OPERATION OF THE BETATRON SQUEEZE AT THE LHC

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Abstract

The betatron squeeze is one of the most delicate operational phases at the Large Hadron Collider (LHC) as it entails changes of optics performed at top energy, with full intensities. Appropriate software was developed to handle the squeeze, which ensured an efficient commissioning down to a β^* of 60 cm at 4 TeV, and a smooth operation. Several optics configurations could be commissioned and put in operation for physics. The operational experience of the LHC runs from 2010 until 2013 is presented and the overall squeeze performance reviewed.

INTRODUCTION

The first running period for physics production of the Large Hadron Collider (LHC) lasted between 2010 and 2013 [1]. After an initial pilot run in 2010 when important operational confidence in handling high stored beam energies was progressively gained, the performance evolved rapidly in the following years. A peak luminosity of about $7{\times}10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved in 2012 with stored beam energies up to 140 MJ.

This outstanding performance relied heavily on the successful commissioning of the betatron squeeze which is of course fundamental to optimize the physics performance for a given stored energy. The β^* was pushed down to 60 cm at 4 TeV, to be compared to the design value of 55 cm at 7 TeV. In this paper, operational aspects of the squeeze at the LHC are reviewed. The achieved configurations in the different operational years are presented and some highlights of the squeeze performance are discussed.

2010-13 MACHINE CONFIGURATIONS

An attempt to summarize the main configuration for physics in the LHC running period 2010-13 is made in Tab. 1, where the key operational parameters are listed for all interaction points (IPs). All runs were carried out with minimum bunch spacing of 50 ns for a maximum of about 1400 bunches. The theoretical durations of setting functions for ramp, squeeze and collision functions are also listed. Special running configurations, such as high-β^* run, Van der Meer scans, runs at intermediate energies, etc. are not discussed here.

Note that the nominal injection configuration was successfully setup in 2010 and not further changed. Improvement of the peak luminosity performance were steered, amongst other improvements [1], by reducing the β^* in the IPs. The time evolution β^* for LHC proton physics runs shown in Fig. 1. Major steps in performance were driven by improving the knowledge of the aperture in the interaction regions [2]. This beam-based approach complements β^* reach models [3] that are developed to improve the prediction for the future LHC operation. It is important to note that the squeeze duration has been improved significantly throughout the years, as illustrated in Fig. 2. This was achieved by optimizing the settings functions [4].

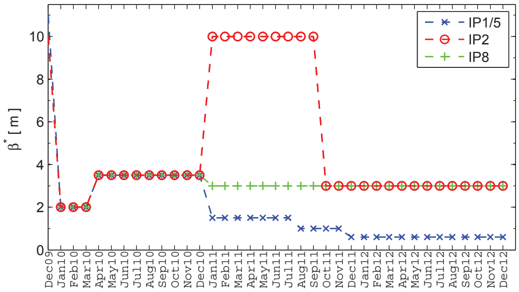

Figure 1: Evolution of the β^* for LHC proton physics.

IMPLEMENTATION AND COMMISSIONING

At the LHC the squeeze is performed at constant flattop energy by driving the matching section quadrupoles to currents that produce a specific β^* value. Each IR can be treated independently, even though IP1 and IP5 were always squeezed to the same values. One cannot move in one single step from the injection optics to the final β^* because the transient errors would be too large. One must instead step through a set of "matched" optics at intermediate β^* to keep transient errors of tune, chromaticity, orbit and beta-beat, at tolerable levels. Linear interpolations versus time with parabolic round-offs of the magnet currents are used to join matched points. More intermediate optics are needed at smaller β^* where errors are critical (see Fig. 2).

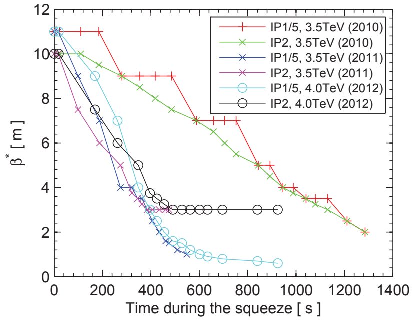

Figure 2: β^* versus time during the squeeze in the different IPs and operational years.

