COMMISSIONING OF RAMP AND SQUEEZE AT THE LHC

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Abstract

The energy ramp and the betatron squeeze at the CERN Large Hadron Collider (LHC) are particularly critical operational phases that involve the manipulation of beams well above the safe limit for damage of accelerator components. In particular, the squeeze is carried out at top energy with reduced quench limit of superconducting magnets and reduced aperture in the triplet quadrupoles. In 2010, the commissioning of the ramp from 450 GeV to 3.5 TeV and the squeeze to 2 m in all the LHC experiments have been achieved and smoothly became operational. In this paper, the operational challenges associated to these phases are discussed, the commissioning experience with single- and multi-bunch operation is reviewed and the overall performance is discussed

INTRODUCTION

The Large Hadron Collider (LHC) has seen an exciting initial operation at 3.5 TeV, with stored energies up to 9 MJ per beam at the time of this workshop. The energy ramp and the betatron squeeze are particularly critical operational phases that involve delicate handling of beams above the safe limits (assumed limit is 3.1×10^{10} protons at 3.5 TeV). Presently, the nominal parameters have been achieved in terms of bunch intensity, ramp rate, transverse and longitudinal beam emittance. The commissioning is now focused on increasing the stored beam energy to reach by the end of the 2010 run the luminosity goal of 10^{32}cm^{-2}s^{-1} and up to 30 MJ stored energy [1].

In order to achieve a good collider performance and minimize the risk of quench and damage, it is clearly important to keep under control losses during ramp and squeeze. Machine protection constraints also impose tight tolerances on the orbit and optics stability. In this paper, we present the performance of ramp and squeeze at the LHC under various conditions. After a brief introduction on the run configurations and on the commissioning strategy, the tools developed to perform ramp and squeeze are presented and the performance in term of beam transmission, orbit stability and tune and chromaticity stability are presented.

2010 RUN CONFIGURATIONS

The main beam and machine parameters for the 2010 LHC run configurations are given in Table 1. After an initial pilot run at a reduced energy of 1.18 TeV (I), limited by the maximum current of the main dipoles, the commissioning of the 3.5 TeV ramp was achieved in March, with ramp rate of 2 A/s (II). The nominal rate of 10 A/s was commissioned with beam in August in preparation for a third run configuration for operation with multi-bunch trains (III). The first operation at 3.5 TeV was limited to about 2.7 MJ stored energy to collect operational experience on the machine protection systems over a period of 4 weeks in summer. Since the month of September, the LHC has entered a new operational phase compatible with up to 400 bunches (which requires crossing angles in all interaction points) with the goal of achieving a luminosity of 10^{32}cm^{-2}s^{-1} by the end of October. The proton run will be followed by 4 weeks of ion run with the configuration III. Presently, the LHC has seen fills with up to 9 MJ stored at top energy, for a peak luminosity up to 5×10^{31}cm^{-2}s^{-1}.

Table 1: LHC 2010 proton run configurations and achieved performance at the time of this workshop. The goal for 2010 is to achieve a luminosity of 10^{32}cm^{-2}s^{-1} by the end of October, with stored energies up to 30 MJ per beam.

Parameter	Value		
	I	II	III
Colliding beam energy [TeV]	1.18	3.5	3.5
Peak luminosity [10^{32}cm^{-2}s^{-1}]	–	0.11	0.5
Maximum stored energy [MJ]	<0.01	2.7	9 #
Single bunch intensity [10^{10}p]	3	11	11
Norm. transv. emittance [μm]	3.5	2.0	2.0
Bunch length at flat-top [ns]	1.	1.4	1.2
β^* in IP1/IP5 [m]	11	2.0/3.5	3.5
β^* in IP2/IP8 [m]	10	2.0/3.5	3.5
Crossing angle IP1/IP5 [μrad]	0	0/100	100
Crossing angle IP2 [μrad]	0	0	110
Crossing angle IP8 [μrad]	0	0	100
Parallel beam separation [mm]	±2.0	±2.0	±2.0
Main dipole ramp rate [A/s]	2.0	2.0	10.0

Achieved on Sep. 29$^{\rm th}$ at time of Workshop

The squeeze to 2 m in all IPs was achieved on April 7$^{\rm th}$ for the configuration II with zero crossing angle. The commissioning took profit from preliminary tests carried out at the end of the 2009 run [2], whose operational experience was feed back into procedures and software implementation. On the other hand, for the operation with 100 μm crossing angle in the multi MJ regime, it was decided to step back and run at 3.5 m in all IPs in order to ensure sufficient aperture margin at the superconducting triplets.

