BEAM BASED OPTIMIZATION OF THE SQUEEZE AT THE LHC

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Abstract

The betatron squeeze is a critical operational phase for the LHC because it is carried out at top energy, with the maximum stored energy and with reduced aperture margins in the superconduting triplets. A stable operation with minimum beam losses must be achieved in order to ensure a safe and efficient operation. The operational experience at the LHC showed that this is possible. The operation in 2010 is reviewed. In particular, orbit, tune and chromaticity measurements are investigated and correlated to beam losses. Different optimizations are then proposed towards a more efficient and robust operation. The improvements obtained for the operation in 2011 are presented.

INTRODUCTION

The performances achieved in 2010 are summarized and used to demonstrate possible improvements. In particular, observations of the remarkable reproducibility of the linear beam parameters allow a feed forward approach to relief the feedback systems, thus increasing the operational efficiency. A systematic analysis of the losses and the linear beam parameters during the squeeze allows to study and deal with small effects before they become detrimental for operation.

In order to perform the systematic analysis of the different beam parameters along the squeeze and other processes apart of the standard operation cycle, such as the energy ramp, a software, the *Systematic Measurement Analyzer*, was developed and is now available in the Large Hadron Collider (LHC) control room. It allows to retrieve selected measurements along a particular process performed systematically during several fills and, in particular, to make an average over the measurements.

The squeezing is performed in steps, decreasing slowly the β^* in each interaction point (IP). From one step to the next, the current of each magnet involved is varied monotonically from its initial value to the next. These steps, are marked as vertical lines on the different plots with the corresponding β^* in IP1/5. In particular, these steps are used to suspend the execution of the squeeze to perform different operations. The time spent there is different for each execution, it is therefore systematically discarded in the following analysis.

SQUEEZE PERFORMANCE

Optics Highlight

The quality of the optics during the squeeze was remarkable. Details of the measurements and corrections are presented in detail in companion papers [2]. It is just recalled that in physics conditions, the β_{beat} could be corrected to within better than ∼20%, and even 10% in 2011 [3].

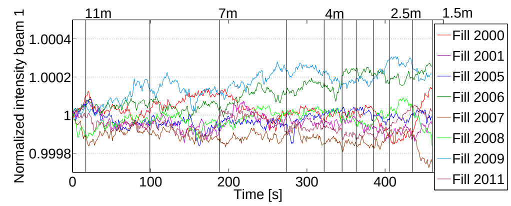


Figure 1: Beam intensity along the squeeze during 9 fills for physics in August 2011.

Intensity Transmission

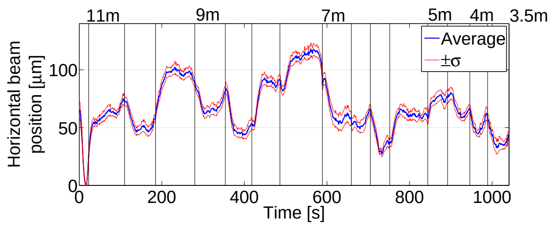
The intensity transmission is defined as the fractional loss of beam intensity between the beginning and the end of the squeeze. It is calculated from beam current measurements. In 2010, the measurements over representative physics fills indicated average losses of 0.3% for beam 1 and 1.6% of beam 2 [1]. These results were obtained for physics fills with up to 368 bunches of about 1.2×10^{11}p. This good performance is confirmed in the 2011 operation with total intensities up to 1.7×10^{14}p, i.e. 1380 bunches. Indeed, losses are now within the measurement noise of the beam current transformers, as illustrated in Fig.1.

It is important to note that the scaling of this encouraging performance to the nominal conditions of higher energy and smaller β^* is not straightforward. The detailed monitoring and optimization of the squeeze will therefore continue in preparation for the operation in tighter conditions.

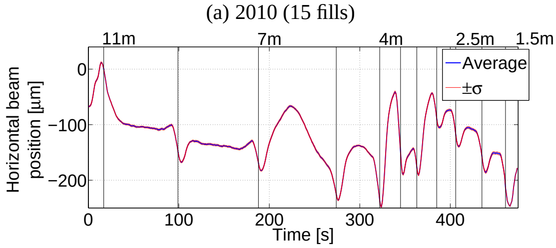
Reproducibility

The fill-to-fill reproducibility of the main beam and machine parameters is important for optimizing the performance, in particular to establish effective beam-based corrections. The beam position measured close to the primary collimator of beam 2 is shown on Fig.2a as a function of time during the squeeze. The orbit stability is particularly important in this area as the collimators are closed to 5.7σ and represent the aperture bottleneck of the machine. This example from the 2010 operation is considered representative of the stability and reproducibility of the orbit during the squeeze. The systematic orbit variations are driven by the change of strengths of the matching quadupoles in the interaction regions, in presence of orbit offsets. In 2011, a similar situation is found (Fig. 2b).

