HOW TO IMPROVE THE TURNAROUND

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Abstract

After one year of operation in the multi-MJ stored energy regime, important operational experience has been gained on various aspects, with stable machine configurations (with fixed reference orbit, optics, collimator settings, etc.). In this paper, the analysis of operational efficiency in the standard operation cycle for physics fills is addressed and possible paths to optimize the LHC turn-around time are presented. The analysis is based on a critical look at the 2010 operational, aimed at identifying the bottlenecks of the present operational mode. Proposed improvements take into account the optimization of the machine cycle while respecting the appropriate boundaries from machine protection constraints and the operational flexibility required during commissioning. Specific aspects related to ramp and squeeze, with pro's and con's of alternatives of the run configurations tested so far, are also discussed.

INTRODUCTION

The 2010 LHC operation was an important success for the first physics goals but also for gaining operational experience. All the critical and complex operational phases were well under control to the extent that stable running conditions with highly automated sequences were achieved in the last months of run. Clearly, in this first operation year the focus was put on machine safety rather then on the optimization of performance aspects like the turnaround. On the other hand, the experience gained provides already an opportunity to look critically at aspects the can be improved for the 2011 operation. In this paper, after a brief introduction of the 2010 run configuration, the nominal LHC cycle is presented and all the relevant operational phases are described. An analysis of the time durations of the various phases during stable operation for proton and ion physics is carried out to identify the major bottlenecks for the turnaround optimization and possible improvements are proposed to optimize the 2011 operation. Before drawing concluding remarks, the possibility of combining ramp and squeeze is also addressed.

RUN CONFIGURATIONS AND APPROACH FOR DATA ANALYSIS

Run configurations in 2010

Figure 1 shows the integrated luminosity delivered in 2010 to ATLAS and CMS as a function of the LHC fill number during the proton operation. Three running periods can be identified [1, 2]:

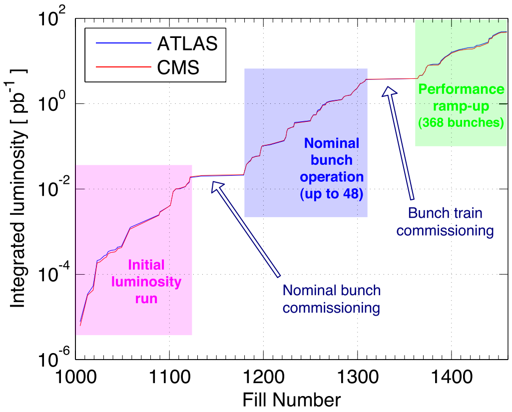

Figure 1: Integrated luminosity in ATLAS and CMS as a function of the fill number during the 2010 run. Courtesy of M. Ferro-Luzzi.

1. Initial luminosity run with reduced bunch intensities (up to 13 single bunch of a few 10^{10} protons);
2. Nominal bunch operation with single bunch injection (up to 48 bunches);
3. Nominal bunch operation with bunch trains (up to 368 bunches for physics fills).

The proton run was followed by a 4 week period of ion physics when the machine was operated in the same mode as period (3), with difference in the settings of crossing and separation in the interaction points (IPs) that are not relevant for the scope of the turnaround studies..

The transition between different periods was made possible through dedicated commissioning phases of the various systems, notably of the machine protection-related systems [1]. These transitions correspond to the flat lines in the delivered integrated luminosity plot of Fig. 1, which are all followed by a rapid increase of the luminosity.

