TURN–AROUND IMPROVEMENTS

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Abstract

An efficient turn–around will be an important parameter for the integrated luminosity performance at LHC in 2012, when an operation with steady beam parameters and machine configuration will be achieved at the beginning of the run. Improvements of the operational cycle were already put successfully in place after the 2010 experience but additional ways to reduce the time required to setup collisions are possible. In this paper, the 2011 turn–around performance is reviewed and the benefits of the improvements from 2010 are presented. Phases of the operational cycle when further amelioration is possible are discussed and some proposal for a faster turn–around in 2012 are outlined.

INTRODUCTION

The LHC performance in terms of integrated luminosity depends critically on the machine turn–around, defined here as the time between a beam dump at top energy and the time of the declaration of the next "stable beams" mode that identifies the start of the physics data taking periods. Minimizing the turn–around is achieved by reducing the time spent in phases that are not providing useful collisions, e.g. by making the injection more efficient, by shortening the ramp and squeeze duration, by optimizing pre–cycle, etc. Improving the turn–around has also an advantage outside physics production periods as machine studies and commissioning periods also profit from a faster operational cycle. For example, at the beginning of 2010 a typical cycle with ramp and pre–cycle would take no less than 4 h whereas in 2011 about half of the time could be sufficient, with a clear advantage for all the "users": commissioners, MDers and physicists. In this paper, the improvements achieved in 2011 are presented and further changes foreseen for 2012 are discussed. See also a companion paper presented at Evian2011 [1].

After introducing the scope of this work and some definitions, the improvements achieved with respect to 2010 are presented for the different 2011 machine configurations. Possible further improvements for the different operational phases are proposed for the baseline machine configuration in 2012. Note that details and definitions of the operational cycle phases can be found in [2]. It is noted that only standard fills for proton and ion physics are considered. Studies requiring special setups (high–β^* optics, fills for Van der Meer scans, etc.) are not addressed.

SCOPE AND DEFINITIONS

Different statistical approaches can be used to evaluate the machine efficiency [3, 4]. Typically, one can look at the average machine availability, and at the fraction of this time spent in physics production. While such approached provides the relevant figure of merit in terms of overall integrated luminosity production, this is not necessarily the appropriate figure to address aspects related to the improvements of operational phases. By definition, the overall average availability is biased by (a few) long fills affected by equipment failures. The study of the optimization of this down times is not in the scope of this paper. The average turn–around varies between 5.4 h and 11.1 h depending on the cut that is applied for the tails with long durations (cuts at 15 h and 60 h, respectively, for the quoted extreme cases). Indeed, a detailed analysis [1] shows that the machine availability is largely dominated by these equipment failures with long recovery and only a small fraction of the fills approached the theoretical turn–around minimum.

In order to identify improvements of the operational cycle for a "failure–free" machine, the same approach used for the 2010 turn–around analysis [2] is used: fills that successfully made it to stable beams are considered. For each fill, the duration of the operational phases (injection, ramp, etc.) is calculated. Average figures are compared to the theoretical minimum duration achievable for each phase, i.e. what could be achieved with no down time of any injector and accelerator system and without mistakes and unnecessary delays by the operation crews. The reasons for discrepancies between achieved average durations and theoretical minima are critically analyzed to identify areas of improvement.

The source of data for the analysis is the LHC logging database where the times of machine mode changes are stored for each fill. The precision in the estimates of the mode durations presented here is in the order of a few minutes due to intrinsic uncertainty coming from possible delays associated to the operational procedures (e.g., beam dump mode might be declared up to a few minutes later than the moment when the dump occurred).

Details and definitions of the LHC operational cycle phases can be found in [2] and are not reviewed here. It is noted that one can distinguish between phases with a well defined duration in time (ramp, squeeze, collision setup and pre–cycle) – when the duration is determined by the length of settings functions played synchronously by power converters, RF and collimators – and discrete phases with undefined time duration (injection, ramp and squeeze prepa-

Table 1: Machine configurations in 2011 at 3.5 TeV.

