10th ICALEPCS Int. Conf. on Accelerator & Large Expt. Physics Control Systems. Geneva, 10 - 14 Oct 2005, PO2.016-2 (2005)

THE CONTROLS ARCHITECTURE FOR THE LHC COLLIMATION SYSTEM.

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ABSTRACT

The high luminosity performance of the LHC relies on storing, accelerating, and colliding beams with unprecedented intensities. Tiny fractions of the stored beam suffice to quench a super-conducting LHC magnet or even to destroy parts of the accelerators. The LHC collimation system is protects the accelerator against unavoidable regular and irregular beam loss.

The collimator control system is required to accurately position the collimators with respect to the beam. The system, whilst needing to be extremely reliable, should be sufficiently flexible to cope with the various requirements in the different stages of the LHC operation cycle.

This paper portrays the operational requirements and control use cases. It then describes the adopted controls architecture including a more detailed description of the various components of the system.

INTRODUCTION

In the initial phase, the LHC collimation system[1,2] consists of 104 collimators; in the final phase this number will grow to 162. Most collimators are constructed from two parallel jaws of fibre-reinforced Carbon. Two motors per jaw permit the adjustment of depth and angle. Ten position sensors monitor absolute and relative jaw positions as well as the collimator gap. Finally the collimators are equipped with end-switches and temperature gauges.

The collimation system serves two purposes: protection and cleaning. The collimators are located in the injection lines and in 7 of the 8 LHC straight sections, with the largest concentration in point 3 (momentum cleaning insertion) and point 7 (betatron cleaning insertion).

The beam cleaning through collimation is a multi stage process. The primary collimators cut the beam halo and the secondary collimators catch the secondary beam halo produced at the primary collimators. The remaining small halo that escapes the cleaning section is caught by various protection elements and by the tertiary collimators located at the aperture bottlenecks of the experimental insertions.

The collimation system is highly safety-critical: a wrong set-up of collimators may result in quenches and compromises the machine protection. The aperture restrictions a (expressed in beam sigma σ) given by the collimators always have to obey to a strict hierarchy, i.e.:

$$a_{\text{primary}} < a_{\text{secondary}} < a_{\text{protection/tertiary}} < a_{\text{machine}}$$

The primary collimator positions will typically be about 2 σ tighter than the machine aperture. The secondary collimators follow at a 1 σ distance. The required accuracy is of the order of 0.2 σ.

During the energy ramp the beam size shrinks and the collimator jaws will follow to some extent in order to improve cleaning and protection and to ensure early detection of sudden beam movements. During the beta squeeze, the machine optics changes and so does the beam size at the tertiary collimators. To maintain the above hierarchy, the collimator positions have to be adapted. An important requirement is that the primary and secondary collimators have to move into the beam halo in a coherent way, respecting the 1 σ relative distance with an accuracy of at least 20 %. The collimator hardware and control system should therefore be able to position the jaws with an accuracy, reproducibility and synchronicity down to the 20 μm level.

The collimator settings are defined in normalised terms around the beam centre and must therefore be converted into real jaw positions at each location. This conversion requires the accurate knowledge of the local orbit and the local beta function at each collimator at any given time. Though the normalised settings remain constant for a given energy and optics, the required real jaw settings must always be consistent with the local orbit and the local beta functions in order to stay within the tight tolerances. Hence, the LHC collimation system must be considered as a dynamic system: its cleaning and protection properties are closely coupled with the actual closed orbit and the local perturbations of the beta functions.

OPERATION REQUIREMENTS

The needs of the collimators through the various stages of the operational cycle have been carefully studied, both during commissioning and during regular operation. The operational scenarios fall in three categories: Injection Preparation, Ramp and Squeeze, Set-up of Collimator System.

