general LHC timestamp just after the synchronization.

In Table 2 we present a summary of the PRS synchronization measurements. The jitter parameters refer to the monitoring profiles of all the 108 collimators. The values in the table represent average values on 30 repeated threshold profiles. As for the MDC characterization, the test profile duration is 30 minutes.

Table 2: PRS Synchronization Performance

Start monitoring profile jitter	Stop Monitoring Profile jitter	Profile monitoring duration jitter
1.6 ms	2 ms	1.8 ms

The **positioning accuracy** during the execution of functions can be characterized by the systematic positioning error and by the reproducibility of settings. Taking as an example a typical 5 TeV energy ramp profile [7], we calculate for each collimators` axis over 11 repeated executions: i) the systematic positioning error as the average of the maximum error (i.e. difference between the LVDT reading and the requested position) over all the profile; ii) the positioning reproducibility as the standard deviation of the max error over all the profile (see fig. 5). The reproducibility is relevant for the system performance because systematic errors can be corrected.

The systematic positioning error is mainly due to the mechanical play and the gear factor approximation error but also takes into account systematic errors in the LVDT calibration. Being systematic, it can be corrected and/or minimized. The positioning repeatability, however, concerns the random part of the positioning and monitoring error including MDC and PRS jitters as well as LVDT reading uncertainty. This, for all the collimators` axes, is contained inside the specified 20 um tolerance, as shown in Fig. 5.

CONCLUSIONS

A complete performance characterization of the LHC collimator low-level controls has been done. The results obtained without beam in the final LHC configuration show the fulfilment of the project requirements.

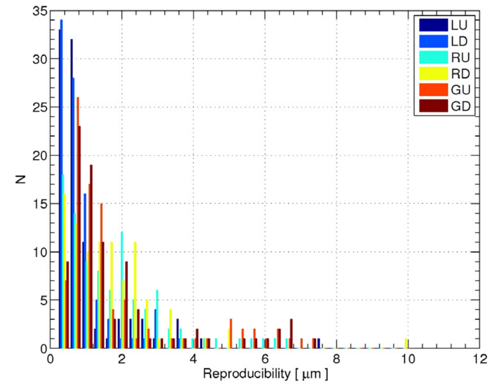

Figure 5: Reproducibility of collimator positions as measured with the LVDTs (6 per collimator, one for each motor axis – LU, LD, RU, RD – and 2 for direct gap measurements – GU, GD). For each sensor, this is calculated as the standard deviations of the maximum errors of eleven 5 TeV ramp profiles.

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