COMBINED RAMP AND SQUEEZE TO 6.5 TEV IN THE LHC

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Abstract

The cycle of the LHC is composed of an energy ramp followed by a betatron squeeze, needed to reduce the beta-star value in the interaction points. Since Run 1, studies have been carried out to investigate the feasibility of combining the two operations, thus considerably reducing the duration of the operational cycle. In Run 2, the LHC is operating at the energy of 6.5 TeV that requires a much longer cycle than that of Run 1. Therefore, the performance gains from a Combined Ramp and Squeeze (CRS) is more interesting. Merging the energy ramp and the betatron squeeze could result in a gain of several minutes for each LHC cycle. With increasing maturity of LHC operation, it is now possible to envisage more complex beam manipulations; this paper describes the first machine experiment with beam, aiming at validating the combination of ramp and squeeze, which was performed in 2015, during a machine development phase. The operation experience with the LHC run at 2.51 TeV, when CRS down to 4 meters was deployed and a the first results of 2016 run are also reviewed.

INTRODUCTION

In the first year of operation the LHC cycle was composed of a phase of energy increase, followed by a betatron squeeze, where the quadrupole gradients vary while the energy is kept constant. As the operation was a big success, some studies [1] have been carried out to prove the feasibility of combining the two operations at the LHC, thus gaining a substantial amount of time; combining ramp and squeeze would allow, in fact, shortening the LHC cycle by about 350 seconds. Tests and studies have also been done in other accelerators to use CRS [2] [3] [4] [5]. Besides, this operation is potentially beneficial, as many quadrupoles would have a reduced current increase, due to the simultaneous change of energy and beta-star, avoiding pushing them close to the HW limits. For all these reasons it was decided in 2015 to perform a first attempt with beam during a machine development session, to confirm the feasibility.

2015 MACHINE DEVELOPMENT

When trying to generate power converter settings for CRS, some problems were encountered, as the control system was not designed to generate squeeze settings with varying energy. For tune trim and lattice sextupole correctors, in fact, the setting generator was creating a smooth function that was incompatible with the energy variation. A modification was then needed to generate a complete set of settings.

The strategy for optics distribution in the ramp was defined, by trying to perform the whole squeeze in the region where the dipole current increase is linear. For this reason it was decided to distribute the optics between 2.5 TeV and 6 TeV, avoiding the snapback, the early part up to 1.5 TeV where orbit, tune and chromaticity have large changes as well as the last part where the parabolic rounding takes place. The decision of squeezing to 3 meters comes from the fact that this is the first optics where corrections have been implemented in the past and the quality of optics measurements performed in a dynamic phase was not guaranteed. Moreover this optics has a margin to guarantee enough aperture in the machine.

The first test of CRS with beam [6] was carried out on July 23rd 2015, during a machine development phase. Two ramps (fill 4035 and 4036) were performed with pilot beams, ramping only primary collimators at relaxed settings to allow optics measurements. In both cases Beam 1 was lost shortly after the beginning of the ramp, as the horizontal tune was driven through the resonance. The problem was then identified as an issue with the settings copied from the standard ramp. On the other hand, Beam 2 survived until 6.5 TeV. The tune was controlled and corrected by the tune feedback and a feed-forward was possible. The orbit was excellent with stabilization better than 60 μm, comparable to that of a standard ramp. An example of optics measurements performed on the fly during the ramp (for beta-star of 7 meters) is shown in Figure 1, compared to the measurements at the same optics, performed in static conditions at 6.5 TeV. Optics measurements with the AC dipole during the energy ramp were already performed in earlier runs [7]. Despite the loss of Beam 1 the result of the test was excellent, as it demonstrated the feasibility of the operation, confirming that the behavior of the beams is very similar to the one in the standard ramp.

2015 INTERMEDIATE ENERGY RUN

Thanks to the excellent results of the test performed during the machine development phase, it was decided to use CRS in operation, starting with the more relaxed conditions of the intermediate energy run [8]. At the end of 2015, in fact, the LHC undertook a phase of operation at 2.51 TeV. The CRS was designed to squeeze the high luminosity points to 4 meters beta-star and the optics were distributed following the same strategy used for the previous test. The five days of operation done in this configuration, including five fills used for physics production with high intensity, guaranteed acquiring a high level of operational experience and were a milestone for deciding to use CRS in standard operation in 2016.