Injection preparation

In preparation for a fill, the collimators are set to the best known position from previous fills. After the injection of a pilot bunch, the orbit is checked and the collimators positions are quickly verified by comparing beam loss patterns to a reference pattern. The accuracy can be improved with a higher intensity beam (but still safe for the machine). If the beam loss pattern is not reproduced, the checks fail and a detailed setting up of the particular collimators has to be performed. With the collimators correctly set up, the collimation system is ready for nominal beam intensity and the system can give its green light (User Permit) to the Beam Interlock Controller[3,4] (BIC).

Collimator handling during the ramp and during the squeeze

During the ramp and squeeze the collimators will have to follow to some extent the evolution of the beam size at the various collimator locations. There are various possible solutions to drive these changes. The simplest solution is to use movement functions of time which are prepared offline by the setting generation. The execution of these functions is synchronised through the central timing system.

Collimation set-up

If the collimator settings need a major adjustment then a full collimator setting-up procedure has to be carried out. We assume, however, that the accelerator is highly reproducible (orbit, beta beat, etc.) such that recalibration of all collimator positions at top energy can be avoided for each new fill. If needed, the collimator positions can be optimised systematically with a fast beam based set-up at the injection energy. With a good understanding of the machine and with a reproducible energy ramp and beta squeeze, the observed changes might possibly be translated to changes at higher energy.

Traditional set-up method: This method starts with producing a well-defined cut-off in the beam distribution. The two ends of each collimator jaw are moved until the beam edge is touched (witnessed by a downstream beam loss signal). This step defines an absolute reference position and angle for each jaw. This method is lengthy and delicate (e.g. moving a collimator too far affects the cut-off in the beam distribution).

Fast Beam based set-up: This method, which is based on experience of other accelerators[5], complements the traditional set-up method. The principle relies on moving jaws in hierarchical order into the beam halo up to the point where a specified beam loss level is recorded. The method works because collimation efficiency is more closely related to beam loss patterns than to collimator positions, which are sensitive to orbit, beta beat, etc. This method, implemented as an automated procedure, can be fast: The collimators starting from at a fixed offset relative to a previously known position only have to move short distances and do not need to be retracted. Furthermore, the two rings can be tuned in parallel.

Advanced set-up with beam loss matrices: To fine tune and optimise the cleaning efficiency (at injection or top energy) other advanced automatic tuning algorithms may be envisaged that take into account collimator response matrices. Such matrices would translate a given beam loss pattern into an adjustment of multiple collimator positions. The detailed process of set-up and optimisation of the collimation system requires further studies and work.

COLLIMATOR CONTROL USE CASES

From the operational scenario, we derived several use cases for the collimator control system. The elaboration of these use cases has shaped the architecture and defined the responsibilities of the various components in the architecture. The most important classes of use cases for the collimator control are described below:

Unsynchronised movement

Unsynchronised movements concern individual collimators. These movements are required for setting the collimators to the injection setting. The use case starts with collimators in an undefined state and without circulating beam present in machine. The objective is to bring the collimators into a well defined state. Variations of this use case can be used for equipment tests.

- The system ensures that the machine is in a state with no beam.
- The User Permit to the BIC is revoked, marking the collimator system as unsafe for beam.
- The nominal settings are read from the setting database. Using the nominal emittance, optics and orbit, these settings are converted into collimator settings and sent to the hardware.
- The collimator tolerances (in mm) are obtained by the Critical-Settings Manager from a secure database that holds all critical LHC interlock levels and are loaded in the collimator equipment.
- The collimators start moving.
- If all movements have been completed, and the actual positions are within tolerance, the system asserts its User Permit to the BIC.

Synchronised movements

Synchronised movements concern a group of collimators that have to move in a coordinated way. During the movement strict relations have to be maintained. The movements may further be synchronised with a machine operation (movements during the energy ramp and beta squeeze). The use case starts with collimators in a well defined state and beam present. The objective is to move the collimators jaws to the new positions without violating the strict requirements on the relations between the collimators.