	Protons 1 Feb.-Aug.	Protons 2 Sep.-Oct.	Ions Nov.-Dec.
Beam energy [GeV]	3500	3500	3500
β^* in IP1/5 [m]	1.5	1.0	1.0
β^* in IP2 [m]	10.0	10.0	1.0
β^* in IP8 [m]	3.0	3.0	3.0
	Duration of setting functions		
Ramp [s]	1020	1020	1020
Squeeze [s]	475	548	1233
Collision [s]	56	56	260

ration, flat–top, adjustment of collision). For the latter case, the human intervention has obviously a larger, and often difficult to quantify, effect.

TURN–AROUND IN 2011

2011 machine configurations

The different 2011 machine configurations for proton and ion physics are listed in Tab. 1. Two configurations with β^* values of 1.5 m and 1.0 m in the high luminosity interaction points IP1/5 were used. The ion run required a further squeeze in IP2 only down to 1 m. The duration of the setting functions for ramp, squeeze and collision functions (i.e., the time required to collapse the parallel separation bumps) are also given for all cases. The ramp was the same for the three configurations. The squeeze for ions took longer because it followed in time the squeeze in the other IPs . The collision functions were also longer to accommodate changes of polarity of the ALICE spectrometer.

The theoretical minimum duration of the different phases of the LHC proton operation cycle are listed in Tab. 2 together with the minimum achieved durations. These results are discussed in details in the next sections. Note that the injection times are listed for two configurations with different number of bunches.

Turn–around statistics and mode duration

The overall distribution of the dump–to–stable beam turn–around durations for proton runs is shown in Fig. 1. The cases with different β^* values are given in different colors. The distribution for ion operation is given in Fig. 2. For protons, the minimum achieved in 2011 was 2h07, to be compared with 2h44 of 2010 [2], i.e. 22 minutes and 44 minutes more than the theoretical minima for the two years, respectively. The average calculated taking into account the fills with turn–around below 20 h was 7.2 h in 2011 compared to about 11 h in 2010. The main reasons for this improvement are presented in the next section. It interesting to note that for both cases the average is about a factor 3 longer than the minimum achieved.

Table 2: Minimum theoretical duration and minimum achieved duration for the different phases of the operational cycle, assuming a typical length of the SPS supercycle.

Operational phase	Min. duration [s]	Min. Achieved [s]
Setup after dump at 3.5TeV	2490	2490
Inject probe (1092 b)	300	336
Inject probe (1340 b)	300	206
Inject physics (1092 b)	1574	1249
Inject physics (1340 b)	1574	1599
Prepare ramp	120	126
Ramp	1020	1026
Flat–top	0	13
Squeeze 1.5 m	475	558
Squeeze 1.0 m	548	663
Adjust	270	270
Total (1340 b, 1 m)	1h45’	2h07’

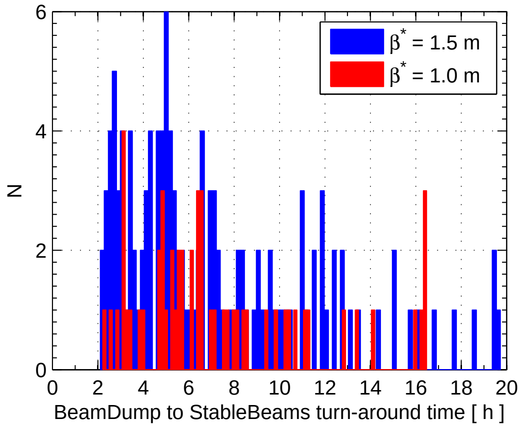

Figure 1: Distribution of dump–to–stable beam turn–around times during the 2011 operation. The configurations with β^* of 1.5 m and 1.0 m are treated separately. The minimum achieved was about 2 h and 7 minutes and the average is 7.2 h (taking into account the fills given in the plot with turn–around below 20 h).

