COLLIMATOR SETTINGS GENERATION, MANAGEMENT AND VERIFICATION

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Abstract

Different collimator settings are required throughout the LHC operational cycle following the evolution of key beam parameters like energy, orbit and β-functions. Beam-based alignment is used to determine the beam centers and beam sizes at the collimators at discrete times in the cycle, such as injection, flat-top and collisions. These parameters are then used to generate setting functions for the collimator positions and interlock limits. An overview of the settings generation, management and verification cycle is presented, and potential error scenarios in the settings generation are identified. Improvements foreseen for the post-LS1 operation are discussed. The present collimator status monitoring system is reviewed with suggestions for improvement. The role of MAD-X online is discussed. Finally, the results and current status towards maximizing the potential of the embedded-BPM collimators that will be installed in 18 collimator slots during LS1 is presented, including the tested automatic alignment procedure, software interlocks and orbit monitoring.

INTRODUCTION

The Large Hadron Collider (LHC) is at the particle accelerator technology frontier, with a stored beam energy higher than any previous collider. It is protected from potential damage by several machine protection systems. The collimation system removes the halo particles before they can quench the super-conducting magnets [1]. Collimators also protect the aperture from single-turn abnormal beam losses, which may occur if the beams are miskicked during injection or dump.

Collimation is required at all phases (injection, ramp, squeeze and physics) due to the high stored beam energies present in the machine. The jaw position settings depend on key beam parameters, such as the energy, orbit and β-functions, which change as a function of time, energy and/or β^*. The result is unprecedented complexity, with approximately 400 axes of motion [2] requiring function-based settings and a redundant interlocking strategy. The settings must be continuously monitored and compared to the desired values.

A schematic of the collimator settings parameter space is shown in Fig. 1. The jaw corner positions in mm (M1, M2, M3 and M4) for any point in the operational cycle are determined from the local beam-based parameters (shown in blue) and the half-gap opening in units of beam σ (shown

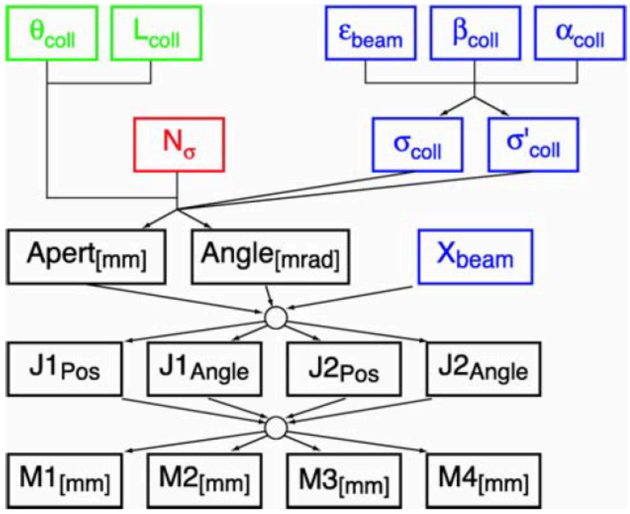

Figure 1: Collimator settings parameter space [3].

in red) at each collimator. The beam-based parameters are typically measured via beam-based alignment [4] at four points: injection, flat top, after the squeeze and in collisions. Functions are generated to ensure that collimators are always at the optimal positions during dynamic changes of configuration. The settings are stored in a beam process, which also contains settings of other LHC devices for a given machine stage in the cycle. Beam processes are then played in the appropriate order by the LHC sequencer [5]. The jaw positions are interlocked at all times by three categories of interlocks:

1. inner/outer limits for each jaw corner and gaps, stored in an actual or function beam process.
2. inner/outer β^* limits on the jaw gap, stored in a discrete beam process.
3. energy limits on the jaw gap, stored in a discrete beam process.

Typical values for the limits are ± 400 μm, or ~ 1 σ. If the limits are exceeded at any time, the beam is automatically dumped. As the β^* and energy limits are stored in a discrete (i.e. a non-function driven) beam process, they are independent of the jaw positions and will still cause a software interlock if the jaws fail to move e.g. during a ramp or squeeze.