Assumptions for turnaround analysis

The analysis of the turnaround statistics is focused on the proton run period (3) that led to the record performance of 25 MJ stored energy, with peak luminosities above $2 \times 10^{32}\mathrm{cm}^2\mathrm{s}^{-1}$ and on the ion run. This configuration is the most representative of the 2011 operation in terms of machine configurations (bunch train injections,

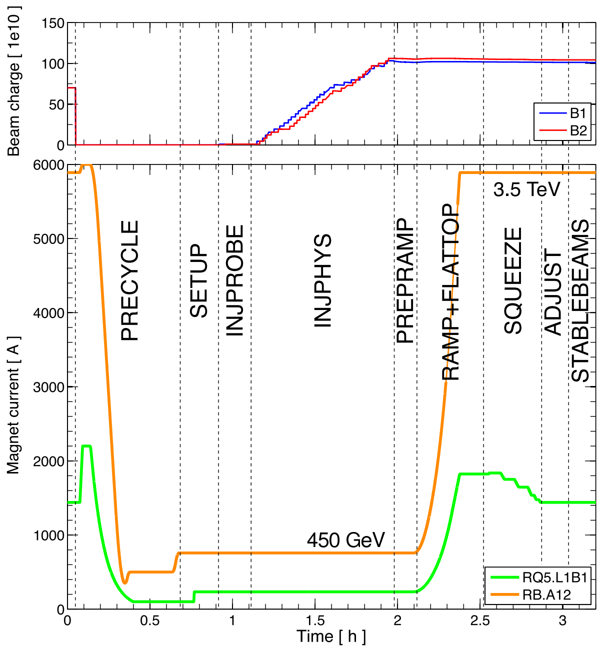

Figure 2: LHC turnaround cycle. Beam charge (top) and current of the main dipoles (orange) and of a matching quadrupole (green) are given as a function of time.

crossing angles, etc.), hardware parameters (nominal ramp rate for the main dipoles of 10 A/s) and beam parameters (single-bunch intensity, emittances, collimator settings, etc.). In addition, throughout the period (3) the parameters were kept constant with essentially no changes except the number of bunch trains injected, which makes a statistical treatment meaningful. The operational sequence had converged to a stable version with minimum manual action that will be used as a solid base for the 2011 sequence.

In the results presented here, only physics fills that successfully made it to physics are considered. The times spent in the various machine phases are calculated from the logged times of the beam mode [3] changes. This information is stored in the LHC logging database. This calculation is only precise to within tens of seconds to minutes, depending on the modes. This uncertainty occurs because some mode changes are not all done in an automated way but still rely on manual executions of sequences. This small error is not relevant for the total turnaround time estimate.

Note that the analysis of system faults and of machine availability is not treated here (see [4]). Additional aspect related to specific improvement for 2011, also affecting the machine turnaround, are discussed in [5].

LHC OPERATIONAL CYCLE

The different phases of the LHC operational cycle, from a top-energy dump to the next "stable beams", is illustrated in Fig. 2. The "stable beams" mode is declared for experiment data taking after the beams are put in collision and does not require further manipulation other than the fine optimization of the collision point. In Fig. 2, the beam intensity (top) and the current of main dipoles and a matching quadrupole, which shows when the squeeze takes place, are given as a function of time. The vertical dashed lines show illustratively when the mode change took place during the cycle. Here, the list of machine phases considered differ slightly from the official mode definition [3].

The minimum time for each mode, calculated with the 2010 parameters, are listed in Tab. 1. Note that the theoretical minimum are in some cases smaller than the ones that were possible in 2010. For example, longer than nominal SPS cycles are required to perform injection quality checks and therefore a $\approx$50 s long cycle was used instead than the minimum of $\approx$18 s (see [6] for possible improvements). In this paper, the parameters of 2010 are taken as a working assumption.

Table 1: Minimum times for the machine phases with the 2010 parameters.

Machine phase	Time [s]
Pre-cycle	2100+300[#]
Inject probe	300
Inject physics	1900 (=50×38)[+]
Prepare Ramp	120
Ramp	1400
Flat top	60
Squeeze	1041
Prepare collisions	108
TOTAL	2h00

[#] An additional time of 300 s must be taken into for a discrete current trim that brings the circuits to the maximum current. Also note that, if a standard precycle starting from zero current has to be performed instead than the recovery precycle from top energy, the total precycle time becomes 3100 s.

[+] Approximate figure for the maximum number of injections used in the 2010 (38) and for a 50 s long SPS cycle.

