SIMULATION OF LINEAR BEAM PARAMETERS TO MINIMIZE THE DURATION OF THE SQUEEZE AT THE LHC

X. Buffat, EPFL, Lausanne and CERN, Geneva, Switzerland
G. Müller, S. Redaelli, M. Strzelczyk, CERN, Geneva, Switzerland

Abstract

The betatron squeeze allows to increase the luminosity of a collider by reducing the β function at the interaction points. This operation has shown to be very critical in previous colliders. In this state of mind, the squeezing was performed extremely safely during the first year of operation of the Large Hadron Collider, at the expense of the duration of the process. As the turnaround time is a relevant parameter for the integrated luminosity, a squeeze of shorter duration is proposed for 2011 and further. MadX simulation of linear beam parameters based on settings extracted from the LHC control system are used to justify the proposal. Further optimization of the squeeze setting generation is also discussed.

INTRODUCTION

In order to perform a squeeze at the Large Hadron Collider (LHC), the strengths of matching quadrupoles and orbit correctors in the four experimental insertions are varied synchronously following pre-defined functions of time that produce the reduction of the β function at the interaction points (IPs), or β^*s. Special care has to be taken in order to keep the linear beam parameters under control during the process, in order to minimize beam losses. From an operational point of view, the duration of the squeeze has an impact on the integrated luminosity, as it represents a non negligible part of the turnaround time. This motivates an optimisation of the duration of the squeeze to find the shortest squeeze duration that meets the requirements from both the beam dynamics and the superconducting magnets, which have limitations on both ramp rate and acceleration.

SQUEEZE AT THE LHC

Configuration

In 2010, the squeeze was performed down to the same β^* values in all IPs. After an initial commissioning to $\beta^* = 2.0$m, the intensity ramp up was carried out at $\beta^* = 3.5$m to fulfil machine protection constraints. In 2011, the configuration was modified to account for the different needs of each experiment and for updated figures for the triplet aperture [1]. IP1 and IP5 are squeezed down to $\beta^* = 1.5$m, whereas IP8 is squeezed down to $\beta^* = 3$m. IP2 is kept un-squeezed during operation with proton. The squeeze is done simultaneously in IP1/5/8 down to 3.0 m, the IP1/5 continue down to 1.5 m, as shown on Fig.1.

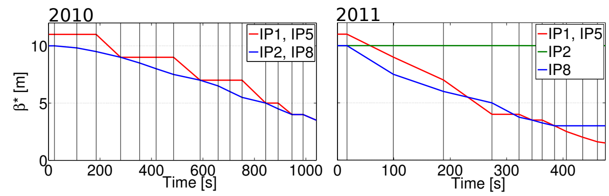


Figure 1: Evolution of the β^*s during the squeeze for 2010 and 2011.

Controls Aspects

The LHC software architecture (LSA) [2] is responsible for managing the settings of various systems during operation, in particular for the strength of the magnets. The settings of a set of parameters as a function of time are stored in so-called beam processes (BPs). Amongst other, a BP contains the functions that will be played synchronously by the magnets. The generation of settings for a BP is mainly constrained by the requirements of the superconducting magnets, in particular, by their maximum ramp rate and acceleration.

In order to generate proper functions for the squeeze, the settings of each magnet is computed in the following way. A set of optics with decreasing β^* values from initial to final targets are defined. Each input optics defines a so-called matched points (MPs) where the optics - i.e., the magnet strengths - are well matched to a set of β^* targets in each IP. For each optics variation, the required time for the strength change is calculated for each circuit concerned, taking into account the ramp rate and acceleration limit. The slowest circuit in each optics transition determines the length of each segment, which is then used for the generation of all other circuits. The interpolation used currently is composed of three phases, uniform acceleration, constant variation, then uniform deceleration (Fig. 3a).

While the optics remains well defined at each MP, this is no longer the case in between MPs. This leads to deviation of the beam parameters that have to be kept at safe levels. The initial set of MPs was determined to minimize the errors, at the expense of the duration of the process. The first very successful commissioning experience [1] motivates an optimization to reduce the squeeze duration. Appropriate software was developed to address this optimization.