This paper reviews the collimator settings generation cycle, the issues encountered during LHC operation and the

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measures taken. An overview of the present collimator status monitoring system is provided, together with suggestions for further improvement. Finally, the current status towards achieving operability of the new BPM collimators and the status of the MAD-X online tools is discussed as a further step towards improving the protection of the machine from the collimation point of view.

SETTINGS GENERATION CYCLE

There are four main stages in the collimator settings generation cycle, depicted in Fig. 2. In the first step, the beam center and beam size are measured via beam-based collimator alignment [4]. The measured beam center is calculated as the average of the aligned left and right jaw positions:

$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2}$$

The beam size is inferred from the ratio of the aligned collimator gap to the cut expressed in units of beam sigma that was made by the IR7 TCP collimator:

$$\sigma_i^{inf} = \frac{x_i^{L,m} - x_i^{R,m}}{N_{TCP}}$$

The collimator settings to be used during operation are then calculated based on N_i, the desired half-gap opening in units of beam sigma:

$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^{inf}$$

$$x_i^{R,set} = \Delta x_i - N_i \sigma_i^{inf}$$

The measured beam size is used at injection energy, but as the jaw gaps expressed in mm are smaller at flat top (and hence more sensitive to setup errors), the nominal beam size is used for the settings at top energy. The second step is to validate the measured settings using beam loss maps [6]. Normally, the validation is performed in the same fill after completion of the alignments. The number and type of beam loss maps that can be obtained is limited by the number of bunches injected at the start of the fill. Once this is completed and validated, the standard settings can be used for high-intensity operation with the standard sequence-driven generation. A list of beam processes and the required operations in each case is provided in Table 1.

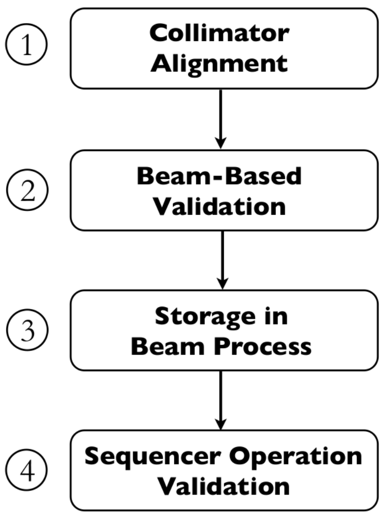

Figure 2: Collimator settings generation cycle.

At injection energy, all collimators are aligned. At flat top, all collimators except the injection protection collimators (TDI, TCLIA, TCLIB) are aligned. A ramp function is generated to move in the collimators as a function of time, using the time-dependent energy and optics functions of the beam, from the injection settings to the flat top settings. Details of the function generation are available in [7]. This procedure is repeated for only the TCT collimators in the squeeze and collisions. During the squeeze, the TCTs are moved as a function of the β^* in each experimental IP, while in collisions the transition depends on the collapse of the crossing bumps.

The beam centers and beam sizes measured during alignment were input manually during the 2010-2011 LHC runs, but following the automation of the alignment procedure, the values were automatically stored in local files on the CERN Control Center (CCC) machines. Using these alignment values, the functions are generated automatically by a Mathematica program and imported into the LHC Software Architecture (LSA) settings database in the third step of the settings generation cycle. Table 2 lists the collimator settings in units of beam sigma (N_i) as used throughout the 2010-2013 LHC run.

The fourth and final step is to validate the sequencer operation in a low-intensity fill. This is normally done in the shade of other fills required for beam-based validation or tune and orbit feedback checks.

COLLIMATOR STATUS MONITORING REVIEW

Current System

As is evident from Fig. 1, there are two levels of abstraction in the collimator system settings. The lower level consists of the jaw positions in mm and the related software interlocks, whereas the higher level consists of parameters which the hardware is not aware about, and which are used to calculate the settings in mm.

The collimator statuses and jaw positions online status display (vistar) shown in Fig. 3 is designed to monitor the system at the lower level. The vistar, displayed online and on the CCC overhead monitors, shows all the LHC ring and transfer line collimators ordered by beam and IP. The averages of the LU/LD and RU/RD LVDT jaw positions are displayed, and the size and position of a white space gives an indication of the gap opening and collimator center. The collimator status, Motor Drive Control (MDC) and Position Read-out Survey (PRS) statuses are shown.