ANALYSIS OF 2010 STATISTICS AND POSSIBLE IMPROVEMENTS

Overall turnaround performance

In Fig. 3 the distribution of time intervals between beam dump at top energy and following stable beams is given. Blue and red bars correspond to the different ramp rates used in the running period (1) and (2), i.e. 2 A/s, and (3), i.e. 10 A/s. Only the proton fills are considered. The best turnaround times are 3h40 and 2h45, respectively. Even in the best cases, this is at least 45 minutes above the theoretical minimum achievable with the 2010 parameters (Tab. 1). In Tab. 2 the average time duration of the key phases of the LHC cycle is given for the proton run period (3) and for the ion run. The data are given also in the bar chart of Fig. 4. Error bars are large is some cases but the average values give a good indication of where time was lost.

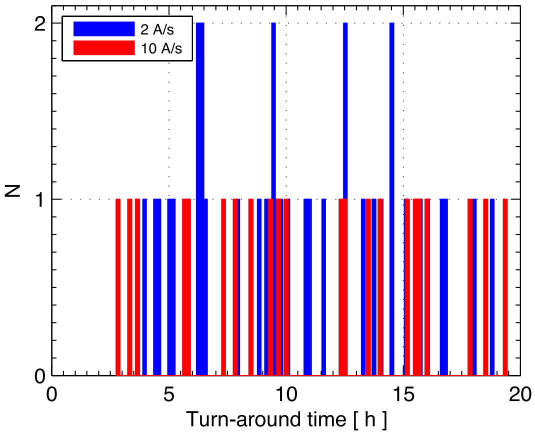

Figure 3: Distribution of turnaround times for proton physics fills, calculated as difference between time of the "stable beams" start and time of the previous beam dump at high energy. The fastest times to re-establish stable beams were 2h45 for the 10 A/s ramp rate and 3h40 for 2 A/s.

Table 2: Average times spent in the different operational phases (physics fills only). One standard deviation of the time distributions is given as error estimate.

Machine phase	Proton run (3) Time [h]	Ions Time [h]
Injection	3.0 ± 2.8	2.6 ± 2.4
Prepare Ramp	0.14 ± 0.09	0.10 ± 0.05
Ramp	0.43 ± 0.08	0.43 ± 0.03
Flat top	0.13 ± 0.18	0.05 ± 0.04
Squeeze	0.56 ± 0.18	0.43 ± 0.05
Prepare collisions #	0.22 ± 0.12	0.25 ± 0.08

For ions, the functions to collapse separation and set the collision crossing angles were 180 s long instead than 108 s for protons to allow larger angles in ALICE.

In the following sections, the different machines phases are analysed separately to understand the address the different sources of efficiency reduction. It is worth noticing that the overall performance is actually a good achievement for the first year of operation of a machine of the complexity of the LHC.

Precycle and setup without beam

After a beam dump at top energy, the LHC magnets are precycled. If there are no errors that required resetting the converters, the previous ramp is used as a part of the precycle and the magnets are brought to the injection values in an appropriate and controlled way [7]. This is the case for the example of Fig. 2. In case of errors, a precycle that starts from the minimum power converter current has to be used, which takes 3100 s instead than 2100 s. For both cases, additional ≈ 300 s must be taken into account to bring the converters to the first point of the functions.

The precycle length is by far sufficient to prepare the machine for the next injection, which includes verification of settings, conditioning of injection kickers, driving collimators to injection settings, performing the injection handshake, RF synchronization, etc. No improvement of the setup time is therefore easily possible unless the hardware parameters of the superconducting circuits are changed, which is not addressed in this paper. The nominal sequence is being improved in order to ensure that actions that can be run in parallel are done by the LHC sequencer in order to minimize the risk of human error while remaining in the shade of the magnet precycle.