- The system retrieves the actual and newly required settings and the functions of time that define the path how these new settings should be attained. Using beam parameters information, the settings are converted into actual jaw positions. The movement functions are loaded into the equipment, but not yet executed.
- The system retrieves the functions that specify the interlock limits in mm from the Critical-Settings Manager and loads them to the equipment.
- The system checks that all functions are accepted by the equipment and ready for execution.
- In case the movement is not synchronised with a machine operation, the system requests the timing system to emit a common start signal for the collimator movements. Otherwise the system tells the LHC sequencer that it is ready for the machine operation.
- The equipment waits for the arrival of the timing event. Upon arrival, the collimators start moving. During the movement, the actual positions are continuously read and compared with the values given by the limit functions as a function of time.
- When the collimators have reached the end position the system reports that the movement is finished.

Beam based fast position optimisation

The collimator positions are adjusted using information of the beam loss monitors. The use case starts with the collimators set at 1.5 σ relative offset with respect to the nominal (i.e. last optimised) value. The objectives is to drive, in a precise order, the collimators jaws one by one into the beam halo with steps of 0.05 σ until an associated set of Beam Loss Monitors (BLM) detects a predefined value of beam loss.

- The system retrieves the order in which the collimator jaws have to be adjusted. For every jaw in the list the system will in turn:
  - Load a function that specifies a movement relative to the actual position.
  - Retrieve the list of associated BLMs and the value that should be reached.
  - Subscribe to the BLM measurement values.
  - Continuously commands the collimator to make one step until the BLM reaches the predefined value.
- When all jaws have been optimised the procedure has finished. The final beam loss pattern is recorded and archived for later reference.

Note that this procedure provides a fast way to optimise the full collimation system. The BLM reference levels are found empirically and may be updated from fill to fill. As the total number of optimisation steps foreseen is 30 x 80 jaws/ring = 2400 steps/ring (doubled in case the jaw angle is taken into account as well), the total time required to adjust all collimators positions can be quite lengthy. The procedure should be highly automated.

Exception Handling

The collimator positions are continuously monitored and it is validated that they are within tolerance with respect to the demanded position. The system obtains the collimator limits through the Critical-Settings Manager. Even during movements, the system knows about the evolution of the positions and verifies that these stay within tolerance. Actually two sets of min/max limits will be used. The first set of limits gives the values that, if not respected, would compromise the protection. If these limits are surpassed, the User Permit of the collimators to the BIC is revoked, causing the beam to be dumped. In order to anticipate problems and to possibly take corrective actions, the system applies a second set of limits which are tighter than the first set. If these warning limits are transgressed, an alarm message will be sent to the operator console, and the software can take possible corrective actions like stopping the movement.

ARCHITECTURE

The architecture of the collimator control system (see Figure 1) is built of three distinct levels. The lowest level, consisting of the systems *Motor Drive Control*, *Position Readout and Survey*, and the *Environmental Surveillance*, are implemented as PLC systems. The low level systems are controlled by the Collimator Supervisor Systems (CSS) that supervises a group of collimators. All the CSS are controlled by the Central Collimation Application running from the control room.

LOW LEVEL CONTROL SYSTEMS

The low level control systems provide direct control of the motors, the position sensors and the environmental conditions sensors. These systems are implemented in PLCs located at a distance of a few hundred meters from the collimators (with one exception of 1.3 km) in an underground area that is protected against direct radiation. A low level control system exchanges data with its supervisor (CSS) over Ethernet. However, the synchronisation of the actions is controlled through synchronisation signals provided by the CSS. Finally, the low level systems are connected to the beam interlock controller by which the beam can be dumped in case of a detected problem. The responsibilities and exchanged data are detailed per subsystem below.

Motor Drive Control (MDC)

The MDC systems execute the jaw position displacement requests. The PLC of a MDC system controls the motors of a group of collimators (depending on the number of channels per Motor Control Unit and the maximum number of such units that can be controlled by one PLC assembly). The MDC system receives from the CSS the requests to move the collimator jaws and the signals for synchronisation of the actual movement. The synchronisation signals are used to start the movement and possibly to control its pace.