The average of the different phases of the operational cycle are given in the graph of Fig. 3. Even if various improvements took place, the turn–around duration is dominated by the time spent at injection that took on average more than 1.5 h (it was about 3 h in 2010). A zoomed–out graph with the other modes only is given in Fig. 4. The durations of the different modes is comparable for ions and protons, with the exception of the squeeze because the one in IP2 was added in series, with other IPs already squeezed. The squeeze duration for protons was improved by about a factor 3 compared with 2010, even if the β^* value was 3.5 times smaller in 2011 [5]. A gain of 6 to 7 minutes was obtained in the ramp by an improved setting generation in the first part of the energy increase where the main dipoles have not yet reached the maximum rate of 10 A/s (expo-

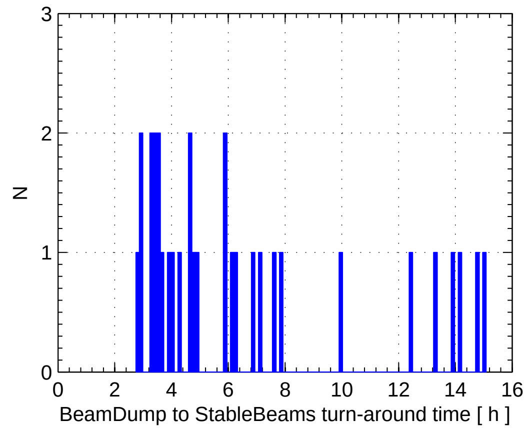

Figure 2: Distribution of dump–to–stable beam turn–around times during 2011 ion operation, calculated as for protons in Fig. 1.

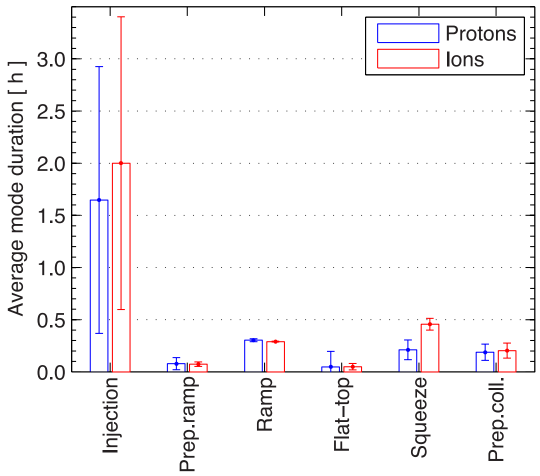

Figure 3: Average duration of the different phases of the LHC operational cycle, calculated for the fills with turn–around below 20 h.

nential and parabolic branches).

Turn–around improvements from 2010

Several proposals for turn–around improvements were discussed in [2]. Without going in detail of what was achieved, we list here some of the key points that determined the turn–around improvements in 2011:

- Injection: (a) Possibility to request B1 and B2 injection requests in parallel (i.e., request one beam while the other is being produced). This change reduced dramatically the dependence of the injection process on delays from the Injection Quality Check (IQC) analysis of the previous injection; (b) Improved threshold settings for BLM analyzed by the IQC that reduced the unnecessary latched; (c) Dynamic compensation of Q and Q decay at flat bottom.

- Ramp: optimization of the functions with reduced duration of the initial exponential and parabolic

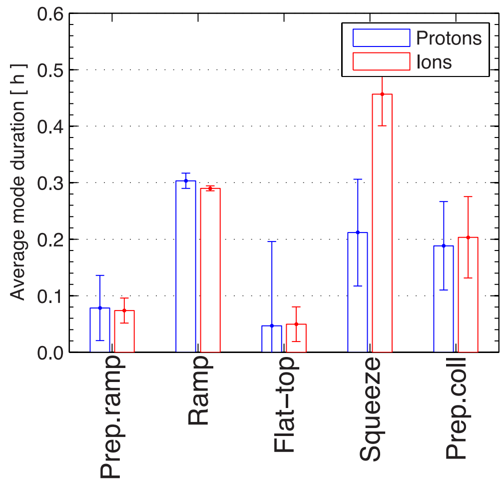

Figure 4: Average duration of the different phases of the LHC operational cycle as in Fig. 3, without the injection phase.

branches; change of crossing angle and separation settings to achieved physics values at the end of the ramp.

