LHC ORBIT CORRECTION REPRODUCIBILITY AND RELATED MACHINE PROTECTION

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Abstract

The Large Hadron Collider (LHC) has an unprecedented nominal stored beam energy of up to 362 MJ per beam. In order to ensure an adequate machine protection by the collimation system, a high reproducibility of the beam position at collimators and special elements like the final focus quadrupoles is essential. This is realized by a combination of manual orbit corrections, feed forward and real time feedback. In order to protect the LHC against inconsistent orbit corrections, which could put the machine in a vulnerable state, a novel software-based interlock system for orbit corrector currents was developed. In this paper, the principle of the new interlock system is described and the reproducibility of the LHC orbit correction is discussed against the background of this system.

INTRODUCTION

The stored energy in the LHC beams can cause serious damage if released in an uncontrolled way. For slow losses, the LHC is well protected by about 4000 Beam Loss Monitors (BLMs), distributed around the ring. These BLMs can trigger a beam dump in case the losses at any location exceed predefined limits. The only protection for fast losses (e.g., in a single turn in case of an asynchronous beam dump) is the LHC collimation system. To be effective, it is necessary that the primary collimators are the global aperture limitations for the beam and that the hierarchy of the different collimators is respected.

This requires the orbit to be well centered at all other elements in the ring. A closed bump, for example, trimmed into the orbit somewhere in the arc, reduces the available aperture in the respective region. If undetected, this could, in combination with an asynchronous beam dump, direct the beam into the walls of the vacuum chamber. Such a dangerous setting of the orbit could e.g. be due to human error (manual orbit correction), a malfunction of the orbit feedback system or wrong readings of the Beam Position Monitors (BPMs).

To prevent such vulnerable states, the settings of the orbit correctors are already observed by the LHC Software Interlock System (SIS) [1, 2]. If the currents of at least two correctors per beam and plane exceed certain limits w.r.t. reference values, then the beams are dumped. The main drawback of the present system is that it does not have any reference functions, but only scalar reference values. This implies that it cannot follow deliberate changes of the orbit. Therefore, during the collisions beam process, where the separation bumps are collapsed in the Interaction Points (IPs), the tolerances have to be widely open at the moment.

PC INTERLOCK SYSTEM

To further improve the situation as described in the previous section, the development of a new software interlock system for the LHC magnet Power Converters (PCs) was launched in summer 2011. As a first step, it will interlock the orbit correctors only, but further magnet circuits will follow soon.

Overview

An overview of the components involved in the new software power converter interlock system (PcInterlock) is shown in Fig. 1. The main component is the PcInterlock server. It subscribes to all power converters (currently 1057 orbit corrector circuits) and receives the actual currents with a rate of about 2 Hz. Every second, a seperate process is invoked, which compares the last received values with values in reference functions, corresponding to the actual LHC state (see next section). The outcome of the comparison is published twice, once as a simple summary (ok={true|false}) and once as a more detailed status. The simple summary is picked up by the SIS, which can dump the beam, in case the status is not ok.

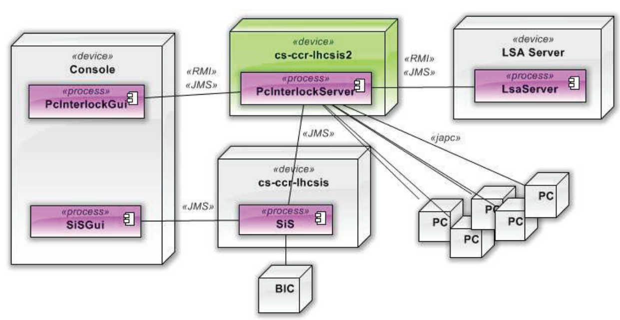

Figure 1: Overview of the components related to the Software Power Converter Interlock.

The publishing of the detailed status allows to display the actual states of all power converters in a dedicated graphical user interface (GUI) and to perform more detailed analysis in case of an interlock. Further, this GUI also allows to extract data from the LHC logging database for offline data analysis (e.g. after a dump). A screenshot of the GUI is shown in Fig. 2.

The LHC State

One of the most challenging aspects in implementing the described interlocking system turned out to be the determination of the exact position within the operational cycle of the LHC. Such a 'state' of the LHC is defined by the following parameters:

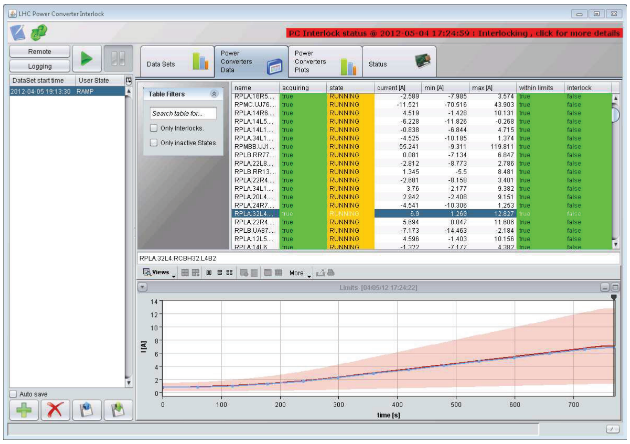

Figure 2: Supervision GUI for the Software Power Converter Interlock.