ONLINE SIMULATION TOOLS

The Methodical accelerator design X (MadX) program [3] can be used to compute linear errors of key beam parameters as a function of time during the squeeze, by extracting the generated magnet strengths at intermediate

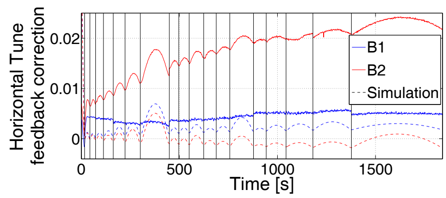


Figure 2: Comparison between the two beams of the correction provided by the tune feedback system during the first run of the un-squeeze BP. The transient errors have been corrected in beam 1 based on the simulation.

points in time. A novel software, the *Beam Process Scanner*, was developed within the MADX online applications [4] to automatize this analysis. This tool is available online in the LHC control room and allows one to run MADX on the settings that are generated for each magnet in the machine, taking into account the real current profiles versus time for precise evaluation of the time-dependent errors. Even though it was developed for squeeze studies, the tool is generic and has in fact been used for other setting functions, like ramp functions.

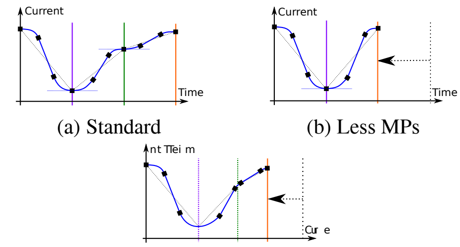
The *Beam Process Scanner* is used to validate generated settings before using them with beam and also to optimize the duration of squeeze BPs. For different sets of MPs, the errors on various beam parameters are evaluated. The duration of the squeeze is minimized by reducing the number of MPs while keeping transient errors at a minimum. The application for the 2011 squeeze configuration is presented in the next Section.

The validation of simulation from the *Beam Process Scanner* has been first addressed in [5] and also in various optics commissioning tests carried out in 2011. For example, Fig. 2 shows an example of simulation results compared to beam measurements performed during the 2011 commissioning of the un-squeeze to 90 m [6]. The simulations were very successfully used to perform a simulation-based feed-forward corrections of the tunes during the 1842s long un-squeeze. The simulated tune variations were trimmed into the machine as corrections to reduce the transient tune variations. An additional beam-based feed-forward correction was required to minimise errors not included in the linear model.

OPTIMISATION OF THE LHC SQUEEZE DURATION

Boundary Conditions

For a given β^* target, the duration of the squeeze functions depends mainly (1) on the maximum ramp rate achievable by the slowest magnets, (2) on the number of matched points and (3) on the type of interpolation used to vary the strengths between consecutive optics. (1) is constrained by the hardware properties of magnets, which have limited ramp rate and acceleration, this cannot easily be optimized without hardware changes. As explained above,



(a) Standard (b) Less MPs

(c) Non-stopping MPs

Figure 3: Generated settings for a fictive parameter between three MPs, using different methods.

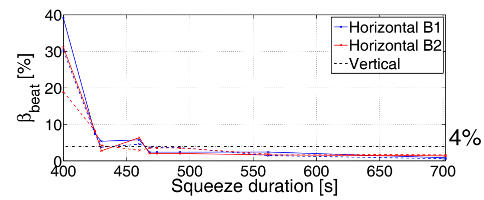
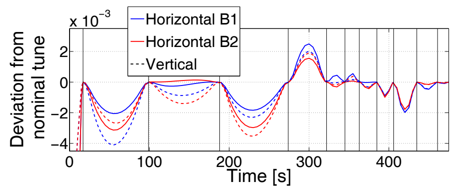


Figure 4: Maximum β_{beat} expected from the simulation of squeeze BPs of different duration with target β^* of 2011.

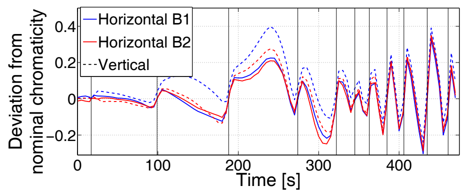
(2) is constrained by the budget that can be allowed for the transient errors of key beam parameters. The budgets depend on various machine constraints and also on the effectiveness of the correction schemes, online or not. For the optimization at the LHC, we considered a budget of about 4% for the β_{beat}, of $5 \cdot 10^{-3}$ for the tune and about 1 unit for the chromaticity. These are transient errors added on top of the machine imperfections. An optimization of (2) is discussed, the options concerning (3) are discussed as a possible future improvement.