Table 1: Machine configurations during different running periods in 2010-13

Parameter	Injection 2010-13 (p / Pp)	Run1-A 02-10/’10 (p–p)	Run1-B 11/’10 (Pb–Pb)	Run1-C 02-08/’11 (p–p)	Run1-D 09-10/’11 (p–p)	Run1-E 11-12/’11 (Pb–Pb)	Run1-F 02-12/’12 (p–p)	Run1-G 01-02/’13 (p–Pb)
Beam energy [GeV]	450	3500	3500	3500	3500	3500	4000	4000
β^* in IP1/5 [m]	11.0	3.5	3.5	1.5	1.0	1.0	0.6	0.8
β^* in IP2 [m]	10.0	3.5	3.5	10.0	10.0	1.0	3.0	2.0
β^* in IP8 [m]	10.0	3.5	3.5	3.0	3.0	3.0	3.0	0.8
Sep. [mm]	2.0	0.7	0.7	0.7	0.7	0.7	0.65	0.65
Xing IP1/5 [μrad]	170	100	0	120	120	120	145	145
Xing IP2 [μrad]	170	110	40	80	80	80	90/145	62
Xing IP8 [μrad]	170	250	250	250	250	250	220	220
Duration of setting functions								
Ramp [s]	–	1400	1400	1020	1020	1020	770	770
Squeeze [s]	–	1041	558	475	558	1233	925	874
Collision [s]	–	108	180	56	56	260	220/285	240

Stopping at matched points is made possible by imposing zero derivative and second derivative by the use of parabolic round-offs and round-ins [5]. This also ensures good power converter current regulation. This functionality is crucial for commissioning new optics: the machine is tuned at each point and the setting functions are optimized in an iterative process based on measurements and feed-forward of the established corrections (orbit, tune, chromaticity, coupling, ...). Once setting functions that ensure tolerable transient errors are established, the squeeze is executed in one single step, which time-wise ensures the most efficient operation.

Tools were developed within the LHC on-line model packages [6] to calculate transient errors for a given set of setting functions, to optimize the squeeze duration while ensuring small transient errors [4]. The simulations also allow one to pre-calculate transient errors during the execution of functions for an efficient feed-forward [7]. These aspects and the crucial role of active feedback systems for the squeeze performance are not presented here [8].

SQUEEZE AND OPTICS PERFORMANCE

The achieved squeeze duration for proton runs in 2010-13 is given in Fig. 3. This is an important aspect for the operational efficiency. The largest improvement was achieved in 2011 thanks to a major optimization of the settings functions. Minor changes were deployed in 2012. The squeeze down to 1 m took a similar time as in 2011 in spite of the larger energy. The additional squeeze to 0.6 m required about 5 minutes. Other improvements addressed a more reliability and operation robustness [5].

The intensity transmission during the squeeze, calculated as ratio of initial to final beam intensities, is shown in Fig. 4 for a selection of fills in 2011 (top) and 2012 (bottom). In 2011 were essentially negligible whereas in 2012 they reached several percents. Beam 2 was worst in both years. This worsening was induced by the deployment of tighter collimator settings that made the squeeze sensitive to even small orbit drifts at the primary collimators (TCPs) [9, 10]. An example of orbit at the TCPs during the squeeze in 2011 and 2012 is given in Fig. 5. Dynamics errors were improved thanks to a better generation of orbit corrector settings and to more performing feed-forward corrections established in dedicated fills by using the orbit feedback with higher bandwidth [11]. In spite of such an important improvement, larger losses were observed in 2012 due to TCP gaps of 4.3 σ instead than 5.7 σ in 2011. Loss spikes during the squeeze remains a serious concern for the future operation at higher intensity and energy.

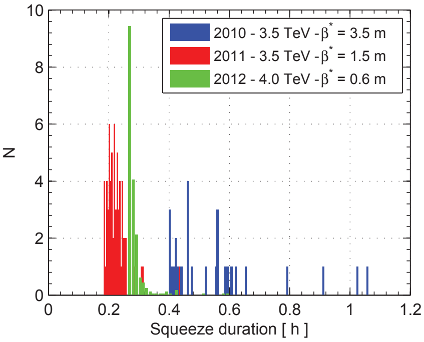

Figure 3: Distribution of squeeze duration in 2010 (blue), ’11 (red) and ’12 (green, times 1/160 for display purposes).