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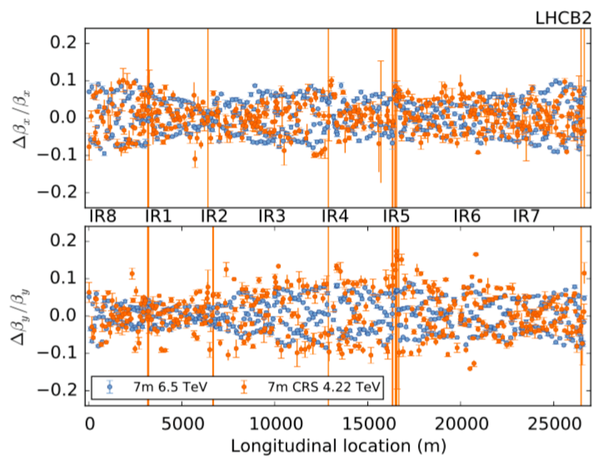

Figure 1: Beta-beating at 7 m compared to standard measurement at 6.5 TeV.

2016 NOMINAL LHC CYCLE

Based on the good experience, for 2016 it was decided [8] to use CRS as baseline for operation. Given the acquired experience, the strategy was left unchanged and the final squeezed point was set to 3 meters beta-star. It was possible to position the optics closer to each other, leaving open the possibility to create a second version of CRS with a further reduction of beta-star, aperture permitting. The details of the optics distribution in the operational configuration can be found in Table 1.

Table 1: Optics Table for 2016 Combined Ramp and Squeeze

IP1/5 beta-star	*Energy*	*Time*	*Parabolic frac*
11 meters	450 GeV	0 sec	0.1
11 meters	2736 GeV	545 sec	0.05
9 meters	3499 GeV	675 sec	0.1
7 meters	4021 GeV	767 sec	0.1
4 meters	4716 GeV	887 sec	0.11
3 meters	5180 GeV	967 sec	0.15
3 meters	6500 GeV	1210 sec	0.05

As explained in [6] the needed parabolic fraction was estimated from the 6.5 TeV squeeze, used in 2015. On March 27^{th} 2016, about 24 hours after the beam was back in the LHC, the first attempt of CRS was carried out. As initial guess the corrections of orbit, tune and chromaticity were copied from the 2015 nominal ramp. Besides, following the change of b_3 of persistent current in the superconducting dipoles [9], the lattice sextupole corrections were re-calculated.

Both beams were ramped to 6.5 TeV, while being squeezed in the high luminosity points to 3 meters, as shown in Figure 2.

Tune and Chromaticity

The corrections applied by the tune feedback during the first attempt of CRS (Figure 2) clearly show the tune excursions due to the optics change and a good control of the tunes during the first part of the ramp. Slightly before 1000 seconds the tune feedback was switched off (traces stops in the graph) as it was pushing the tunes away from each other, due to very high coupling. The orbit control during the ramp was again excellent and just light corrections were applied at flattop.

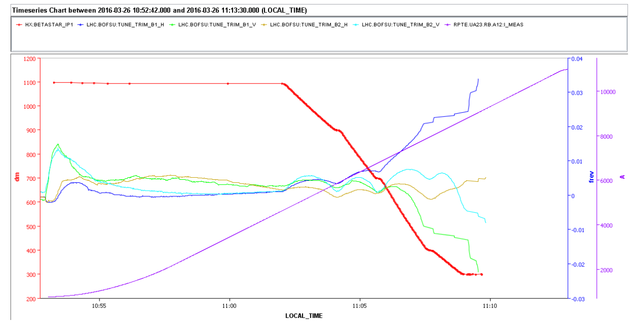

Figure 2: Energy, beta-star and tune corrections during the first 2016 CRS.

All corrections were then incorporated and in few attempts a good control of tune and coupling was obtained. It was then possible to measure the chromaticity, as this measurement is derived by small oscillation of the radio-frequency signal, which generate a tune oscillation. The first measurement of chromaticity during the ramp is shown in Figure 3. The top graph shows the tune oscillations and the bottom one the chromaticity evolution during the central part of the ramp. The chromaticity stays constant during the whole squeeze process and till the end of the ramp. On the other hand, the corrections are not optimal during the first 10 minutes, as expected, due to the change implemented in the model of b_3 of the superconducting dipoles. Through few steps of feed-forward corrections and measurements, it was possible to obtain a control of the chromaticity in within ± 1 unit all along the CRS.