During the commissioning of the squeeze, running through the whole squeeze without corrections would be difficult because of small unknowns of the magnetic model can cause intolerable errors and beam losses, requiring several time-consuming iterations of feed-forward corrections before converging on stable corrections. The possibility to stop the execution of the squeeze functions at intermediate MPs was therefore implemented in the controls system [7]. This is made possible by adding the constrain that the derivative of the magnet current functions is zero at the MPs, which lengthens the functions (Fig. 3a). The number of intermediate optics is therefore a crucial parameters for the squeeze duration optimization. In order to minimize the duration of the squeeze, different BPs are generated with different sets of MPs, the maximum error in the beam parameters are then simulated to find the squeeze of minimum duration that respects the error budgets.

Squeeze Function for 2011 The operation experience of 2010 showed that closed-orbit, tune, chromaticity and coupling were well reproducible during the squeeze and could be kept under good control by online feedback systems and by regular feed-forward corrections [8, 9]. The driving parameter for the optimization of squeeze



(a) Tune



(b) Chromaticity

Figure 5: Simulation of tune and chromaticity for the optimised squeeze used in 2011.

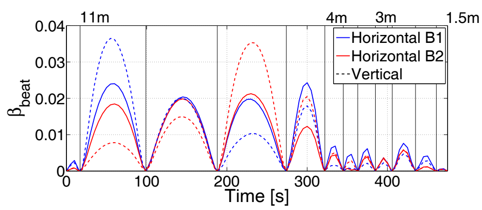


Figure 6: Simulation of β_{beat} along the optimized squeeze. The β^* in IP1 and IP5 is shown as indication on top.

duration was therefore the dynamic β_{beat} from the settings functions, which is added on top of the static errors and can cause problems of machine aperture and collimator hierarchy if not kept under control. In Fig. 5, the maximum β_{beat} is given as a function of squeeze duration for different sets of optics solutions providing β^*s of 1.5 m in IP1/5 and 3.0 m in IP8. The agreed tolerance of 4 % is respected for squeeze durations above 475 s. The solution of this duration was chosen as baseline for the 2011 run. The commissioning of the new squeeze functions worked smoothly and proved that the estimates from simulations were reliable.

In Fig. 1, the squeeze functions of 2011 are compared with the ones of 2010. The remarkable gain between the two years is not only due to the optimization presented here. Indeed, it was found during the optimization that the acceleration limit of a subset of magnet was overestimated, resulting if functions 30 % longer than needed. On the other hand, the length of the BP is extended because of the new squeeze configuration, which includes smaller β^*s.

The aperture available during the squeeze diminishes with the β^*, for this reason the optimization was focused on the first part of the squeeze, during which the β^*s are the highest. As shown in Fig. 6, β_{beat} approaching the limit fixed is only allowed when $\beta^* > 4$m, and kept as small as possible else where.

Non Stopping Matched Points

As shown in Fig. 3c, a significant amount of time could be saved while keeping dynamic errors to a minimum by stepping through intermediate optics giving up the zero derivative condition. One would also have to give up the possibility to stop at these selected points, which could be acceptable in some cases. However, the amount of parameters and the complexity of their generation makes this task difficult to implement. This option is very promising and the software development is continuing in this direction.

CONCLUSION

The squeeze performance in 2010 was good and this encouraged us to optimize its duration to improve the machine turnaround. Simulation tools were developed for simulating errors during the squeeze, with the aim to reduce its duration while maintaining optics errors under control. The result of this study was that we could improve the duration by more than a factor 2, for smaller target β^*. The new proposed squeeze has been successfully commissioned and used for the 2011 run. Possible further optimization are under study, in particular the possibility to perform part of the squeeze during the ramp. The tools proved to be flexible and have become a key element for the preparation of new optics changes at the LHC.

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