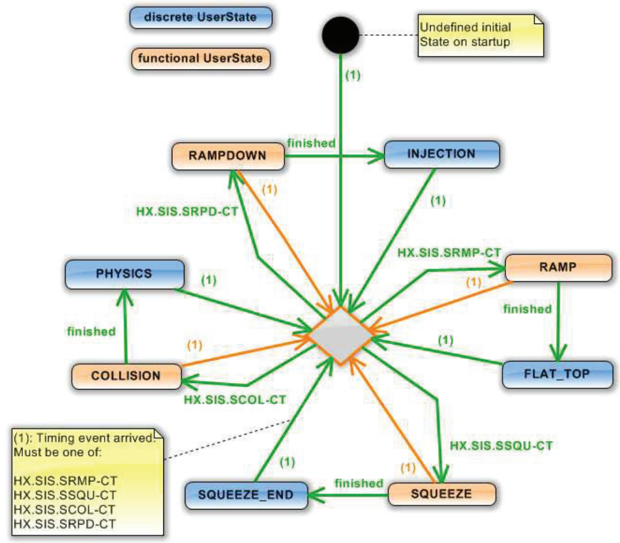

Figure 3: Possible changes of the LHC state on initialization and triggered by timing events.

- The currently running segment of the operational cycle (e.g. ramp, flat top, squeeze...). These segments correspond to beam processes and beam modes in the LHC. This is called 'UserState' in the following.
- The actual time spent in the beam process, if it is a functional beam process. This is necessary to determine the correct point within the reference functions to compare to.

No easy determination of this state was possible at the time when the development of the interlock started: Simple detection of the beam process changes in the control system is too unprecise, since these changes occur already several seconds before starting the corresponding segments to arm the power converters. Althought other implementations exist to gather this information, based on the mentioned information plus subscriptions to power converters to observe their state [3], it was decided to put in place a separate, independent mechanism to track these states, which does not rely on external systems, like power converters or collimators, but uses only information from the control system and the timing system.

For that purpose, four new timing events were introduced which are published by the timing system at the exact start times of the functional UserStates (RAMP, SQUEEZE, COLLIDE, RAMPDOWN). The time within the beam process can then simply be determined as difference of the actual time to the time of the reception of the corresponding timing event. Since the order of the states is fixed and their length is known from the control system, the switch to the discrete UserStates after the functional ones can be simply done based on this information.

Figure 3 shows a diagram of the state changes, relevant for the interlock operation. The 'natural flow' of the states is clockwise (e.g. RAMP $\rightarrow$ FLAT_TOP $\rightarrow$ SQUEEZE $\ldots$). These changes are merely triggered by the mentioned timing events and the length of the beam processes (green transitions in the diagram).

The only moment when other information is used to determine the state is on startup: If the process is still in an undetermined state and a discrete beam process is detected currently in use in the control system, then this is used as a 'best guess' for the actual state of the LHC. This might be wrong, but avoids to stay in an undefined state e.g. when rebooting the server at injection (not shown in the diagram).

CORRECTION REPRODUCIBILITY

To gain confidence in the settings for the interlock system, data of recent operational cycles was extracted from the logging database and analyzed in view of the actual settings. For the commissioning period, the settings for the current functions were initially copied from the operational settings on 05 April 2012. After several changes, the settings for the squeeze and collissions beam processes were copied again on 07 May 2012. For all the following analysis the later settings will be used as references. For the tolerances a value of $\pm 15\,\mu\text{rad}$ was used throughout for the orbit correctors, which results in tolerances on current level at injection between $0.6\,\text{A}$ and $8\,\text{A}$, depending on the type of the corrector magnet.

The following analysis is based on data from the operational cycles between 10 April 2012 and 07 May 2012. After removing incomplete data sets and some data from the Machine Development (MD) period (21/22 April) this results in a set of 41 ramps, 31 squeezes and 30 collisions. Data points for the corrector currents were extracted from the logging every 30 seconds (ramp, squeeze) or 20 seconds (collisions).

