# STRATEGY FOR THE FIRST TWO MONTHS OF THE LHC BEAM COMMISSIONING AND KEY EARLY MEASUREMENTS

S. Redaelli, G. Arduini, M. Giovannozzi, M. Lamont, R. Tomás, J. Wenninger
CERN, Geneva, Switzerland

*Abstract*

The LHC beam commissioning in 2015 will be based on the experience accumulated during Run 1 and on scenarios further developed during LS1. On the other hand, the operation at higher energies and with different bunch spacing will pose new challenges and will require additional measurements to be carried out in earlier commissioning phases. The commissioning plans for the first months of operation, until the establishment of first stable collisions, are discussed and the required key measurements with beam are presented. The additional requirements for systems that underwent significant upgrades or changes during LS1 are also taken into account.

## INTRODUCTION

At the start-up of the Large Hadron Collider (LHC) in 2015 after the Long Shutdown 1 (LS1) the setup of the first "stable beams" at energies close to 7 TeV will represent an important beam commissioning milestone. This is the machine mode when the LHC experiments are allowed to be fully switched ON and to acquire data from collisions. This condition is met when, amongst others, the machine protection validation is completed for all configurations of the operational cycle. Indicatively, two months of beam time are allocated in the 2015 LHC schedule until first stable beams [1].

The validation of a machine configuration entails a lengthy series of measurements that culminate with the complete set of loss maps and asynchronous dump tests to demonstrate that the machine elements, as well as the experiments, are protected for the relevant loss and failure cases. If this validation is successful, the following commissioning step consists in the beam intensity ramp-up until the maximum number of bunches is achieved. Otherwise, key parameters such as aperture and $\beta^*$, collimator settings, crossing angles for an assumed emittance, have to be reviewed.

It is crucial that these key parameters are finalized in the first commissioning phase, before proceeding with the intensity ramp-up: later adjustment of beam and machine parameters would be very costly in terms of commissioning time and should be avoided. Thus, one important goal of the initial commissioning is to make the necessary measurements to ensure that, within the given uncertainties, an adequate set of key parameters is chosen. An optimum trade off between peak performance and commissioning risk must be found, taking into proper account the operation experience of the LHC Run 1 and the uncertainties for the post LS1 conditions (e.g., beam energy, 25 ns spacing, electron cloud, etc.). While it is clear that some limitations can only become apparent at high intensity, we propose a set of measurements that can provide feedback on the choice of $\beta^*$ for physics early on.

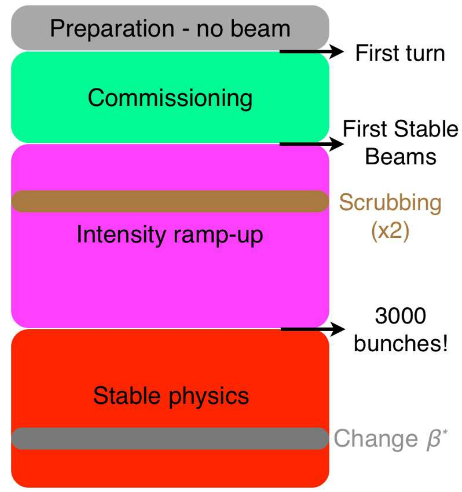


Figure 1: Illustrative view of the 2015 commissioning strategy. Beam commissioning with individual bunches is followed by an intensity ramp-up before achieving a period of stable physics operation without further modifications of the number of bunches. The proposal of changing $\beta^*$ after a period in physics is envisaged.

In this paper, a first look at plans and measurements of the initial commissioning phase until the first stable beams is presented. Rather than outlining the detailed commissioning steps as established in previous operational runs, focus is given to the new commissioning requirements that are consider necessary in order to face the challenges of the operation at higher beam energies and intensities. After recalling the baseline commissioning strategy and the relevant input from the experience in Run 1, important system changes affecting the commissioning plans are presented. First ideas of commissioning requirements are then collected.

Two extreme commissioning approaches might be envisaged: (1) achieve the smallest $\beta^*$, computed as ultimate limit under the assumption that the LHC works as well as at the end of 2012 or (2) relax the beam parameters to minimize the risk of instabilities and machine protection constraints, at the expenses of $\beta^*$, e.g. opening collimation hierarchy and increasing $\beta^*$. Detailed scenarios are worked out in [2], where a proposal is made for the $\beta^*$ value of 65 cm at 6.5 TeV in the high luminosity points. This is assumed as baseline.