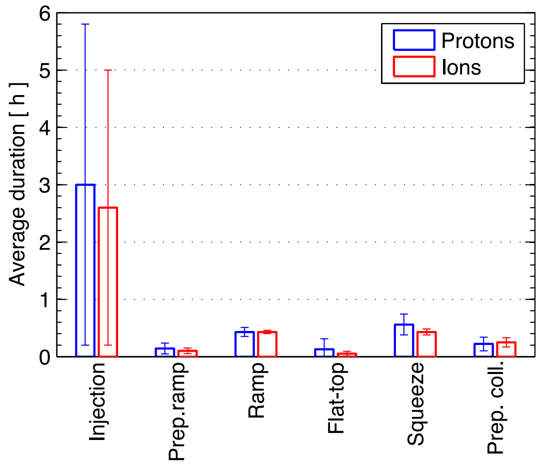

Figure 4: Bar chart of the data of Tab. 2.

Injection

The distribution of times required for injecting physics fills, calculated as the sum of setup time with pilot beams and of physics beam injections, is shown in Fig. 5. The minimum time (dashed red line) is calculated for the case with the largest number of bunches (368) and hence it is a pessimistic estimate. Nevertheless, the achieved values are well above this minimum value, with an average of 3 hours (with a large spread). Even if one excluded cases above 5 hours that might indicate specific and severe problems, the typical injection times range between 1 and 4 hours. There is obviously room for improvement so it is necessary to review the reasons that caused loss of time.

Without going into the details of the problems encountered, which are treated extensively in other papers of this workshop [8, 9, 6], the main sources of problems are listed below with possible paths for improvements:

- *Problem*: Injection losses (1) on the collimators at the end of the lines seen by the LHC BLMs and (2) on the superconducting triplet and on the tertiary collimators caused by uncaptured particles kicked by the injection kickers.
  Possible improvements: addressed in detail in [8, 9]. Ideally, one should be able to mask the beam loss signals at injection to avoid interlocks (*sunglasses*).

- *Problem*: Long setup times of the LHC beams in the

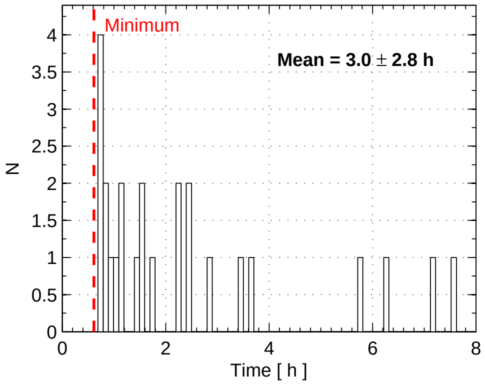

Figure 5: Distribution of times spent for injecting fills for physics, calculated as the sum of the times required for setup with pilot beams and of the physics beam injections. The red dashed line represent the minimum injection time calculated for fills of 368 bunches.

injector, primarily caused by the complexity of the many parameters to optimize (transverse and longitudinal blow-up, bunch intensity, tails scraping, etc.) [10].
Possible improvements: Procedures should be established to make sure that the beam setup in the injectors is completed timely during the recovery after a beam dump. Ideally, if agreed by the physics coordinators, one could consider to check the beam availability/quality before dumping the LHC beams in order to exclude major faults in the injector chain. A more efficient communication with the operation crews of the injectors is needed. The setup time would also profit from shorter SPS cycles (see next item).

- *Problem*: Long reaction times of the Injection Quality Checks (IQC) that stops the injection requests for both beams if either beams has errors, with subsequent loss of 1 to several SPS cycles.
Possible improvements: the injection request for one beam should be separated from the IQC results of the other beam (as it is for the software interlocks already) to allow continuing alternates injection while the IQC of the other beam is reset.
IQC thresholds should be adjusted to reflect real problems, e.g. requiring the expert intervention. In 2010, often the injection were blocked by conditions detected as problems that could simply to be ignored to continue the operation.
In addition, the time for the IQC analysis should be reduced as much as possible because in 2010 this was the reason to use long SPS cycles.