- Orbit feedbacks: addition of dynamic references (linear variations in time) to enable change of settings with feedback on.

- Squeeze: (a) Optimized distributions of intermediate optics to reduce the duration of settings [5, 6]; (b) automated handling of orbit reference changes through dedicated sequences (no need to stop at intermediate points); (c) Function–driven collimator settings; (d) continue execution of squeeze functions without stop points (except for the addition of the squeeze down to 1. m).

- Miscellaneous: (a) Improved operational sequences and graphical user interface of the sequencer application; (b) possibility of parallel execution of the beam preparation phases in the shade of the magnet pre–cycle; (c) reduction of the manual phases; (d) Updated procedure for the dump handshake, with maximum timeout of 5 minutes.

It is important to note that many other improvements have taken place between 2010 and 2011 to improve the operational efficiency and robustness, even if their benefits are not directly visible in this turn–around statistics analysis. For example, the automated handling of orbit feedback reference and the execution of the squeeze in one single step led to a more robust operation that translated into a much reduced number of beam dumps due to operational mistakes. Clearly, not all the important operational improvements are reducing the turn–around duration.

Table 3: Working assumption on the 2012 machine configuration for proton operation.

Parameter	Value
Beam energy [TeV]	4.0
β^* in IP1/5 [m]	0.6
β^* in IP2/8 [m]	3.0
Ramp duration [s]	770
Squeeze duration [s]	819

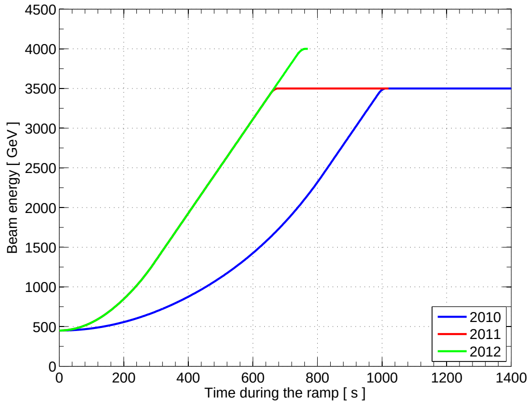

Figure 5: Energy settings versus time in 2010 and 2011 and proposed settings for 2012. For 2012 it is foreseen to remove the decay *plateau* at flat–top with an alternative method for the field decay compensation.

IMPROVEMENTS FOR 2012

Working assumption

The estimates of turn–around in 2012 and the optimization of the different phases are performed assuming the parameter set of Tab. 3. This is the parameter set proposed for the operation at 4 TeV. In case of different beam energy (3.5 TeV instead than 4.0 TeV) or β^* values in IP1/5, the configuration of 2011 in Tab. 1 should be taken as reference. Details of the crossing angle and parallel separation values are not yet determined but this has a minor impact on the turn–around duration.

Injection

Aspects related to the improvement of the injection process were discussed in detail in a dedicated session at the Evian2011 LHC Operation workshop. A few operational aspects where there is still room for improvement are listed here: (1) The communication with the injector chain should be improved in order to anticipate the preparation of the LHC beams: the manipulations of the LHC beams in the injectors are not trivial and it should start as soon as possible after an beam dump at the LHC, to exclude as much as possible problems; (2) Dedicate LHC injection cycle with a minimum of CNGS cycles in the SPS should be used, to reduce the average duration of the SPS cycle while injecting in the LHC; (3) The possibility to start steering on the TEDs downstream of the transfer lines during the LHC pre–cycle should be envisaged; (4) the injection sequencer could be modified to allow injection requests before the IQC analysis is completed: this would allow continuous injections in the LHC for every SPS cycle whereas presently only one cycle out of two can be used for one single beam.