Collimators

For optimum performance, the two-sided LHC collimators are operated in all phases of the operational cycle with jaws set symmetrically around the beam orbit and gaps varying depending on the local beam size. Beam size changes from energy and optics used to be treated separately in the standard operation with betatron squeeze at top energy [10]. The operation with combined ramp and squeeze requires performing at the same time changes of collimator centre position and gaps. The setting generation software has been update accordingly. This change affects only tertiary collimators in the interaction regions, which are now equipped with integrated beam position monitors [11]. Preliminary results from the 2016 indicate that the handling of new collimator settings for CRS can be done as required. It is envisaged to used feed-forward correction based on collimator beam position monitor readings if required.

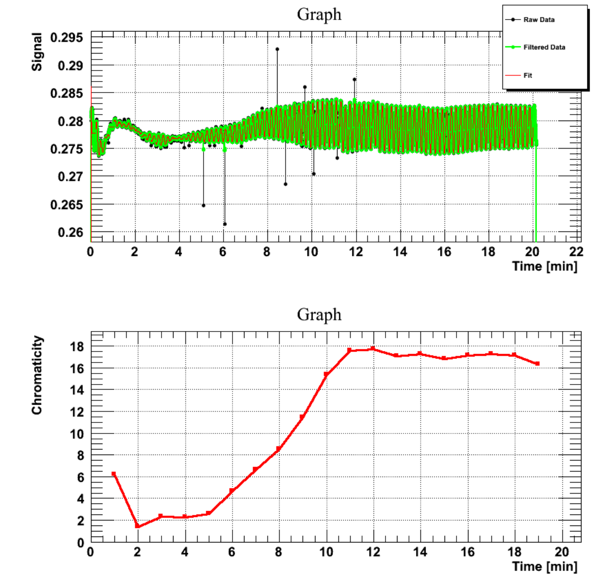

Figure 3: Uncorrected chromaticity evolution during CRS.

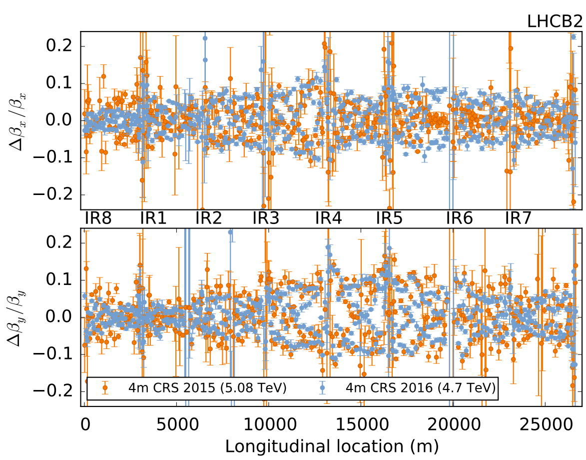

Figure 4: Comparison between optics at 4 meters during CRS in 2015 and 2016.

Optics Measurements and Corrections

Optics measurements, performed triggering the AC-dipole manually as close as possible to the matched points, show a good optics quality during CRS. As expected a peak of beta-beating below 20% is observed. A second iteration of local corrections were computed to be effective all along the squeeze down to 40 cm. The two local optics corrections are gradually brought up to the nominal setting during CRS to be at full strength at 3 meters beta-star. These measurements also allowed for coupling corrections throughout CRS, as done in [12].

Figure 4 shows a comparison between the results obtained in 2015 and those obtained in 2016 at 4 meters beta-star. As it is possible to see there is a very high level of agreement between the two measurements.

CONCLUSIONS

The success of the test performed in 2015 opened the way to use CRS in operation. The nominal 2016 LHC ramp has the same length as the 2015 (1210 seconds), but at the same time the beta-star in the two high luminosity points is reduced to 3 meters. Several measurements demonstrated that this operation does not compromise the quality of LHC operation, while resulting in a gain of 352 seconds per cycle. Considering that the operational conditions are the same as in 2015, the total gain of CRS can be estimated in about 20 hours over one year of operation [8]. Moreover, given the success of the operation, CRS will be used in 2016 in different configurations. A ramp to 6.5 TeV with (de)squeeze to 19 meters to be used for Van der Meer scans has already been tested and it is ready to be used. A third configuration with a ramp and (de)squeeze to 60 meters has also been generated and will soon be tested. This would allow to perform high beta physics without spending too long in increasing the beta-star in the interaction points. The high level of flexibility of the settings would theoretically also allow to allocate a pre-squeeze for IP2 before 2.5 TeV to use the present configuration also for the ion run.

Ultimately, with increased knowledge in the process, the possibility of further squeeze should be considered. Studies are ongoing to verify the aperture conditions and to confirm whether a more aggressive scenario is possible with squeeze to beta-star around 1 meter, which would result in additional gain of 250 to 300 seconds (depending on the chosen value).

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