A more detailed view of the MDC and PRS error and

Table 1: The beam processes for various beam modes, and the operations required to determine the settings for each case. This set of beam processes, which contain the necessary settings for all machine components from the start to the end of fill, form a unique hypercycle.

Beam Mode	Beam Process	Settings Generation
Injection	Ramp@start	Alignment of all collimators
Ramp	Ramp function	$f(\gamma, t)$
Flat Top	Ramp@end / Squeeze@start	Alignment of all collimators except inj. prot.
Squeeze	Squeeze function	$f(\beta^*, t)$
Adjust	Squeeze@end / Collisions@start	Alignment of TCTs
Adjust	Collisions function	$f(\theta, t)$
Stable Beams	Collisions@end	Alignment of TCTs

Table 2: Collimator settings in units of beam sigma used throughout the 2010 - 2013 LHC run.

Collimator Family	Injection	Top Energy (2010) Relaxed Settings	Top Energy (2011) Relaxed Settings	Top Energy (2012 - 2013) Tight Settings
TCP IR3	8	12	12	12
TCSG IR3	9.3	15.6	15.6	15.6
TCLA IR3	10	17.6	17.6	17.6
TCP IR7	5.7	5.7	5.7	4.3
TCSG IR7	6.7	8.5	8.5	6.3
TCLA IR7	10	17.7	17.7	8.3
TCSG IR6	7	9.3	9.3	7.1
TCDQ IR6	8	10.6	9.8	7.6
TCT IR1/5	13	15	11.8	9
TCT IR2/8	13	15	26 / 11.8	12
TCL	30	30	30	10
Inj. Prot.	8	30	30	30

warning messages is provided by the collimator controller application GUI (see screenshot in Fig. 4). Hence, the overhead vistar can act as a quick diagnostic tool for the collimator expert, while the exact warning or error message is viewed by hovering the cursor over the collimator name in the GUI. All the relevant errors and warnings are reported in the LHC Alarms SERvice (LASER) [8].

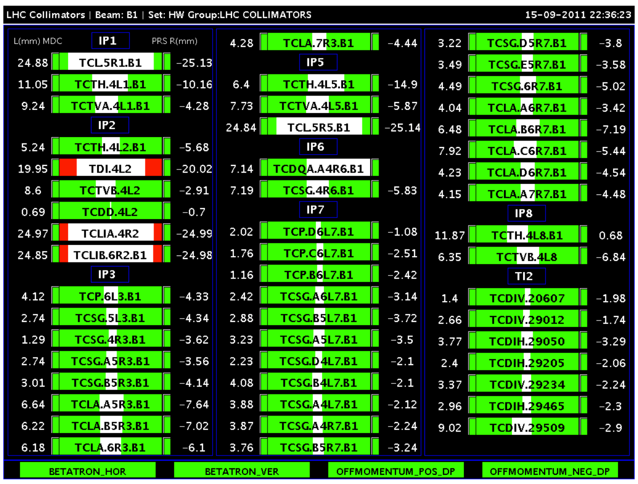

Figure 3: Collimator statuses and jaw positions B1 vistar [9].

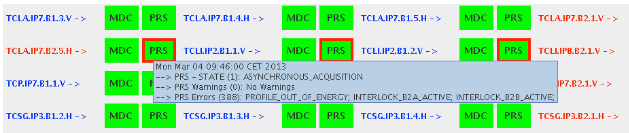

Figure 4: Collimator status display with detailed error and warning messages.

Parameters related to the higher level of abstraction can be viewed in the display shown in Fig. 5. These include the half gap opening in units of σ, as well as the nominal β-functions at each collimator. This display is also used between step 1 and step 2 of the settings generation cycle to confirm that the collimator settings in units of σ are correct before performing the beam loss maps. It is the only tool which provides an online view of the jaw gaps independently of the beam process settings.

