COMBINED RAMP AND SQUEEZE AT THE LARGE HADRON COLLIDER

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Abstract

In the first two years of operation of the CERN Large Hadron Collider (LHC), the betatron squeeze has been carried out at constant flat-top energy of 3.5 TeV after the completion of the energy ramp. This ensured a maximum flexibility during commissioning because stopping at all intermediate optics for detailed measurements and optimization was possible. In order to improve the efficiency turn-around in the future, combining the ramp and squeeze has been considered. In this paper, the feasibility of this scheme at the LHC is discussed and settings at different beam energies are proposed.

INTRODUCTION

The operational experience at the Large Hadron Collider (LHC) has shown that the energy ramp and the betatron squeeze – considered amongst the most critical phases with stored beam energies of hundreds of MJ – can be handled without major problems. The 2011 operation at 3.5 TeV with β^* = 1.0 m was carried out with beam current transmission close to 99 % between end of injection and start of collisions for fills with total stored intensities up to 110 MJ [1, 2]. The remarkable performance of ramp and squeeze is confirmed by the initial operation in 2012 at 4.0 TeV and β^* = 60 cm in the interaction points (IPs) IP1 and IP5, to be compared with the design value of 55 cm at 7 TeV [3].

Presently, the squeeze is done at constant energy after the execution of the ramp. This modular implementation has clear advantages in terms of operational flexibility but is not optimized for machine efficiency. The durations of these two phases add up so the turn-around is expected to increase for higher beam energies. The possibility to have a combined ramp and squeeze (CRS) was studied.

In this paper, some basic controls aspects of ramp and squeeze are introduced and a new scheme based on a CRS is presented. CRS settings prepared for different LHC energies are presented. In particular, a detailed study is presented for the 3.5 TeV case, which could unfortunately not be tested with beam due to scheduling issues for the LHC studies in 2011. Some conclusions with the outlook of the feasibility of this scheme for the LHC are then drawn.

RAMP AND SQUEEZE SETTINGS

Present Implementation of Ramp and Squeeze

In the present operational cycle, the ramp and the squeeze are carried out separately. The ramp is done at constant the optics, i.e. by scaling linearly with energy the magnet strengths. For a given energy, the ramp duration is determined by (1) the maximum current ramp rate of the main LHC dipole magnets and by (2) the choice of the exponential and parabolic segments that are chosen to optimize the dynamic field changes at the beginning of the ramp [4]. The current versus time for the LHC main dipole during the energy ramp is given in Fig. 1. The ramp to 3.5 TeV took 1020 s, including a 340 s long decay *plateau* at flat-top. The ramp to 4 TeV in 2012 takes a total of 770 s, without decay *plateau* that was removed thanks to a better strategy for the compensation of the field decay effects [5].

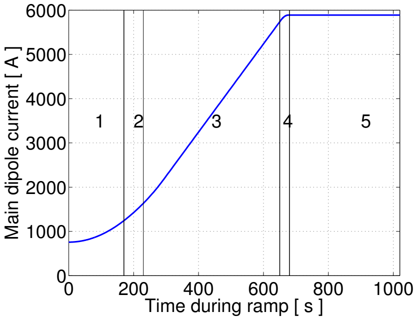

Figure 1: Current versus time during the energy ramp to 3.5 TeV for the LHC main dipole. Different segments are indicated: parabolic (1) and exponential parts (2), linear part (3), parabolic round-off (4) and constant decay *plateau* (5). The 2012 settings at 4 TeV use the same parameters but the segment (3) is stretched as required for higher energies.

The squeeze is done at constant flat-top energy: the required circuits (IP "matching" quadrupoles and quadrupoles for β-beating corrections, orbit correctors, correctors for global tune, coupling and chromaticity and dipole kickers for IP bumps) are set to the currents that produce the desired optics. Several intermediate optics "matched" for different β^* values are needed to maintain transient errors to tolerable values [6]. Linear interpolations of the current settings between the intermediate points, with gentle round-offs for the power converter functions, are used for this purpose. The β^* versus time at 3.5 TeV in 2011 is given in Fig. 2. For a target β^* value, the squeeze duration is determined by the parameters of the circuits used in the squeeze and by the number of intermediate optics that are used, which has been carefully optimized in the last years [6] to minimize the squeeze duration.