Functions can be either simple, i.e. to move a predefined number of steps in a given time interval, or complex, giving the position as a function of time over a longer period. Complex functions are required to avoid abrupt starts and stops, but are also useful to describe the complete movement during the ramp or the squeeze.

Position Readout and Survey (PRS)

The PRS systems assure that the collimators jaw positions stay within tolerance with respect to the demanded positions. The tolerance should be maintained both while the collimators are at rest and during the collimator movements. To assure these tasks, the PRS systems receive from the CSS the functions that describe the allowed tolerances during the movement. In addition, the PRS also receive the synchronisation signals from the CSS. The PRS systems continuously read the positions of the collimators and validate that these are within limits. As described above, for every position sensor, the PRS keeps track of both warning limits and dump limits.

The number of sensors that can be treated by one PLC assembly is determined by the required response time (or loop time). This time should not exceed the ratio of the position tolerance for generating a warning message and the maximum run-away speed of a collimator jaw.

Environmental Survey System (ESS)

The ESS surveys the environmental parameters of the collimator system and provides an independent last line of defence. The ESS, which essentially surveys temperatures and water flow, dumps the beam in case of abnormal situations. A collimator may start heating up due to some undetected malfunctioning (either a badly controlled beam parameter or an undetected bad collimator jaw position). When a temperature gauge exceeds a preset threshold, the system will generate a warning message to the CSS, if the temperatures exceed an even larger threshold, the ESS system will revoke its User Permit to the BIC and the beam will be dumped.