- *Problem*: Failing over-injections implying loss of the pilot beam, which the require restarting the injection procedure with several change of users for the injectors.
Possible improvements: The causes of this problem are several and cannot be fully excluded. It is recommended to leave a slot for witness pilot beams in the physics beams or to over-inject onto the pilot at the second injection such that a failing injection of the first high-intensity beam will not affect the circulating pilot. One should also consider the possibility to have an SPS cycle with pilot and physics beams to avoid frequent changes [6].

- *Problem*: Lengthy setup times with pilot beams before establishing reference orbit, tune and chromaticity.
Possible improvements: Tune and chromaticity reproducibility would profit from preventive trims that take into account the multiple decay as a function of the time spent at injection current [11]. These types of trims have be done manually in 2010 and should now be incorporated in the LHC sequence.

- *Problem*: Poor quality of the injected beams, e.g. missing or excessive scraping, unequal bunch intensities or emittances, etc., which occasionally required to dump and re-start injection in the LHC.
Possible improvements: The SPS BQM [10] detect efficiently longitudinal problems and prevents injections of poor quality beams. One should consider similar checks for the transverse parameters. For the moment, checks can only be done manually by disabling the SPS extraction with the hardware button, which is clearly not efficient nor error prone.

- *Problem*: Several iterations required to converge with the RF loops. Time was lost for the setup of the synchro loop also because the energy of the injected beams was mismatched from the reference orbit energy.
Possible improvements: The operation crew must be provided with sensitivity tables for the energy trims needed to correct synchro loop errors and with detailed procedures and tolerances that clarify when corrections are needed (this was often left to the choice of the shift crew). Ideally, the reference orbit should have the same energy as the injected beams. Differences should be corrected with the orbit correctors instead of with frequency trims (implementation is ongoing [12]).

In addition, if the need for frequent entries of snapshots remain actual for the 2011 operation, it is suggested to make available tools for automated entry of images into the operational logbook because this cause losses of time.

Preparation of the ramp

The distribution of times spent preparing the ramp is given in Fig. 6: the average time is slightly above 8 minutes, with several cases above 15 minutes. Special care in this phase is justified because mistakes leading to a beam dump after the start of the ramp functions would cause a

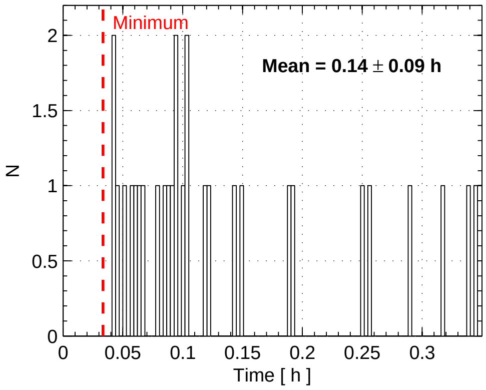

Figure 6: Distribution of times spent for preparing the energy ramp.

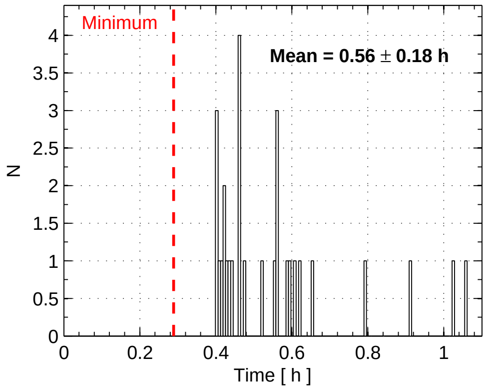

Figure 7: Distribution of times spent for betatron squeeze.

loss of several hours. On the other hand, improvements are possible.

In order to prepare the energy ramp, the operation crew has to verify orbit, tune and chromaticity, switch ON orbit and tune feedback, incorporate the injection trims into the ramp functions, secure the injection kickers (MKIs) and then open injection collimators, close the injection handshake and load ramp functions for power converters, RF and collimators. A number of checks are also performed before triggering the ramp. Strictly speaking, only the movement of injection protection, the preparation for the MKIs and the load of ramp functions must wait until the end of the injection.