Ramp and flat–top decay

The beam energy functions achieved in 2010 and 2011 and the proposed functions for 2012 are given in Fig. 5. As a baseline, it is foreseen to use the same parameters for the settings generation, which give a ramp time of 770 s between 450 GeV and 4.0 TeV. The time for the ramp was 680 s in 2011 however the change of energy was followed by a *plateau* at 3.5 TeV for the compensation of tune and chromaticity decay, that stretched the total length of ramp functions to 1020 s. The tune decay was below 0.002 and the chromaticity decay was for both beams about -2.5 units in the horizontal plane and 4.5 in the vertical plane. These errors were corrected over 340 s with trims in the global tune and chromaticity knobs. This scheme is not optimized because the decay should be rather corrected locally by the sextupole spool pieces that compensate the b_3 decay in the main dipoles. Another side effect is that the machine remains "frozen" during this time because the knobs are also needed for the squeeze that has then to wait until the 340 s are elapsed.

In order to improve this situation, it is proposed to move the correction of the chromaticity decay into dedicated settings of the sextupole spool pieces (the compensation of the tune poses no concerns as it is taken care of by the tune feedback that remains until the beams are brought in collision). This can be done by using longer ramp functions only for the spool pieces while keeping 770 s long functions for the rest of the power converters. Indeed, the spool pieces are not used during the squeeze thus they can continue running while the squeeze starts. No delay is therefore induced. This also has the advantage that the duration of the decay can be tuned to an appropriate length without increasing the turn–around duration, with full flexibility on the correction function shape.

The proposed scheme for the decay compensation can easily be achieved with some trivial gymnastic in the LHC sequencer by separating the converters of the sectupole spool pieces from the rest of converters. Two ramp beam processes of different lengths are then required, one for the spool pieces and one for the rest of the converters. This approach will enable to achieve the minimum duration of the ramp determined by main dipoles. It is noted that the spool pieces are powered in series and can not be used to apply different corrections for the two planes. The proposed scheme can therefore only be used to compensate the mean value of the chromaticity decay. Dedicated measurements are required early on during the 2012 commissioning to ad-

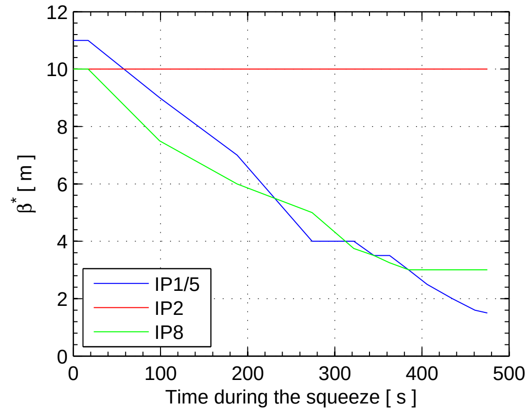

Figure 6: β^* functions versus time during the squeeze in 2011.

dress this aspect as well as to establish an optimum duration and correction settings for the spool pieces.

Squeeze

The β^* versus time during the squeeze for the configuration "Protons 1" of Tab. 1 is given in the top graph of Fig. 6. The duration was highly optimized [5] by a proper choice of the intermediate matched optics, respecting the following criteria: (1) Remove optics in the β^* range above 2 m already commissioned in 2010; (2) Use all the available optics in the un-explored range below 2 m; (3) try to equalize the β^* values in the different IPs. The latter constraint was motivated by the concern that dynamic variations during the squeeze could be optimized by having similar β^* values, as the tertiary collimators in the IPs must be set to protect the global bottleneck (protection setting are determined by the smallest β^* value anyways). The experience in 2011, when IP2 was squeezed with the other IPs already at their minimum values, proved that this constraint can be relaxed.

The proposed squeeze functions down to 0.6 m in IP1/5 and 3.0 m in IP2/8 are given in the bottom graph of Fig. 7. Compared to the 2011 functions, a further optimization of the number of matched points is carried out in the range above 1 m and the squeeze is done without minimizing the differences of β^* in the different IPs. This allowed a reduction of the overall duration by proceeding faster with the squeeze in IP1/5 while the (slower) squeeze in IP2 proceeds. The total squeeze duration is 819 s, however this preliminar estimate is carried out with a known problem of the function generation application that does not model correctly the inductance of monopolar Q4, Q5 and Q6 quadrupole. The final squeeze functions are likely to be about 100 s longer.