Possible Improvements

Several possible improvements can be made to the existing monitoring system. Currently, the status of the injection protection collimators systematically turn red due to an energy interlock when the beams are ramped to top energy. To a non-expert, this may seem as though there is an issue which requires action. When the beams are dumped, all collimator statuses turn red until they are sent back to the

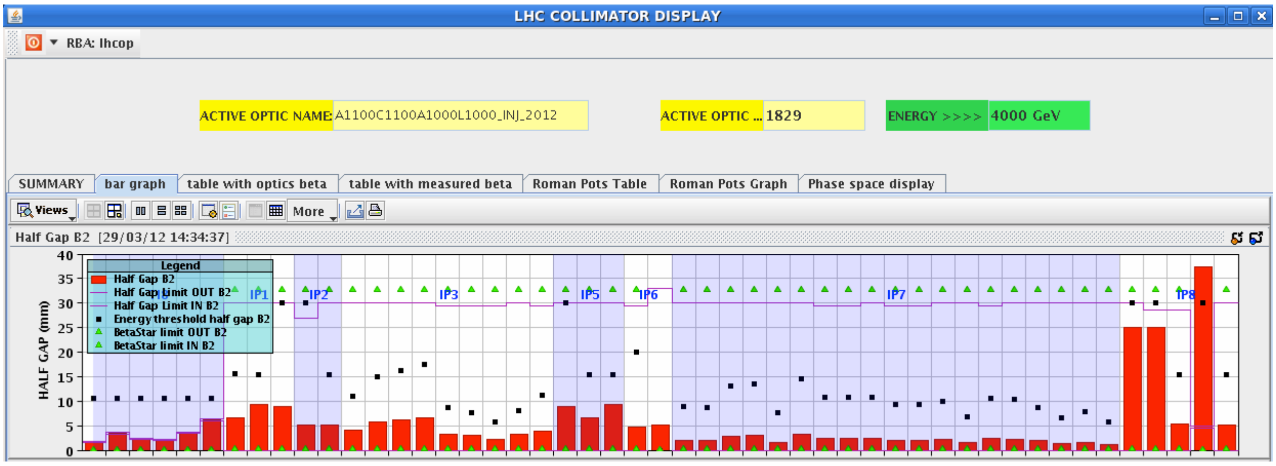

Figure 5: Higher-level collimator settings display (courtesy of D. Jacquet).

injection energy settings. Although improvements have already been made to the sequencer such that errors related to these collimators are caught during the ramp-down, the current colour-coding could potentially mask underlying problems which would otherwise be visible earlier in the fill. A clearer interlock colour-coding scheme can be introduced to cater for these scenarios.

There is a plan to develop the post-mortem collimation buffer, so that the collimation expert does not need to dig through the data when called by the operators in case of errors. Another possible improvement is the acquisition of the measured rather than the nominal β-functions by the collimator settings display in Fig. 5. Finally, the OP shift crews are encouraged to use LASER more frequently for diagnostic purposes, for example to identify warnings that appear in the collimator display. Actions can be assigned that should be taken by the shift crews for different categories of collimator warnings and errors. Input from the operations team regarding the colour-coding schemes and actions list will be required.

ERRORS ENCOUNTERED AND MEASURES TAKEN

Errors Encountered

Two types of human errors were found in the collimator settings in the March 2012 alignment campaign [10]. The first type of error occurred when aligning the TCTVA.4R1.B2 at flat top and the TCTVA.4R2.B2 in collisions. A mistake in sign was introduced for the right jaw when inputting the aligned jaw positions manually in the setup sheet used to temporarily store the values before they are imported into the beam process. This resulted in an effective shift of the TCTVA.4R1.B2 center by 1.8 σ at a correct gap of 26 σ, and of the TCTVA.4R2.B2 center by 3.8 σ at a correct gap of 12 σ.

In both cases, the increase in the losses during the loss map acquisition was too small to indicate problems with the set up. Indeed, the errors were discovered in an unrelated analysis three weeks after the alignment was made, and as the wrong settings were deemed to be not critical for the machine protection, the values were only changed two weeks later during a technical stop. These errors would not have occurred if the utility for automatic saving of the measured jaw positions would have been ready for deployment before the 2012 collimator alignment campaign.

Table 3: Beam center errors encountered in the 2010-2013 LHC run, where Δx represents the shift in the beam center.