It is recommended to start the orbit and tune feedbacks during injection: this would allow the OP crew to keep the parameters constant without need of further trims and thus to anticipate the setting incorporation. Some care must be taken in switching ON the radial feedback only at the end of injection because it has to be kept OFF during injection in case of energy differences between injected beam and reference orbit for the ramp.

Energy ramp

The energy ramp is performed with functions of well-defined length and there is no way to improve the ramp time without changing the hardware parameters of the main dipole circuits or to change the setting generation [13]. As the maximum ramp rate of 10 A/s is only obtained for about 20 % of the ramp time after a gentle start with parabolic and exponential shape, work is ongoing to speed-up the initial part of the ramp functions [14].

After the energy ramp to 3.5 TeV (1020 s), a flat branch of 380 s is used to compensate the decay of orbit, tune and chromaticity: feedbacks are left ON while the fields decay after having reached the energy and a feedforward correction of the chromaticity is applied. The length of this branch was determined empirically and it will be reviewed with the new ramp functions in order to see if some time can be gained there.

Flat top

After the end of the ramp function execution, a flat top setup is dedicated to the preparation for the squeeze: orbit, tunes and chromaticities are checked, the reference for the feedbacks are updated if necessary and the end-of-ramp settings are incorporated into the squeeze functions. This phase took 8 minutes with a couple isolated cases above 30 minutes. Theoretically, all this preparation could be done during the ramp: the experience with the operation in stable machine configuration showed as good reproducibility at top energy so no trims are usually required.

Changes of the orbit reference were still needed due to a change of crossing angle settings performed during the first part of the squeeze. Minor differences between orbit at injection and at top energy were also often seen because of the reference used for different collimator setups. For the 2011 operation, focus should be put in establishing one common reference to be kept throughout ramp and squeeze.

Squeeze

The execution of the betatron squeeze is done like the energy ramp by executing functions of a well-defined time length. Stops in two points were needed at intermediate β^* values in order to (1) change the orbit feedback reference for a reduced crossing angle configuration and to (2) close the tertiary collimators to their protection settings (one step movement done at $\beta^* = 7$ m). These stops at intermediate points were done by loading parts ("segments") of the functions [15]. This mechanism was fully implemented in dedicated sequences. As shown in Fig. 7, the total time for the squeeze took in average twice the theoretical minimum of 1041 s that one would get by running continuously the functions without stopping. The squeeze required longer time than the energy ramp (Tab. 2).

It is interesting to note that the time lost at the stop points has been reduced as the operational experience improved (see Fig. 8). This performance improved further during the ion operation (Tab. 2) thanks also to an improvement of the sequences and to the confidence gained by the operation

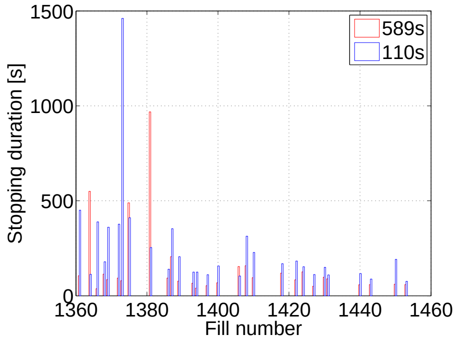

Figure 8: Time lost at the squeeze stop points as a function of the fill number. Courtesy of X. Buffat, EPFL.

crew.

Even if the time lost due to stop points is moderate compared to other phases of the operation, this mode of operation of the squeeze was often source of human errors, in particular for the feedback setting change. The manual manipulations combined with some issues with the implementation of the set of feedback reference caused several mistakes that led to beam dumps. An important goal for the 2011 operation will be to run the squeeze functions through without interruption. This can only be achieved if the feedbacks will be modified to to accept time-functions as reference, both for orbit and tune values (first implementation tested already in 2010).