It was investigated, if there would have been any (false) dumps if the interlock system would have been active during the fills under investigation. For this purpose, the maximum of the absolute deviation from the respective reference function for all the extracted points is plotted in

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Fig. 4 in units of µrad All the values in this plot are lower than 9 µrad and thus only about 60% of the current limits (15 µrad). Therefore, clearly no dump would have been triggered in that period. Nevertheless, it is also evident from this plot, that the larger kicks w.r.t. the reference functions happen close to the interaction points. In these regions, larger kicks are applied during Van Der Meer scans and luminosity leveling.

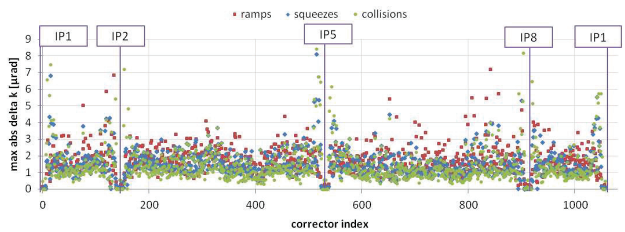

Figure 4: The maximal absolute differences to the reference functions in the operational cycles between 2012-04-10 and 2012-05-07.

A simple way to estimate the stability of the orbit correction over time is shown in Fig. 5. The plot shows the maximum absolute kick deviation from the respective reference function per fill. Since the reference functions were copied from operational settings on 07 May, it is clear that the lowest kick differences appear close to that date. The maximum kicks are relatively stable (between 4 and 6 µrad for ramp and squeeze and around 7 µrad for collisions) before the technical stop (period indicated as 'MD+TS' in the plot).

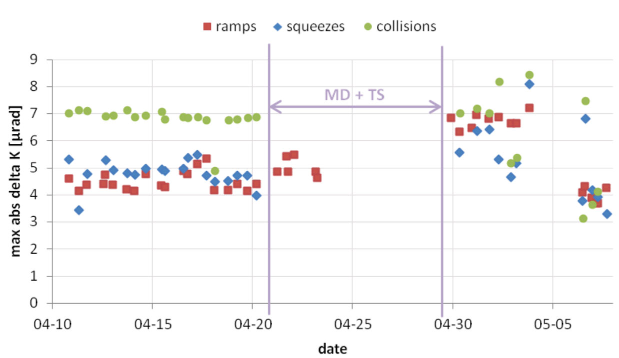

Figure 5: Time evolution of the maximal differences to the reference funtions in µrad for the orbit correctors in the operational cycles between 2012-04-10 and 2012-05-07. 'MD+TS' denotes the period for Machine Development (MD) and the subsequent Technical Stop (TS).

It is also worth to note, that the largest kicks always appear in the collision beam process. These do not result from the feedback system, since it was never used up to now during the collisions beam process. Instead, these relatively large changes mainly come from backwards incorporations from orbit corrections at the IPs.

Finally, it is important to understand, if the maximum kick deviations are artifacts of inappropriate reference functions or if they really vary from fill to fill. For that purpose, the maximum absolute difference to the reference function for each corrector within a beam process was calculated per fill. To estimate the variation over the fills, the standard deviation (σ) of these maxima was calculated for each corrector throughout the different fills. The result is shown in Fig. 6. It is evident, that near the IPs the large kick differences really vary between fills, while in the arcs they are far more stable ($\sigma < 1\,\mu\text{rad}$). The only exception to this is arc 78, with some correctors in the vertical plane, that also had large variations like in the IPs during the investigated period. In this region, some corrector magnets had problems and their kicks had to be compensated temporarily by neighbouring correctors, which is the reason for the variations.

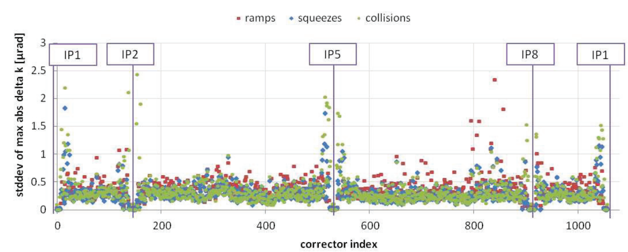

Figure 6: The standard deviation of the differences to the reference functions in the operational cycles between 2012-04-10 and 2012-05-07.

SUMMARY AND OUTLOOK

Considering logged orbit correction data of 41 recent fills, it was shown that the new software interlock system for magnet power converters would not have triggered any false dumps in that period. The maximum deviation from the respective reference functions was smaller than 60% of the currently set tolerances.

The new system is operational since 16 May 2012 with the described settings (except some higher tolerances for correctors used for luminosity scans). From the upcoming experience, it will be decided, if and how far it is possible to further reduce the tolerances in the arcs.

ACKNOWLEDGEMENTS

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