Collimator	Beam Mode	Δx [σ]	Gap [σ]
TCTVA.4R1.B2	Flat Top	1.8	26
TCTVA.4R2.B2	Collisions	3.8	12
TCLA.6R3.B1	Flat Top	0.2	17.6
TCLA.B5R3.B1	Flat Top	1.2	17.6
TCSG.A5R3.B1	Flat Top	2.3	15.6
TCSG.B5R3.B1	Flat Top	2.2	15.6

The second type of error was introduced when calculating the ramp functions for 4 IR3 collimators, whose beam centers were mistakenly set to zero by the Mathematica program at the end of the ramp. In this case, the errors were deemed to be small and were not corrected. As the beam process settings are generated from the measured beam center and beam size, and not from the calculated jaw positions in mm during alignment, the errors are never in the jaw gap but only in the jaw center. A list of all errors is provided in Table 3. For 1097 collimators aligned in 41 alignment campaigns in 4 years of LHC operation, this represents an error of 0.55 %.

Measures Taken

Several measures were taken to prevent similar issues in the future. The temporary setup sheet is now generated automatically by the alignment application, thus eliminating any potential human errors at this stage. In addition, a tool was created to check that the measured alignment values are consistent with the values in the setup sheet and the values in the beam process (see screenshot in Fig. 6). Since March 2012, no further issues were encountered. Future

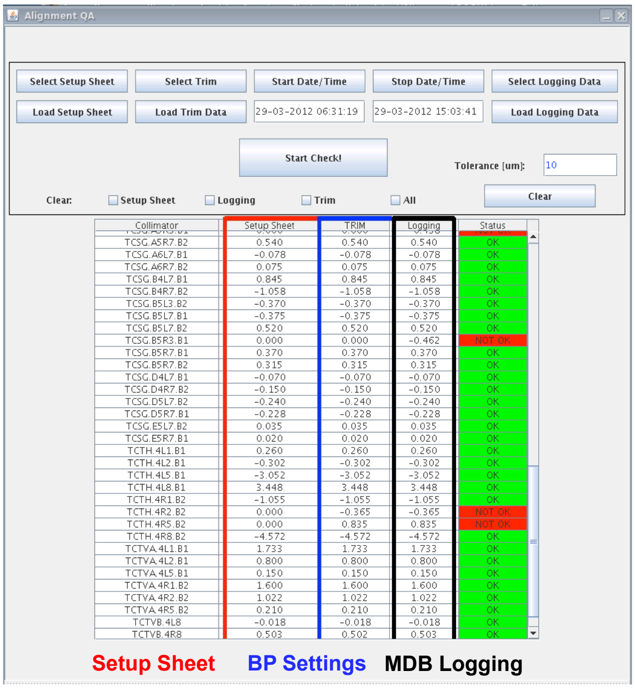

Figure 6: Tool used to check the settings consistency across the values in the setup sheet, the beam process and the logged measurements.

developments envisage the storage of the beam-based measurements in LSA database tables, rather than in local files on the CCC machines.

MAD-X ONLINE AND THE LHC APERTURE METER

The online model [11] provides an environment a) for the use of MAD-X simulations and calculations as control system inputs, b) to support the operators while coping with the machine complexity, and c) to simulate various machine manipulations. The LHC Aperture Meter [12] is designed to inform operators about the current bottlenecks in the LHC. It has a number of uses, including orbit checks (e.g. ATS optics, β^* = 90 m) and aperture measurements, providing the BPM-interpolated centers at the collimator locations to speed up alignment [13]. Work is ongoing to provide a playback of the settings during ramp and squeeze, which will allow to catch errors in the settings (see example in Fig. 7).

RESULTS AND STATUS OF BPM COLLIMATORS

Collimators with embedded BPM pick-up buttons will replace the current TCTs and IR6 TCSGs in LS1. Proof-of-principle tests were held in the SPS in 2010-2011 [14], and an automatic successive approximation BPM-based alignment algorithm was developed and tested in 2012 [15]. A typical BPM-based alignment is shown in Fig. 8, with the BPM electrode signals, measured beam center and jaw positions as a function of time. The collimators are aligned by equalizing the electrode signals of the opposing buttons. The alignment is made at large jaw gaps and is completed in $\sim$30 s (a factor 120 less than the current BLM-based alignment time).