This reproducible behavior is also found in the tune measurement, as well as in the correction provided by the tune

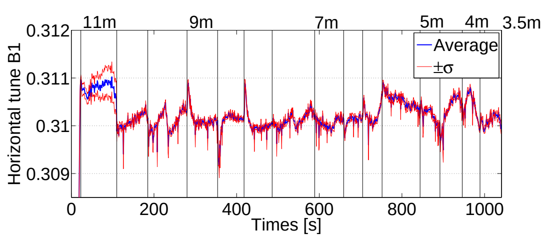


(a) 2010 (15 fills)

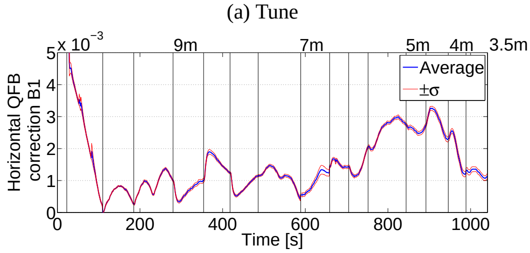


(b) 2011 (25 fills)

Figure 2: Average over fills for physics with proton of the measured beam position 18m downstream the primary collimators of beam 1.



(a) Tune



(b) Correction provided by the QFB

Figure 3: Average over the last 15 fills for physics with proton in 2010 of horizontal tune and correction from the QFB of beam 1. Similar behavior is observed for the other beam and other plane.

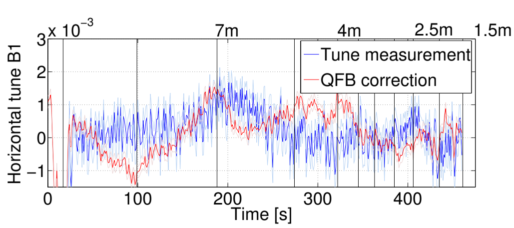
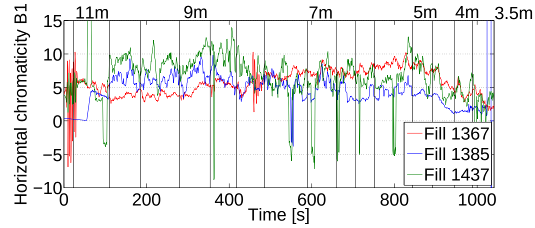
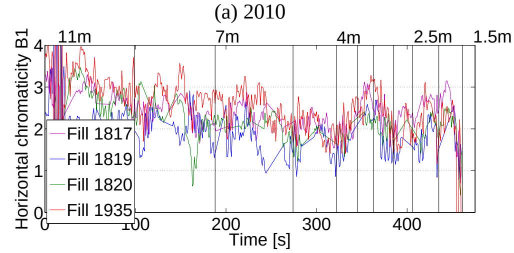


Figure 4: Average over 25 fills for physics in August 2011 of the measured difference to the nominal tune and corrections provided by the QFB.



(a) 2010



(b) 2011

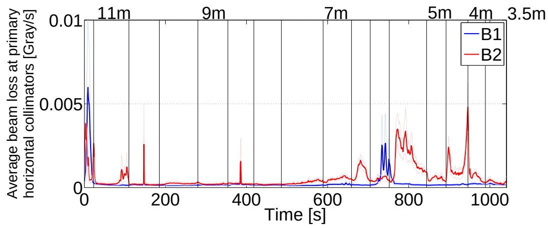
Figure 5: Continuous measurements of chromaticity, similar behavior is observed for the other beam and other plane.

feedback system (QFB) (Fig. 3). The QFB stabilizes the tunes to a few units of 10^{-3} and the required corrections are reproducible within a few 10^{-4}. Also the chromaticity and the coupling are well reproducible fill to fill. This enables reliable feed-forward correction mechanisms.