The squeeze performance was also improved by feedforward corrections of the tune and by regular coupling compensation [16]. Coupling is particular important for the operation of the tune feedback because it can compromise its performance if not controlled better than 3 % of the tune split of 0.01. Feedforward correction are important to reduce the dependence on the feedbacks and should therefore be applied regularly in 2011.

Work is ongoing to improve the time length of the squeeze functions by optimizing the number of intermediate matched points that presently are being stepped trhough. Preliminary results indicated that at least 5 minutes could be gained while keeping the relevant beam parameters under control. Final results will be available by the end of January 2011.

Preparation of collisions

In this phase, the parallel separation of the counter-rotating beams is collapsed to establish collisions and at the same time the knobs for the optimization of the collision point are ramped to the values of the previous fill. At the same time, the tertiary collimators in all IPs follow the local orbit to maintain optimum settings all the time. This is achieved in mode “ADJUST” and the minimum time for the function execution was 108 s (180 s for ion with larger crossing angle change), limited by the ramp rate of the orbit correctors in the IPs. On average, this phase took took 13 minutes.

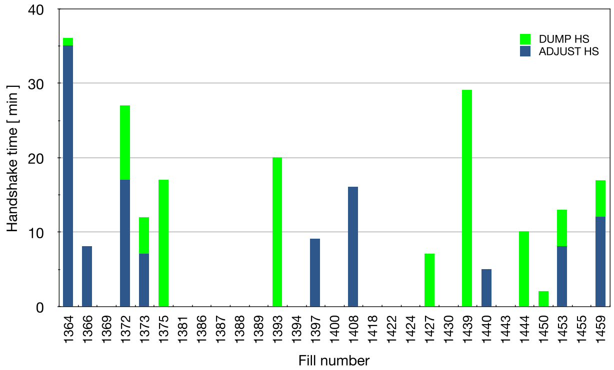

Figure 9: Duration of the dump and adjust handshakes as a function of the fill number for the physics fills of the proton running period (3). Fills with no data were ended by emergency dumps. The durations given here are calculated from the automatic handshake entries in the LHC OP logbook.

A way to improve this phase will be to reduce the parallel beam separation during the energy ramp. For beam-beam constraints, the separation at the IP’s could be reduced proportionally to the square root of the beam energy, which would yield a 700 μm separation at 3.5 TeV for the nominal separation of 2 mm at 450 GeV. A linear variation of the separation versus time during the ramp will be implemented in the orbit feedback for the 2011 operation.

Closure of the dump handshake

The dump handshake [17] is a protocol used to communicate to the experiments an upcoming *programmed* beam dump request. According to the present procedure, a dump can only be made after all the experiments have successfully responded to the handshake. On the other hand, safety conditions are fulfilled all the time because unforeseen emergency dumps can occur anytime. Indeed, a significant fraction of the physics fills was ended by dumps triggered by the machine protection system [18], with no problems so far. An adjust handshake is used to exit from the stable beams mode while keeping the beams in the machine, typically for end-of-fill studies.

The times required for the dump and adjust handshakes of the fills under consideration are given in Fig. 9. Fills with no data represent cases of emergency beam dumps without handshake. Blue and green bars are added in case both adjust and dump handshakes took place for the same fill, for example if an end-of-fill study that required the adjust mode took place. Typically, the dump handshake takes less time if done after the adjust handshake. Up to 30 minutes could be lost due to punctual problems with some of the experiments. For 2011, the need for dump handshake has been questioned. The argument is that the experiments might loose precious time of data taking if they respond promptly to the handshake request and switch OFF sensitive equipment while other experiments have problems that block the handshake closure and hence delay the beam dump. The possibility to skip or revise the procedure for the dump handshake is being addressed.

Miscellaneous

It is recommended to establish clear procedures for the beam measurements at top energy: a homogeneous approach should be agreed upon about the need of chromaticity measurements (after the ramp and before bringing the beams in collision) and about the set values. Measurements can be time-consuming at top energy and are not completely risk-less so the choice should not be left to the people on shift.