## OVERALL COMMISSIONING STRATEGY

A very simplified view of the 2015 proton run commissioning outline is illustrated in Fig. 1. The detailed LHC schedule taken as a baseline at the time of this workshop was presented in [1]. The start of beam commissioning is foreseen at the beginning of February 2015 and about two months are allocated to produce the first stable beams. Following a hardware commissioning and cold checkout period, the initial phase aims at establishing the first stable beams with a few colliding bunches at 6.5 TeV. This is followed by an intensity ramp-up period aiming at setting up the maximum number of bunches at 25 ns bunch spacing (with the option of switching to a possible fall-back scenario at 50 ns in case of severe issues with the 25 ns spacing). Two beam scrubbing periods are planned in this phase to prepare the machine for the 25 ns operation [4]. The initial ramp-up of intensity, by means of increasing the number of bunches, will be done at 50 ns, before continuing at 25 ns. Stable beams will be regularly declared in the ramp-up phase, while gaining experience in handling larger and larger stored beam energies. The machine will then enter a period of stable physics runs at high intensity. Adiabatic improvement of parameters like bunch intensity, bunch length and emittance will take place with the maximum number of bunches, without major changes of machine configuration.

The possibility to consider a re-adjustment of $\beta^*$ after an appropriate time of stable physics is also proposed. A similar approach was adopted during the 2011 operation, when the $\beta^*$ was squeezed from 1.5 m to 1 m in September [3]. This proposal is being evaluated, taking into account the experiments' requests [5]. The advantage of this approach is that one could start with relaxed parameters until sufficient operational experience is accumulated on machine and optics stability, available aperture, beam losses, impedance and beam-beam instabilities etc. The $\beta^*$ would then be squeezed further by precisely targeting a more performance-oriented parameter set. Such an approach would have to be prepared early on, e.g., with optics preparation in the first commissioning phase, to minimize the impact on the duration of the recommissioning period (see below).

The detailed discussion of the initial commissioning steps is not reviewed in this paper. The operational experience of Run 1 provides a mature baseline that makes us confident that the standard phases [6](first threading, beam capture, beam diagnostics commissioning, initial orbit and optics checks, polarity checks; setup of feedback systems, collimation, RF, injection, LBDS, BI, etc.; detailed optics measurement and correction, aperture, ramp and squeeze, collisions, etc.) can be addressed successfully. Adequate commissioning time will have to be allocated to cope with the system changes and upgrades that occurred in LS1 and new requirements for the commissioning at a higher beam energy, as discussed below.

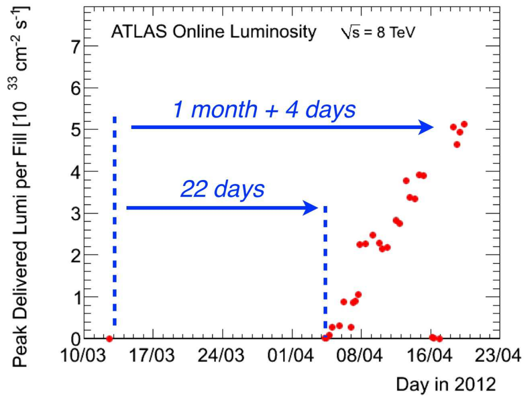


Figure 3: Luminosity versus time as recorded in ATLAS in the first weeks of the 2012 run. Courtesy of the ATLAS collaboration.

## RELEVANT INPUT FROM RUN I COMMISSIONING EXPERIENCE

The key milestones of the first weeks of operation in 2012 are illustrated in the diagram of Fig. 2. The first stable beams were achieved only 22 days after the beginning of beam commissioning. A record intensity ramp-up took then place, completing the increase in number of bunches – 1380 at a 50 ns spacing – eleven days after. This is also illustrated by the graph of peak luminosity recorded in ATLAS, see Fig. 3, which reached 80 % of the typical operational values in 2012 only about one month after the start of the beam operation.