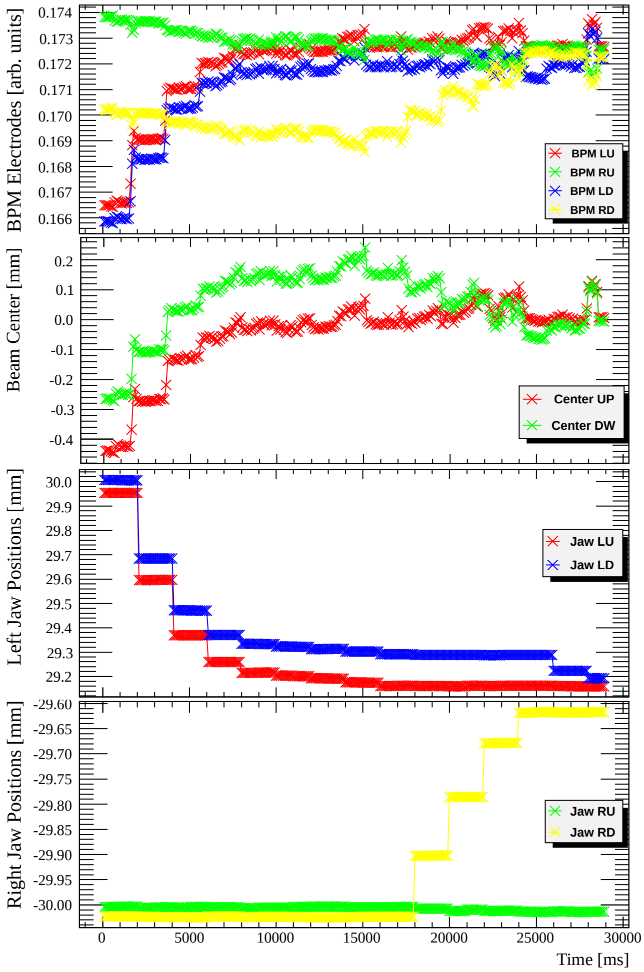

Figure 8: BPM-based collimator alignment [15].

In standard operation, the BPMs will allow to eliminate all orbit-related settings errors at the collimator locations. They will provide online monitoring of the beam position, including the possibility of placing interlocks on the orbit measurements, and fast TCT alignments, which can be performed every fill or as often as required. However, any collimator movements will have to be studied in detail to ensure that no additional risks are introduced for machine protection. A better monitoring in IR6 means that possible issues can be identified early on, rather then when the infrequent loss maps are acquired. In addition, the orbit measurement can be used for the SIS interlock of the TCDQ centering/retraction. The use of embedded-BPM collimators in operation can help to improve the β^* reach by about 15 % [16].