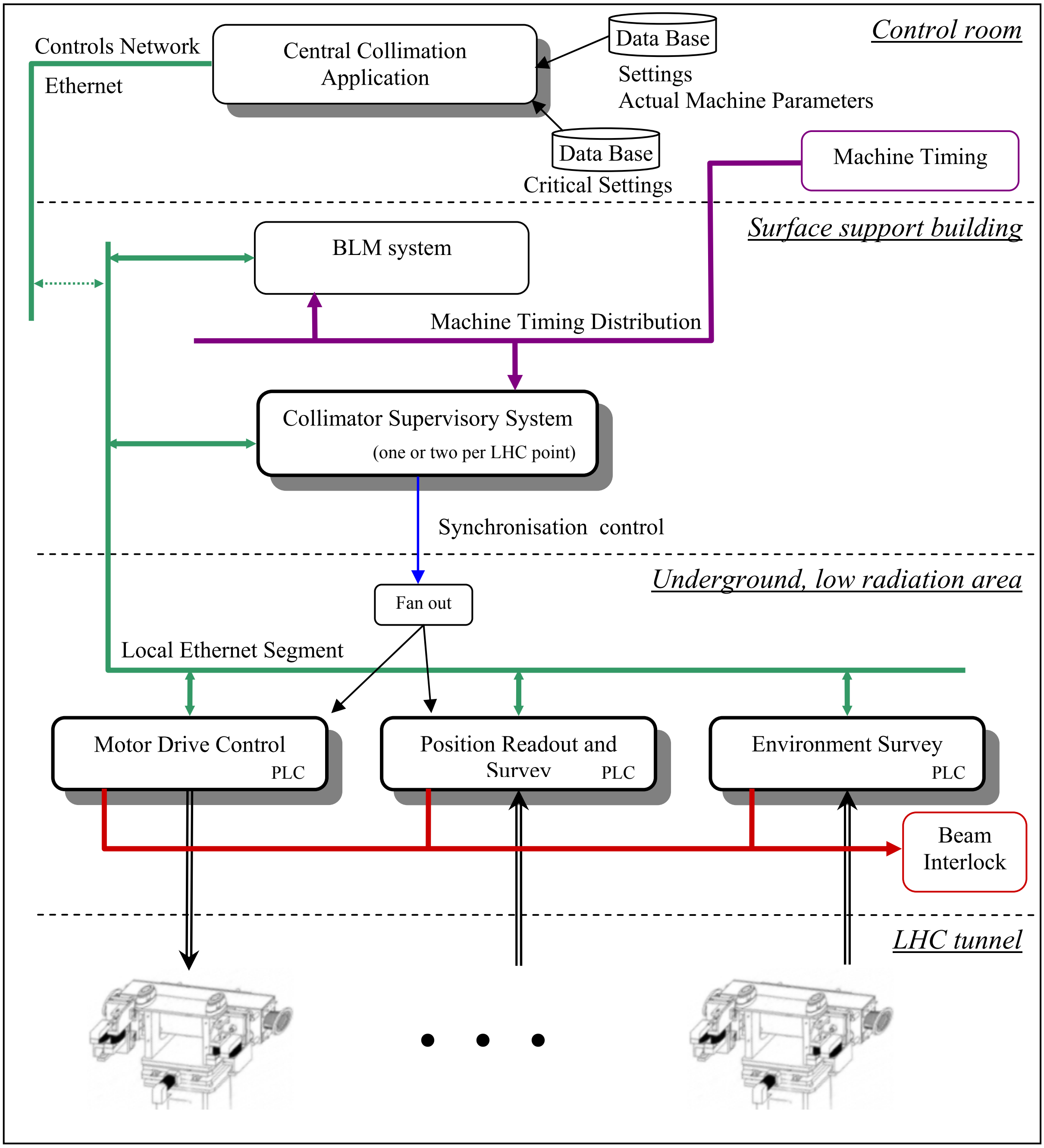

Figure 1 Architecture of the Collimation Control System

COLLIMATOR SUPERVISOR SYSTEM (CSS)

A CSS supervises a group of collimators that are local with respect to the LHC straight section. Depending on the number of collimators, there will be one or two such systems per straight section. For reason of accessibility and maintenance the supervisor systems are located in the surface building. The system will be implemented based on the FESA[6] architecture and deployed on standard PC based gateways running the LynxOs operating system.

A CSS acts as a gateway between the Central Collimation Application and the low level control systems: It receives parameters, displacement functions, commands and data requests from the Central Collimation Application and forwards this information to the low level systems. The actual synchronisation of the collimator movements is orchestrated by synchronisation signals that are sent over dedicated optical fibres to the low level systems. To synchronise the movements of all collimators around the machine, the CSS uses the synchronisation signals that are distributed by the LHC machine timing system.

The CSS also relays information from the low level systems to the control room such as position readings, position error reports, and post mortem data.

Besides this role of gateway between the Central Collimation Application and the low level systems, the CSS also plays an important role in the fast beam based alignment which is described above. To optimise this procedure, the CSS provides the service to drive one or two motors with predefined step size until the associated beam loss monitors reach a given level. In order to perform this task, the CSS communicates the step size to the motors involved, subscribes to the beam loss information from the BLM system, and repeatedly sends the start signal to the low level systems, until the beam loss monitors reach the predefined level of beam loss.

Currently, the communication with the BLM systems is based on TCP over Ethernet. It is believed that the performance of the communication is sufficient for all cases. However, if the BLM communication turns out to become a bottleneck, faster communication mechanisms could be envisaged.

CENTRAL COLLIMATION APPLICATION (CCA)

The Central Collimation Application provides the coherent interface to all the moveable objects in the LHC and its injection lines. The application itself will make use of standard components in the LHC control environment[7], such as Trim and Setting Management, Critical-Settings Mechanism, Alarm System, Post Mortem System. The features that differentiate collimator control from other LHC equipment control are the dependencies of the jaw positions on various beam parameters and the setting optimisation procedures which will take into account the readings from the beam loss monitors.

The application will be driven by the operator, but also by the LHC sequencer that drives the machine through various stages of the operational cycle.

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