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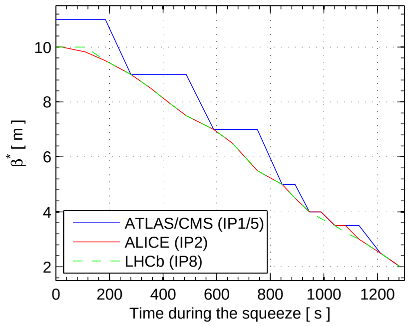

Figure 1: Beta functions as function of time during the squeeze in all LHC experiments (21 different optics).

SOFTWARE IMPLEMENTATION

The settings of all LHC circuits are generated from optics strength files provided by the accelerator physics team using the FiDeL magnetic model of the LHC [3, 4]. For the energy ramp that is done at constant optics, the length of setting functions is determined by the hardware parameters of the main dipole circuits. Maximum ramp rates of 2 A/s and 10 A/s (nominal) were used this year, with an optimized start of functions designed to minimize dynamics effects of the superconducting magnets [4]. The ramp times for the two cases are 2700 s and 1200 s, respectively.

For the squeeze [2], the setting generation works differently: the energy is constant and one has to step through different optics. This affects the matching quadrupoles in IP1/2/5/8 and the lattice sextupole for correcting the aberrations from the IPs. A number of so-called *matched optics* is provided between the maximum and the minimum β^* values of each IP. Smooth current functions are then generated by taking into account the ramp rates and accelerations of each circuit of the matching sections. The slowest converters (notably, the monopolar Q4 quadrupole magnets) and the total number of matched points determined the total length of the squeeze. In Fig. 1, the beta functions versus time are given for all LHC experiments with for the present run configuration. The first segment of the squeeze functions (23 s) is used to change the tunes at constant β^* from the injection (0.28,0.31) values to the collision (0.31,0.32) values. This is done with the quadrupoles in IP1 and IP5.

A special functionality that has been extensively used during the squeeze operation is the possibility to execute setting functions in steps by stopping at intermediate matched points. This is possible because the squeeze functions are generated with the constraint that derivative and acceleration of the current functions versus time are null at the matched points, which allows the power converters to stop and re-start without perturbations (this would not be possible, for example, in the linear part of the function with constant slope of the current function). An example is given in Fig. 2, where the measured current of one quadrupole used during the squeeze is given for the case without (top) and with (bottom) stopping points (two in

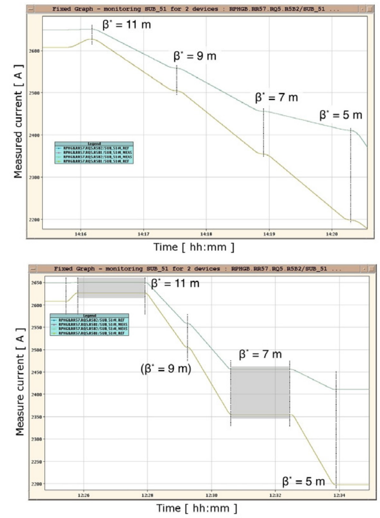

Figure 2: Measured Q5 currents in a 5TeV squeeze test without beam, without (top) and with (bottom) stop points.

this example). This functionality was used during commissioning to optimize the machine at every intermediate β^* optics and to build improved functions that can then be run through without interruption. During standard operation, one or two stop points are still used for various purpose's such as moving the collimators (done with β^* of 7 m in all IPs) and changing the feedback settings.