Pre–cycle

The duration of the pre–cycle in 2011 was limited by the ramp–down of the monopolar magnets. After promising hardware tests [7], a solution was found to reduce the ramp–down time of these magnets. The predicted net gain in time is 11 minutes. Tests will be performed during the 2012 hardware commissioning to address the feasibility of this scheme before the final implementation in the nominal operational cycle.

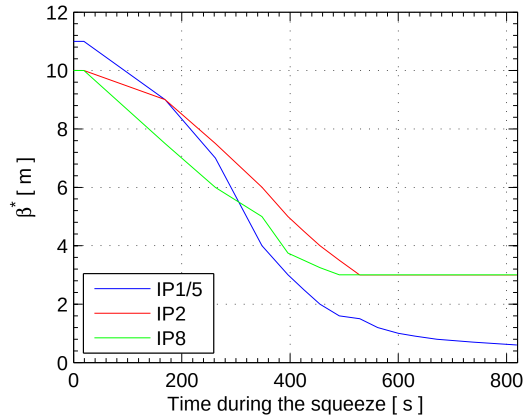

Figure 7: Proposed β^* functions versus time during the squeeze in 2012. The duration of 819 s is likely to be increased due to the slow response of the monopolar Q4, Q5 and Q6 magnets. Detailed figures have to be evaluated in detail at the beginning of 2012.

Table 4: Minimum theoretical duration and forecast for the minimum achievable in 2012, calculates with a best–guess of the operational delays for each phase.

Operational phase	Theoretical [s]	Achievable [s]
Pre-cycle from 4.0 TeV	1740	1740
Inject probe	300	340
Inject physics	1574	1600
Prepare ramp	120	420
Ramp	770	770
Flat–top	0	60
Squeeze	900	960
Prepare collisions	56	360
Total	1h31’	1h44’

Achievable turn–around in 2012

The estimated minimum theoretical turn–around time achievable in 2012, calculated on the basis of the improvements proposed above, is given in Tab. 4. This figure assume an operation at 50 ns. A guess of the minimum achievable duration for each phase is also given, based on the experience of 2010 and 2011. In 2012, a shorter duration than in 2011 could be achieved even if the LHC will operate at higher energy and smaller β^* values in all IPs. The main improvements will come from a faster pre–cycle, the alternative scheme to compensate the decay at flat–top and an optimized squeeze.

CONCLUSIONS

The analysis of the LHC turn–around in 2011 was presented and the improvements with respect to 2010 were discussed. The operational experience in 2011 shows that the minimum achieved turn–around is about 15 minutes longer than the theoretical minimum: 2h07 could be achieved in the best case. On the other hand, the average turn–around is more than three times longer even for the case of a ”fault–free” machine considered in this analysis, i.e. for the “good” fills in which stable beams could be established in less than 20h. The analysis of the overall LHC availability shows that in practice the integrated luminosity performance is dominated by bad fills where system faults induce delays well above the quoted average figures. It is nevertheless very important to continue the work to optimize the minimum theoretical turn–around in order to push the performance. The improvement obtained with respect to 2010 (faster ramp and squeeze, more efficient injection, more robust operational procedures, etc.) enabled an better machine availability during physics production but also during MDs and commissioning periods.

Further improvements are possible in 2012. Assuming an operation at 4 TeV with β^* of 60 cm in the high luminosity points, we expect to achieve a shorter overall operation cycle than in 2012: about 1h30 instead than 1h45 in 2011. This will be achieved thanks to a better implementation for the compensation of the field decay at flat–top, to a faster pre–cycle and to a further optimized squeeze done in parallel for the four experiments. The main bottleneck will remain the injection process that only for few fills can be completed with a duration close to its minimum. Overall, it should be possible to achieved a turn–around times below two hours.

ACKNOWLEDGMENTS

The authors would like to kindly acknowledge the colleagues in the OP teams working on the LHC and its injectors and all the teams from the LHC accelerator system who participated to the LHC operation. G. Kruk, M. Lamont, G. Müller, M. Strzelczyk, N. Ryckx, J. Wenninger contributed significantly to the work on ramp and squeeze. Data on the fill statistics are provided by C. Roderik.

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