Having separated ramp and squeeze provides a maximum flexibility that is important for an efficient commissioning: the squeeze is initially performed by stopping at each intermediate optics to optimize the machine in this configuration (stopping is possible thanks to the round-off

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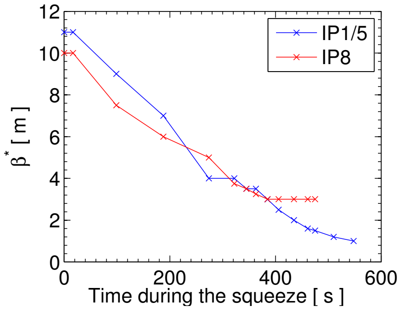

Figure 2: β^* functions in IP1/5/8 versus time during the squeeze (the total duration is 548 s). IP2 was kept at the injection optics with $\beta^* = 10$ m during the proton physics run. The crosses indicate the times of the matched optics.

Table 1: β^* Versus Time and Energy for a CRS at 3.5 TeV

Time s	Energy GeV	$\beta^*_{\mathrm{IP1/5}}$ m	β^*_{IP8} m
0	450	11	10
233	986	11	10
354	1656	9	8.5
450	2225	7	6.5
574	2959	5	4.5
634	3314	4	3.5
680	3500	3.5	3.0

of current settings). The beam-based corrections are feed-forwarded into the squeeze settings to improve the execution of the next squeeze in an iterative process that continues until one converges to a set of corrections that allows to run through the squeeze without stopping. In 2011, this could be achieved within 4-5 attempts. Note that stopping during the ramp is excluded because this would change the dynamics field changes in super-conducting magnets.

Generation Combined Ramp and Squeeze Settings

The generation of CRS settings was carried out without modifications of the existing setting generation tools. For a given optic, the initial sources for function generation are the normalized magnet strengths K's of each circuit. These K's are converted in currents by using the LHC magnetic model [7] in the same way as it is done for the standard ramp. For the CRS, a set of optics is defined at different energies, i.e. at different times during the ramp. For each circuit, these series of K's are interpolated with linear segments to build a continuous $K(t)$ function. The scaling by the energy is automatically taken into account. The time intervals between intermediate optics must however respect the hardware parameters like current ramp rates and accelerations. This poses constraints on the minimum β^* that can be achieved for a given ramp duration.

In practice, CRS settings are produced through a manual iterative process to minimize the distance in time between matched optics during the ramp while respecting the power converter constraints, in order to achieve the minimum β^* value at top energy. The flexibility of this rather cumbersome iterative algorithm [8] was appropriate for this pioneer study of CRS but clearly the mechanism to optimize the time intervals between optics must be automated for future implementations of the CRS functions.

Table 2: Time Gain from CRS at Different Energies Based on Conservative Assumption for the β^* Reach during the Ramp

Energy	β^* at flat-top	Duration baseline	Duration if CRS	Time gain
4 TeV	3.0 m	2045 s	1688 s	357 s
5 TeV	2.5 m	2264 s	1860 s	404 s
6 TeV	2.0 m	2596 s	2128 s	468 s
7 TeV	1.5 m	2866 s	2307 s	559 s

The target for the CRS setting generation is to achieve the smallest possible β^* value in the time of the real energy ramp (680 s and 770 s for 3.5 TeV and 4 TeV). The following criteria were applied for the setting generation: (1) Optics changes take place only after the first 200 s from the ramp start, see Fig. 1; this is a soft constrain that could be relaxed to push further the gain in time if needed; (2) The squeeze is carried out during the time of the "real" energy ramp and not during the decay *plateau* (removed from the ramp settings after 2011); (3) Optics changes are concentrated as much as possible in the linear part of the ramp (branch 3 in Fig. 1). (4) For feasibility study at 3.5 TeV, the minimum β^* value during the CRS was set to 3 m as this is the first optics for which beta-beating corrections were applied. The last constrain can be obviously be relaxed however it is important that during the energy ramp only optics for which beta-beating corrections are well understood are used. Indeed, it is not possible to stop the function execution during the CRS for detailed measurements.

Note that the ramp is done at injection tunes of (0.28, 0.31) that are then changed to collision tunes (0.31, 0.32) at constant β^* as first step of the squeeze, see Fig. 2. Following promising studies of injection and ramp at the collision tunes [9], it is assumed here that the CRS is carried out at collision tunes. The tune set point does not affect the conclusions of this study.