Settings for other accelerator systems such as collimators and radio-frequency (RF) systems are also generated in a similar way using the momentum and the optics functions versus time during ramp and squeeze. A detailed overview of these settings is beyond the scope of this paper. See [5] for more detail on the collimation system settings.

PERFORMANCE

Transmission and Beam Losses

An example of time evolution of beam intensity during a typical fill with 56 nominal bunches per beam is given in Fig. 3. The measured current in one of the matching quadrupole used during the squeeze is also given to illustrate the time intervals when ramp and squeeze take place. Seven injections of eight bunches each are visible on the injection flat-bottom as steps in the beam current measurement. A zoom out of the beam current lines is shown in Fig. 4. In this example, the measured beam losses are below 1 % (one division in the Y axis of the graph corresponds to less than 0.1 %). The change in lifetime visible at the right side of the plots coincides with the time when the beams are brought into collision. No dependence of the transmission on the number of bunches has been observed after the setup of nominal bunch intensities.

The statistics of beam transmission during several ramps and squeezes is shown in Fig. 5 and 6 (22 fills are considered). The percent loss is calculated as the relative loss between beginning and end of ramp and squeeze, respec-

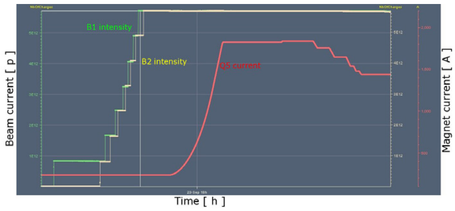

Figure 3: Beam 1 (green) and beam 2 (yellow) intensity and Q5-L1-B1 current as a function of time during one recent fill, from injection up to collision.

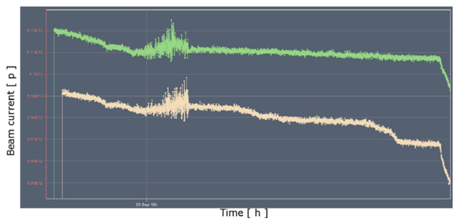

Figure 4: Zoomed plot of the beam intensity lines of Fig. 3. In this example, total losses during ramp and squeeze are about 1 %. The measurement noise depends on the bunch length variation during the ramp.

tively. This transmission analysis shows an excellent performance. Except for a few exceptions not shown in the plot, when beam losses occurred for known reasons (problems with feedbacks, missing Landau octupoles, wrong beam manipulations, ...), the transmission it typically above 98 %. This statistics includes physics fills as well as fill for various studies and machine setups. The total beam intensities range from single bunches up to 56 bunches. At the time of this workshop, the total achieved intensity is 152 nominal bunches and the performance of ramp and squeeze confirm the previous results.

Another way to estimate the beam losses is to consider the measurements of the beam loss monitoring (BLM) system [6]. This provides a higher dynamic range for loss measurements than the one from beam current transformers (BCTs). By looking at the losses at the primary collimators, which represent the aperture bottleneck of the LHC where beam particles are eventually lost in case of instabilities, one can observe losses that are not easily measurable

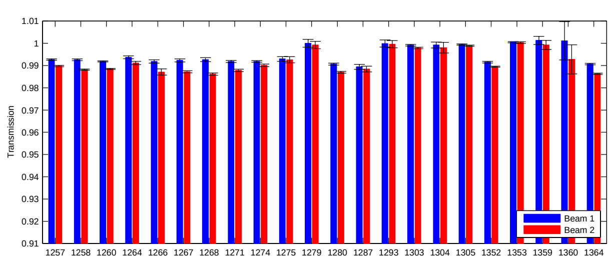

Figure 5: Beam transmission during energy ramps of recent fills (Aug.–Oct. 2010). Transmission is calculated from the bunch current measurements.