It appeared clear that the tools to address operational statistics are not adequate (see also [4]). This problem should be addressed consistently. More automated changes of the beam modes are also to be envisaged because in some cases they are still not done homogeneously by the different shift crews.

It is noted that the fill number is changed during the machine setup before the injection. This complicates significantly the analysis of the fill statistics because the setup time belongs to the previous fill. It is therefore proposed to change the fill number immediately after the beam dump.

A LOOK AT ION OPERATION

The 4 weeks of ion operation that followed the proton run provided a good playground to test some of the improvements that were identified for protons. Magnetically, the machine behaved essentially in the same way as for protons and the proton sequence could be used with minor changes. The improvements can be summarized as:

- The filling scheme did not require over-injection nor change of the SPS cycle as the pilot used for injection setup was part of the physics scheme (same intensity). This improved as expected the problem with the missing extraction from that SPS that often kicked out the pilot for protons. The other issues related to the injection remained (except for the intensity related ones).

- The sequence improved further the automatization of some manipulations, like the change of tune feedback reference (only checks were available for the proton run).

- The learning curve for the squeeze continued and the time lost at the stop points was reduced by more than 20 % with respect to the proton run (Tab. 2).

- Improvement of the nominal sequence to execute in parallel the tasks that can be done without beam during the precycle.

Other than these improvements, the issues and limitations discussed for protons remained similar and the conclusions of the ballpark figure are the same.

COMBINING RAMP AND SQUEEZE

Ideally, one could optimize the LHC cycle length and virtually reduce to zero operational mistakes by driving the machine through one continuous function for ramp, squeeze and collisions. The time gain would be of about 0.5 h if the average figures of Tab. 2 are considered. From the beam physics point of view, the 2010 experience indicates that this could be achievable considering the machine reproducibility and the performance of the relevant systems (rarely trims were required in standard operation with feedback operational). On the other hand, this approach would also require more pilot fills to optimize the machine, as all the systems will be fully frozen in the standard operation while playing one long function. Essentially, much of the present operational flexibility would be lost. A very efficient method to stop when desired must be put in place (most likely, with different sequences than the nominal one). The total gain in time must therefore be evaluated and is not given for granted. New software implementation would also be required (1) for the generation of settings for combined functions and (2) for breaking in segments critical limit functions for the collimators. This implementation cannot be started timely for the 2011 because more urgent actions were identified.

For similar arguments, the possibility to perform (part of) the squeeze during the energy ramp is also considered a pre-mature option, in particular taking into account the fact that the most critical squeeze steps at low β^* can only occur at top energy due to aperture consideration. The price for a limited gain in time will be a loss of flexibilty that we still plan to profit from in 2011.

Having said that, it is clear that these two options (continuous functions for ramp, squeeze and collisions and combined ramp and squeeze) remain very promising and will be pursued. The implementations required will be followed up during 2011 with the aim of testing the new schemes in dedicated MDs to address their feasibility and the potential gains.

CONCLUSIONS

The analysis of the different LHC cycle phases during stable operational periods of the 2010 operation has been used to identify bottlenecks of the machine turnaround and possible improvements for 2011. Even if the 2011 performance is outstanding for the first year of operation of a machine of the complexity of the LHC, it is clear that there is a lot of room for improvement. The turnaround time is often dominated by the injection process, which can be improved in many respects. The gain from other machine phases can realistically sum up to 0.5-0.8 h, driven by a further improvement of the actions that for the moment are still relying heavily on manual operations. Paths for improvements have been drawn for all the phases.

Even if additional improvements could be achieved with more aggressive approaches, such as continuous and/or combined functions for ramp, squeeze and collision, these solutions seem still premature at this stage of the LHC commissioning and will be addressed after having improved the turnaround in the present mode of operation. The benefits do not seem yet to compensate the reduction of flexibility that will be imposed. These solutions are nevertheless being followed up for MD studies.

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