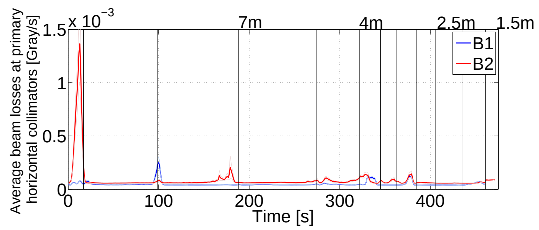
Unlike tune and orbit, the chromaticity is measured only in dedicated squeeze tests, to avoid frequency trims with high intensities in physics fills. Some of the available measurements performed in 2010 and in 2011 are given in Fig. 5. The chromaticity during the squeeze has remained stable over long periods and could be corrected to the required values. We are presently running with 1.5 to 3.0 units during the squeeze. No further corrections were applied after the initial commissioning setup.

Feed-forward Corrections

Presently, real-time feedback systems are used during injection, energy ramp and squeeze for tune and orbit [5]. Their reliability and the machine availability is improved by applying regularly feed-forward corrections to minimized the trims required by the feedbacks. In particular, it is beneficial to keep the corrections from the feedback at a minimum to ensure that the beams are not lost e.g. in case of problems with feedback trips occasionally observed in operation. Thanks to the remarkable reproducibility of the machine, it turned out that only a few feed-forward corrections were needed throughout the year to maintain the trims from the feedbacks under good control. Three feed-forward iterations in 2010 were performed and allowed to maintain the tune correction within a range of $5 \cdot 10^{-3}$, which is enough to safely keep the beams in case of problems with the feedback. In 2011, we have so far performed 2 iterations and achieved even better results (Fig. 4). An automatize feed-forward is not required in these conditions, regular monitoring of the crucial parameters and punctual corrections are sufficient.



(a) 2010 (15 fills)



(b) 2011 (25 fills)

Figure 6: Average over fills for production of physics of the losses detected at the primary horizontal collimator, normalized with the beam intensity at the beginning of the squeeze and scaled to the nominal intensity.

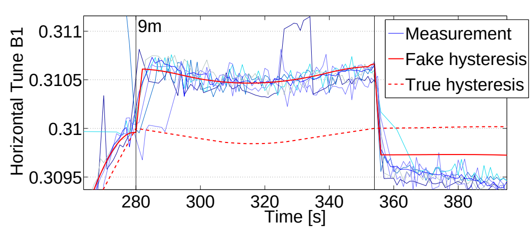


Figure 7: Simulation of tune using MADX, introducing fake changes of hysteresis branch in the settings compared with measurements.

ANALYSIS OF SYSTEMATIC LOSSES

Even in case of good intensity transmission, it is possible to study losses during the squeeze by monitoring the losses at the primary collimators in the betatron cleaning insertion. Beam loss monitors have an higher dynamic range than the beam current transformers. As can be seen on Fig. 6, the average beam losses observed at these locations have a systematic component, with spikes occurring at well defined times in the squeeze, in particular close to the matched optics. Some of these systematic losses occur at the same time as fast variations of orbit and tune (Figs. 2,3) that could not be corrected by the feedbacks due to limited bandwidth. Even though the maximum losses observed did not represent an immediate limitation for the operation, they were studied in detail to investigate possible problems with the squeeze settings.

Indeed, it was found that loss spikes and tune and orbit changes appeared to be well correlated to "jump" in the settings functions of some quadrupole magnets. These jumps were caused by a mistreatment of the hysteresis of superconducting magnets that was implemented to deal with changes of sign of the current derivative [8]. The change of hysteresis branch was applied even for small current changes, which lead to unphysical jumps on the current settings. Simulations performed with MADX (Fig. 7) showed that the measured tune shifts were well reproduced if this hysteresis effect was introduced as an input for simulations. The same effect could explain orbit shift in the presence of offsets in the quadrupoles concerned [4]. On the basis of these observations, it was decided to remove this implementation of the hysteresis. During the 2011 commissioning, it was confirmed that the new settings did not show the same behaviour around matches optics. While this did not cure all the changes of tune and orbit, it certainly improved the situation, (Figs. 4,6b).

CONCLUSION

The squeeze at the LHC is well under control. The key machine and beam parameters like orbit, tune, chromaticity and losses are well reproducible over periods of months. This allowed to converge rapidly to stable operational conditions within a few iterations of beam-based measurements and corrections. The good performance achieved in 2010 has been improved further in various respects for the 2011 operation, with higher intensities and lower β^*. Presently, we are operating in the stored energy regime of about 100MJ and we have transmissions close to 1 during the squeeze. This achievement is very promising and makes us confident the we could push the performance by squeezing further down.

ACKNOWLEDGMENT

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