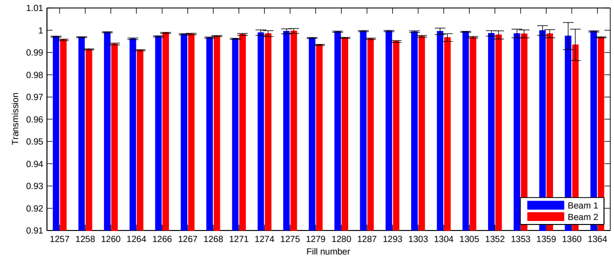

Figure 6: Beam transmission during betatron squeezes of recent fills (Aug.–Oct. 2010). Transmission is calculated from the bunch current measurements.

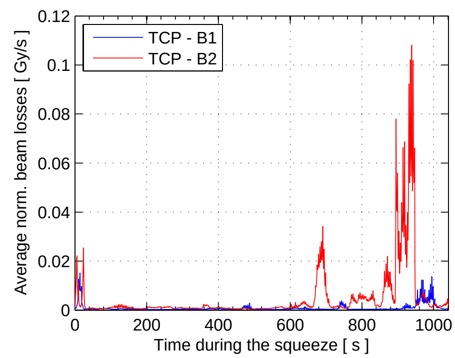

Figure 7: Average normalized losses measured at the primary collimators during the squeeze (6 fills).

by the BCTs. As an example, the BLM signal measured at the primary collimators as a function of time during the squeeze is given in Fig. 7. The average of 6 fills, normalized to the total beam intensity and scaled to the nominal, is given. Beam losses during the last squeeze steps are measured, in particular for beam 2. These losses have been partly cured by optimizing the coupling but are not yet fully understood. If scaled to higher intensities, they will represent no immediate limitations for the 30 MJ goal of the 2010 run because they can be safely handled by the collimation system [5].

Orbit Stability

Clearly, the stability of the beam orbit is a primary ingredient for the the good transmission performance described in the previous section. It is worth reminding that the primary collimators in the betatron cleaning insertion (IR7) are closed to gaps as small as $\pm$1.5 mm at 3.5 TeV. The minimum collimator gap at injection is about $\pm$4.3 mm. Orbit perturbations in the level of a few hundreds microns could therefore cause significant beam losses.

The time evolution of the RMS orbit error during a typical energy ramp is given in Fig. 8. The error is calculated as the RMS of all the difference readings of the beam position monitors (BPMs) with respect to the reference orbit at injection. This stability performance is achieved with orbit feedback ON during the ramp (see next session) [7].

A primary concern for protection constraint is the orbit

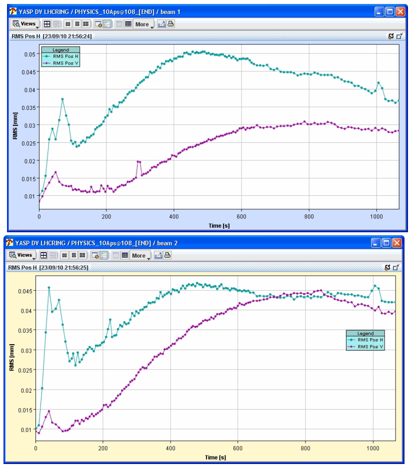

Figure 8: Evolution of the RMS orbit error versus time during a typical energy ramp from 450 GeV to 3.5 TeV.

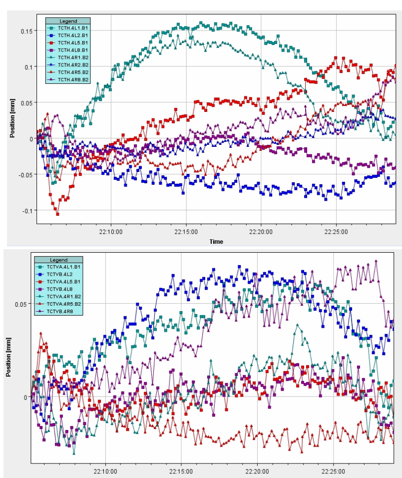

Figure 9: Interpolated orbit as a function of time during the energy ramp at the horizontal (TCTH) and vertical (TCTV) tertiary collimators in all interaction points.