In the attempt to identify key ingredients for this outstanding operational achievement, one could point out that, amongst others:

– The commissioning effort was focused on high-intensity proton operation. Set up of special runs was left for later phases.

– A minimum number of hardware changes to the key accelerator systems had occurred compared to the 2011 run.

– Up to 3 nominal bunches at top energy were within the safe limit for machine protection. This eased and made more efficient several commissioning procedures.

These aspects come in addition to the excellent performance of the accelerator systems, which were very efficiently commissioned thanks to the experience accumulated until 2011. This will likely not be the case at the start-up in 2015 due to the LS1 activities.

The careful choice of 2012 machine parameters was based on a solid knowledge of the LHC and of the accel-

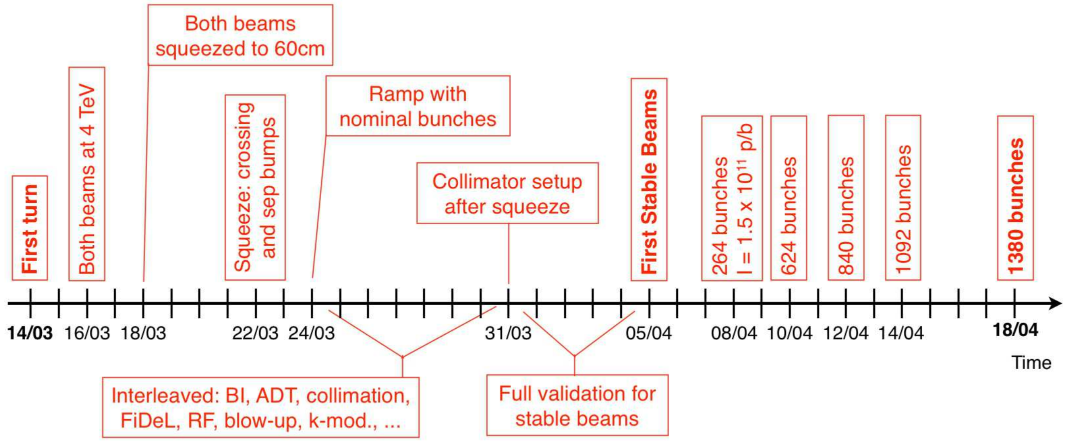


Figure 2: Dates of the main commissioning milestones that led to the first stable beams in 2012 and to record intensity ramp-up from a few bunches to the maximum 1380 bunches for the high-intensity proton operation.

erator systems. For example, the triplet aperture was predicted [7] within 0.5 beam sigmas and the beta-beating errors were kept below 10 % [8]. For 2015, the machine has to be considered as brand new under several aspects due to the long stop of about 2 years. Other uncertainties also apply, like the reproducibility of the machine aperture after having opened the vacuum and the behaviour of magnets at 6.5 TeV and of beam losses and beam instabilities at higher energies.

The machine protection aspects pointed out in the list above should not be underestimated. At 4 TeV, 3 nominal bunches were still below the safe limit. This allowed an efficient setup of the collisions in all interaction points and in some cases allowed speeding up the validation (transverse loss maps followed by asynchronous dump tests in the same fill). At higher energy, operational efficiency might in some cases be reduced if validations have to be split over several fills.

## SYSTEM CHANGES AND REQUIREMENTS

The hardware changes that have taken place during LS1 and the corresponding new system requirements were the subject of two sessions at this workshop that addressed status and commissioning plans of various key systems, see for example [9, 10, 11, 12, 19]. It was pointed out that important upgrade of the systems will need adequate recommissioning time. Some key points are recalled, leaving the details for the quoted references.

– Injection and dump systems [12]: new hardware will be used for the TDI and TCDQ protection blocks; new interlocks on the TDI and TCDQ, based on hardware implementations into the BETS, will be deployed; dedicated beam measurements are requested for the TDI heating; measurements done at the beginning of Run 1, such as wave form scans and kick response, are planned to be repeated.

– Collimation [11]: 18 new devices with in-jaw BPMs have been installed and 8 new IR collimators will need to be commissioned. The new BPM functionality will need dedicated time from the collimation and BI teams.

– Beam instrumentation [14, 15]: there will be new beam size measurements, new BLM layout (note in particular the addition of LIC's in the injection regions [12]).