PROPOSED SETTINGS

The times of matched optics for a CRS at 3.5 TeV are listed in Tab. 1. We could achieve a minimum β^* of 3.5 m in IP1/5 and 3 m in IP8 for a time gain of about 330 s. The functions generated for 3.5 TeV CRS were tested on the real LHC circuits to exclude hardware problems. An example is shown in Fig. 3 for a selection of matching quadrupoles in IP5. All circuits behaved as expected. At 4 TeV, 3 m is within reach also in IP1/5, thanks to a longer ramp. The gain in time by using the CRS scheme at different energies is summarized in Tab. 2. The total durations for the baseline case with separated ramp and squeeze is to be considered as preliminary as it is based on setting generation as of 2011. The time gains are calculated with

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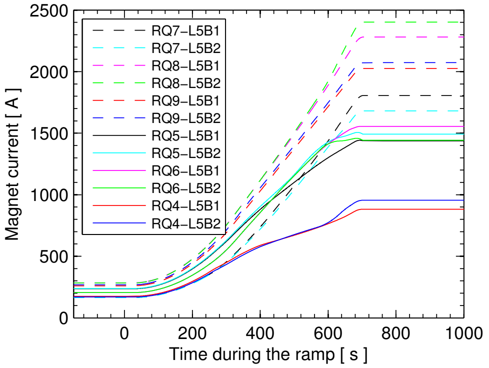

Figure 3: Current of several IP5 quadrupoles during a CRS dry-run at 3.5 TeV.

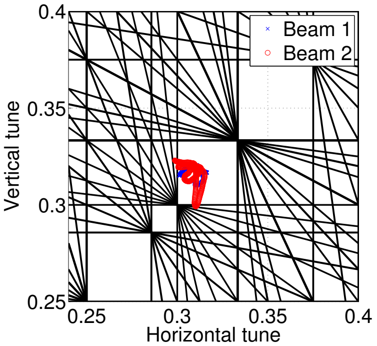

Figure 4: Tune drifts in the tune diagram for the proposed CRS functions to 3.5 TeV.

conservative assumptions for the β^* reach during the ramp. Up to about 10 minutes per cycle could be gained at 7 TeV.

The dynamics errors of linear beam parameters like orbit, tune, chromaticity and β-beating were evaluated by simulating the time-dependent errors during the CRS [6]. Typical tune errors are shown in Fig. 4. These errors can be easily taken care of by the tune feedback and optimized with feed-forward corrections. Orbit and chromaticity are under good control. It was however found that the dynamics β-beating between matched points can reach up to 10-15 % (top graph of Fig. 5). The time-dependent simulations were used as input for the standard β-beating correction algorithms used at the LHC for optics corrections. As a proof of principle, the errors for beam 2 at 500 s [8] were reduced below 5 % (bottom graph of Fig. 5), which is acceptable for the operation. This was done with a correction knob activated only in the required time range, corresponding to β^* between 6.5 m and 4.5 m in IP8. This simulation-based β-beating correction might be used also to reduce optics errors between the other pairs of matched points if needed.

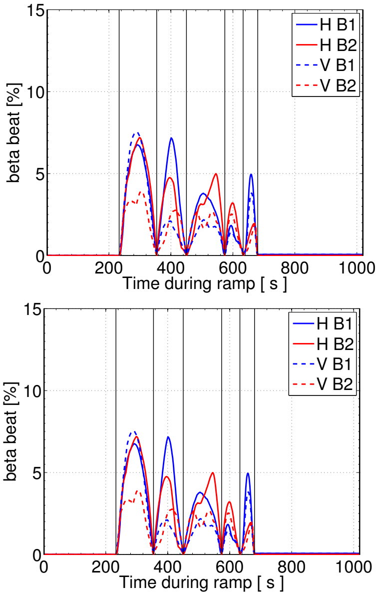

Figure 5: Simulated dynamics beta-beating errors during the CRS to 3.5 TeV before (top) and after (bottom) having applied to correction knob. Vertical black lines indicate the times of matched optics as listed in Tab. 1.

CONCLUSION

A first feasibility study to combine the ramp and the squeeze at the LHC was presented. This scheme seems feasible and can allow time gains of up to about 10 minutes at 7 TeV (based on preliminary conservative assumptions on the minimum β^* reach during the ramp). The gain in time at lower energies is less and therefore it was decided not to implement the CRS concept for the 2102 operation at 4 TeV in the absence of solid beam test results that are required for a conclusive proof of principle The knowledge of the LHC optics has reached already a maturity that makes us confident that the CRS scheme can work. Future studies should be focused on improved CRS setting generation and on detailed implementation of orbit feedback references, not yet addressed. Setting generation for other accelerator system like the collimators must also be addressed but is expected to pose no problems.

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