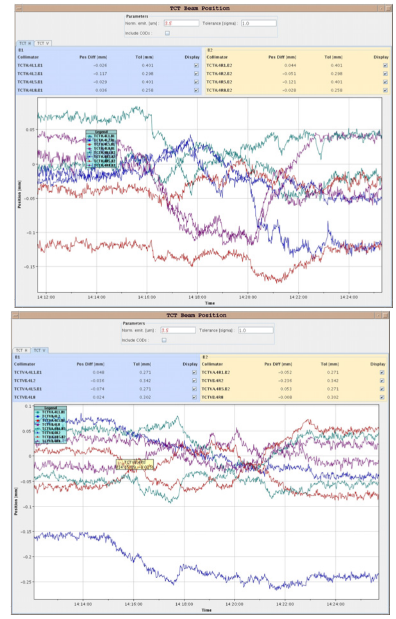

Figure 10: Example of orbit stability versus time at the horizontal (top) and vertical (bottom) tertiary collimators in all IPs during the squeeze to 3.5 m.

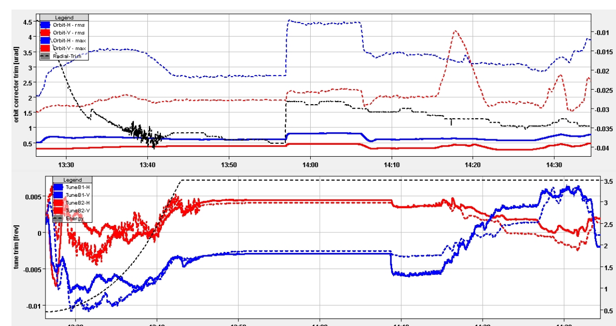

Figure 11: Example of real-time orbit (top) and tune (bottom) corrections during a ramp and a squeeze.

stability at the tertiary (TCT) collimators in all the interaction regions. The orbit at the TCTs must be controlled to a fraction of a sigma level to ensure that these collimators are protected by the beam dump protection elements. The interpolated orbit at all tertiary collimators during a typical ramp and squeeze is given in Figs. 9 and 10, respectively. The stability is better than one betatron sigma as the typical beam sizes at the TCTs with β^* = 3.5 m range between 200 μm and 500 μm.

Tune and Chromaticity

The tunes measured for both beams and planes during ramp and squeeze of the fill of Fig. 3, are given in Fig. 12. The measurements during the ramp are more noisy because because the transverse damper was kept ON to stabilize single bunch instabilities. We can nevertheless see a tune stability well below the 10^{-3} level throughout the fill. Presently, the tune feedback has to be switched OFF during the tune change at constant β^* done at the beginning of the squeeze. It is also kept OFF during collisions. An example of orbit and tune feedback corrections is given in Fig. 11 for a typical ramp and squeeze.

In Fig. 13 the average tune corrections applied by the tune feedback is given for both beams and planes. These corrections are regularly fed-forward to reduce the required real-time corrections from the feedback. The example of Fig. 13 shows corrections up to more than 0.01 units. They can be reduced to a few 0.001 units with regular feed-forward corrections. An example is given in Fig. 14.

Continuous measurements of chromaticity are only possible with a radial modulation that is not fully parasitic and therefore they are not carried out on a regular basis but only with dedicated low-intensity fills. Two examples for ramp and squeeze are given in Figs. 15 and 16, respectively. Whenever available, the measured errors are feed-forwarded into the settings functions of the lattice sextupole correctors for the following fills. Presently, the chro-

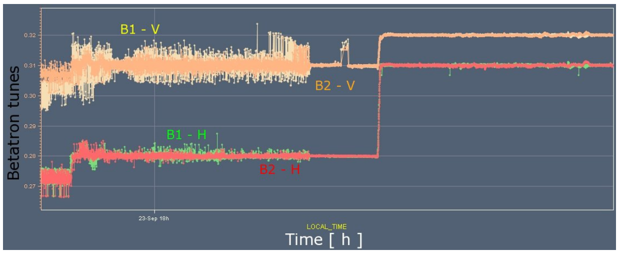

Figure 12: Tunes as a function of time for both beams and planes measured during ramp and squeeze of Fig. 3.