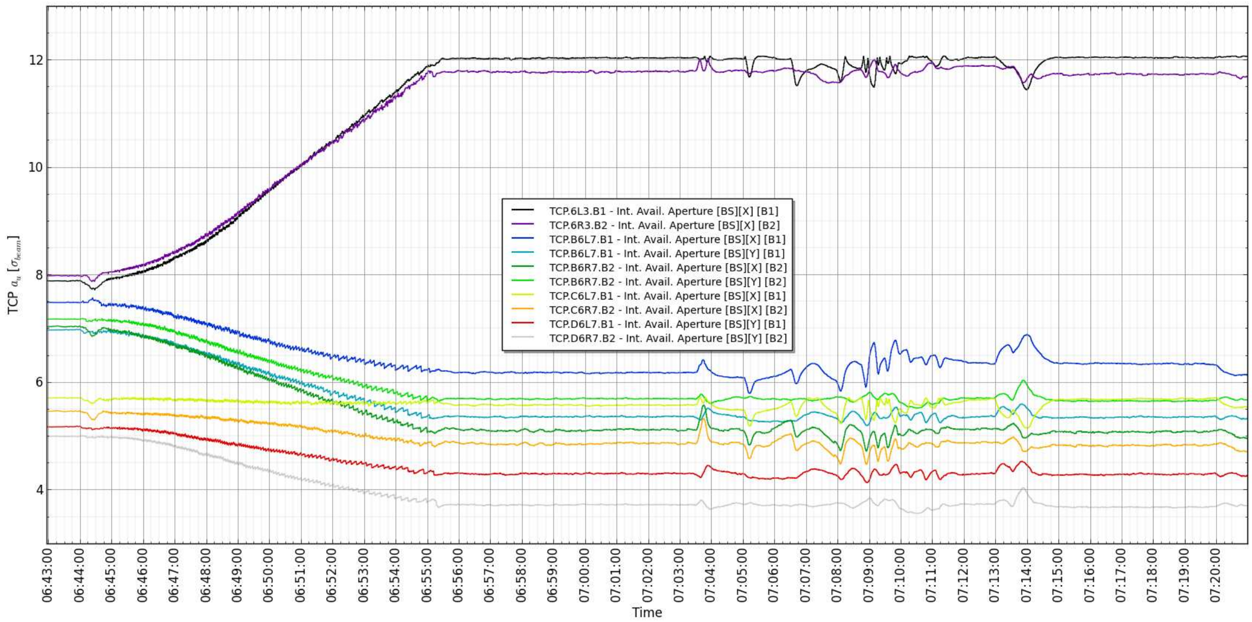

Figure 7: Evolution of the TCP collimator apertures during the ramp as calculated by the LHC Aperture Meter. Courtesy of G. J. Müller.

SUMMARY

The high energy LHC beams require cleaning at all times. The collimator settings generation and verification cycle was presented. Potential error locations in the cycle were identified, and tools to verify the settings were developed. The different components of the present top-level collimator monitoring system were discussed, highlighting the various layers of abstraction. The results and current status towards achieving operability of the new embedded-BPM collimators was discussed.

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REFERENCES

[1] LHC Design Report v. 1: The LHC main ring. CERN-2004-003-V1, edited by O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock.

[2] S. Redaelli, R. W. Assmann, R. Losito, M. Donze, A. Masi, "LHC collimator controls for a safe LHC operation", Proceedings of ICALEPCS'11, Grenoble, France, pp. 1104-1107, 2011.

[3] S. Redaelli, R. W. Assmann, M. Jonker, M. Lamont, "Application software for the LHC collimators and movable devices", EDMS LHC-TCT-ES-0001 (2007).

[4] G. Valentino, et al., "Semiautomatic beam-based LHC collimator alignment", Phys. Rev. ST Accel. Beams 15, 015002 (2012).

[5] R. Alemany-Fernandez et al., "The LHC sequencer", Proceedings of ICALEPCS'11, Grenoble, France, pp. 300-303, 2011.

[6] B. Salvachua et al., "Beam-based validation of settings", these proceedings.

[7] R. Bruce, R. W. Assmann, S. Redaelli, "Principles for generation of time-dependent collimator settings during the LHC cycle", Proceedings of IPAC'11, San Sebastian, Spain, pp. 3753-3755, 2011.

[8] F. Calderini, B. Pawlowski, N. Stapley, M. W. Tyrrell, "Moving towards a common alarm service for the LHC area", Proceedings of ICALEPCS'03, Gyeongju, Korea, pp. 580-582, 2003.

[9] G. Valentino, E. Veyrunes, "LHC collimator fixed display", LHC Project Document No. LHC-OP-ES-0025 (2011).

[10] S. Redaelli, G. Valentino. "How to avoid wrong collimator settings after beam-based alignment", presented at the LHC Machine Protection Panel meeting on 28.09.2012.

[11] G. J. Müller et al., "The online model of the Large Hadron Collider". In Proceedings of IPAC'10, Kyoto, Japan.

[12] G. J. Müller, K. Fuchsberger, S. Redaelli, "Aperture Meter for the Large Hadron Collider", in Proceedings of ICALEPCS'11, Grenoble, France.

[13] G. Valentino, et al., "A Tool Based on the BPM-interpolated Orbit for Speeding up LHC Collimator Alignment", in Proceedings of HB 2012, Beijing, China.

[14] D. Wollmann et al. "First beam results for a collimator with in-jaw beam position monitors", in Proceedings of IPAC'12, New Orleans, USA.

[15] G. Valentino et al., "Development and beam tests of an automatic algorithm for alignment of LHC collimators with embedded BPMs". In Proceedings of IPAC'13, Shanghai, China.

[16] R. Bruce et al., "Collimator hierarchy limits: assumptions and impact on machine protection and performance", these proceedings.