The quality of the LHC optics is remarkable. The peak β-beat errors without corrections is shown for all beams and planes in Fig. 6. The errors are very stable over the reference period of 3 years. The possibility to correct these errors is clearly crucial for the LHC performance as a beating of 40–100 % is measured at the smallest β^* values. Optics correction proved to be very efficient at the LHC [12]: the achieved beating after correction is below 10 % is shown in Fig. 7. An important aspect of optics corrections is the compensation of local sources of coupling originated in the triplet magnets, done using dedicated skew correctors. This proved to be essential to speed up the commissioning be-

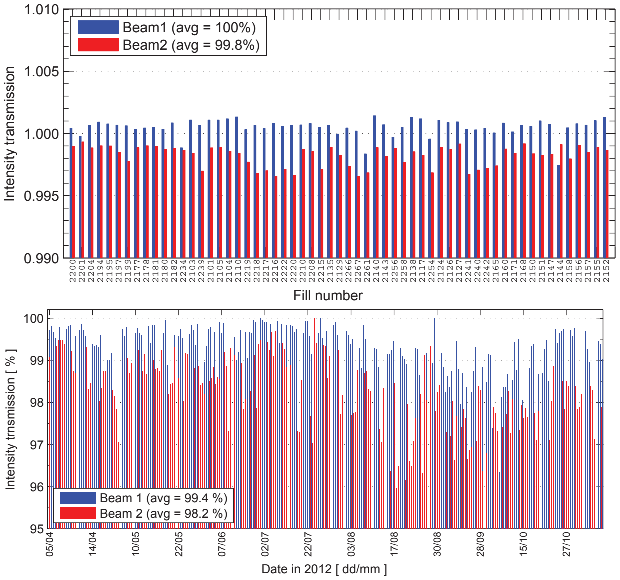

Figure 4: Intensity transmission in the squeeze for a selection of proton physics fills in 2011 (top) and 2012 (bottom).

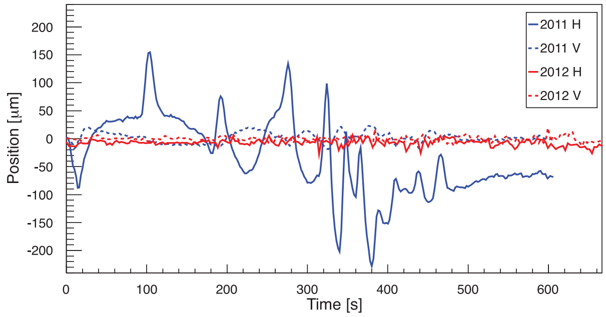

Figure 5: Interpolated orbit at the primary collimators versus time during the squeeze in 2011 and 2012.

cause global corrections are not effective to reduce these local coupling sources.

CONCLUSIONS

The operational experience with the betatron squeeze at the LHC was presented. The overall performance of the LHC in this critical phase of the operational cycle has been excellent during the first years of operation. Several different optics configurations were successfully deployed. The smallest achieved β^* in the high-luminosity experiments was 60 cm at 4 TeV. For all optics, the LHC is remarkably stable (tune, chromaticity, orbit, ...) and the optics could be corrected to record β–beating levels below 10 %. In 2012, the operation suffered however from loss spikes in the squeeze. This change from the "loss–free" operation before 2012 was caused by the deployment of tighter collimator settings for 60 cm β^* reach, which largely repaid the operational nuisance caused by beam losses (some 10-15 fills were lost in the squeeze). This aspect remains the main concern for the future operation at higher energies.

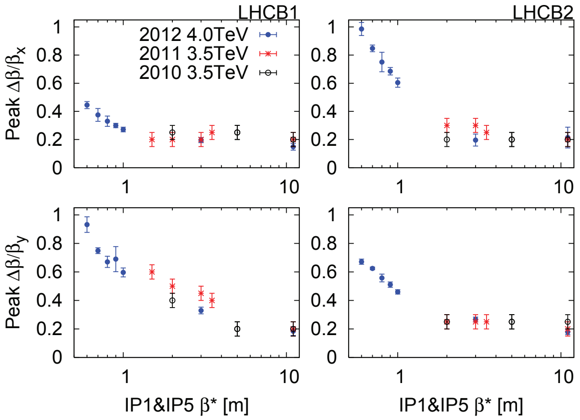

Figure 6: Uncorrected peak β-beating versus β^*.

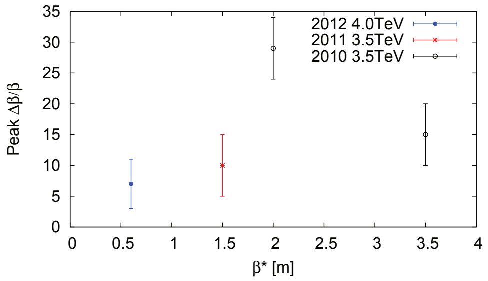

Figure 7: Peak β-beating after correction versus β^*.

The authors would like to sincerely acknowledge all the people of the teams that contributed to this work, in particular the LHC operation team, the accelerator physics teams responsible for the optics definition, measurement ad correction and the controls team for the support in the implementation of the squeeze mechanics.

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