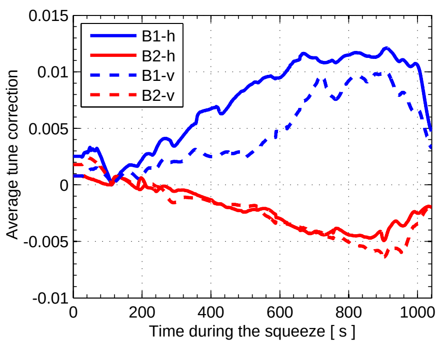

Figure 13: Average tune corrections versus time during the squeeze as calculated over 6 recent fills.

maticity is controlled within a few units. Dedicated measurements are performed at the end of the ramp, at intermediate squeeze points and before bringing the beams into collision for fine adjustments.

CONCLUSIONS

The first phase of the LHC commissioning has seen a rapid and efficient commissioning of energy ramp and betatron squeeze. Ramp to 3.5 TeV and squeeze to 2 m were achieved at the first attempts. We have then operated routinely the LHC in the few MJ regime (up to 50 bunches per beam) with transmission close to 100% during ramp and squeeze. Presently, losses at top energy are basically driven by the collision process. Clearly, an excellent magnet model has been the key for the smooth commission-

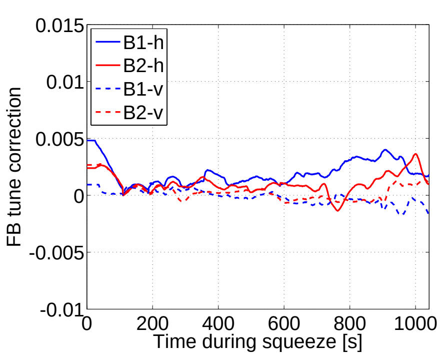

Figure 14: Tune corrections from the feedback after feed-forward corrections of the curves of Fig. 13.

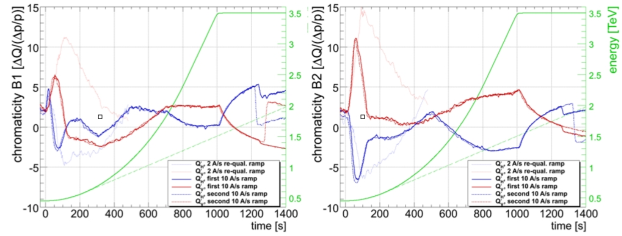

Figure 15: Chromaticity during an energy ramp measured continuously with a radial modulation.

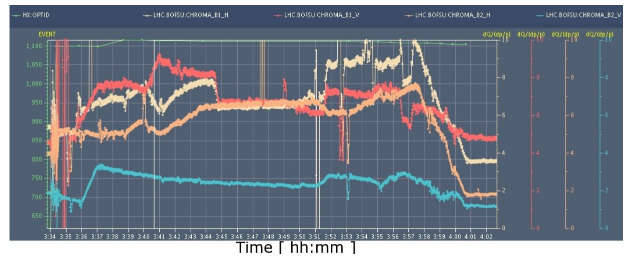

Figure 16: Tune and chromaticity for both beams and planes during ramp and squeeze. Measurements were performed with continuous radial modulation.

ing and also ensured optimum conditions: orbit, optics and aperture were essentially well under control since the beginning of the commissioning, The squeeze commissioning has taken profit from powerful software implementation that allowed stopping at intermediate points and re-incorporate intermediate point correction into the squeeze functions, with a rapid convergence to stable solutions. The stable beam operation for physics production, which has exceeded the 3 MJ level at the time of this workshop, was made possible by the good performance of orbit and tune feedback.

This work has been presented on behalf of the LHC commissioning team. The authors would like to acknowledge the colleagues from the operation crew and from the accelerator physics teams. The colleagues from the controls team, in particular G. Kruk, and from the FiDeL team (E. Todesco and P. Hagen) are also kindly acknowledged.

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