– The FiDeL model will have to be assessed for the new pre-cycle. Saturation effects in the magnet yoke will become relevant for the first time and should be take into account.

– RF: several hardware and software changes occurred for the main RF system as well as for the transverse damper, see [9, 10, 16].

This list is not exhaustive but reflects a selection of topics that were discussed at this workshop. Note that the LBOC and LMC panels are in the process of reviewing in detail each accelerator system. A complete list of system requirements will be re-assessed and put into a coherent beam commissioning plan.

The experiments presented their views and wishes for the start-up [5]. One important requirement is to prepare early on various special physics runs such as the ones for Van Der Meer scans and for the LHCf data taking. Contrary to the case of Run 1, these activities now require different optics with respect to the physics and flat-top optics of the standard operation cycle. The impact of this requirement on the commissioning time should not be underestimated as it will add new constraints and requirements, like additional optics measurements and machine configuration validations, in a phase when the operational experience will still be limited.

Other important scenarios under discussion are the luminosity levelling with $\beta^*$ and the squeeze with colliding beams [17]. Both have important impact on the commissioning strategy. This topic is not addressed in this paper as at the time of the workshop a decision on these scenarios was not yet reached.

It is assumed that the operational cycle in 2015 will be as the one in Run 1: the squeeze is performed at constant energy with separated beams; collimators in cleaning (IR3/7) and dump (IR6) insertions are closed to their final settings during the ramp, then only collimators in the experimental regions are moved during squeeze and collision setup; luminosity levelling in IR8 is performed with beam-beam offsets. Impact on commissioning strategy will have to be quantified.

## 2015 BEAM MEASUREMENTS AND "DECISION POINTS"

In addition to dedicated commissioning time for hardware changes and for fulfilling new requirements, additional measurements are proposed. These are measurements that were not part so far of the initial beam commissioning but are now considered crucial to validate early on the choice of machine configuration parameters. It is proposed to define several "decision points" in the commissioning plan when the choice of parameters is re-assessed before moving to the next step.

- ◇ **IR aperture at injection**: the Run 1 experience has shown that IR aperture measurements at injection can already provide solid extrapolations for the $\beta^*$ reach [18]. The IR aperture at injection was only measured systematically in the 2009 pilot run. This should be now part of the commissioning and take place as soon as the reference orbit at injection is established (corrected orbit and optics with nominal bunch intensities).

- ◇ **Dedicated local orbit and optics correction in the IRs**: Dedicated time to establish local corrections of orbit and optics around the experiments are essential to provide feedback on the feasibility of various scenarios like $\beta^*$ levelling. Comapred to what was done in the past, addition care should be taken to ensure that non-local transients are minimized (e.g., orbit leakage around the ring while changing IR8 $\beta$).

- ◇ **Collimator impedance with single bunch**: One important question that could not be solved during Run 1 is the role of collimation impedance on the instability observed in 2012 [19, 20]. Early measurements with nominal single bunches should be carried out with high priority to identify potential impedance issues for different collimator settings [2]. It should also be mentioned that there are proposals for collimator settings for reduced impedance with acceptable losses of cleaning [21]. These configurations should also be addressed. Additional monitoring of the system cleaning performance should also be envisaged.

- ◇ **Stability of orbit and BPM signals**: reproducibility and stability of the machine are crucial inputs for the tolerance margins used to define the achievable $\beta^*$ and should thus be monitored regularly. This include dedicated orbit measurements with the new DOROS acquisition system.

Additional decision points that can only be addressed during the intensity ramp-up phase are: multi-bunch impedance and beam-beam effects (for possible iteration on crossing angle values), two-beam effects and octupoles, monitoring of machine stability and UFOs. The topic of electron cloud effects is discussed in other contributions to this workshop [16]. Nevertheless it is clear that the outcome of scrubbing runs will be also crucial input in the decision-making process.

In addition, new measurements requirements are

- ▷ **Chromaticity measurements in different conditions**: Regular chromaticity measurements should be performed to assess the accuracy of the measurement and the reproducibility of the chromaticity along the cycle. These measurements should be repeated in case settings are changed that are expected to affect chromaticity (e.g. octupole settings).

- ▷ **De-tuning versus amplitude and MCO/MCD settings**: Dedicated tests with octupole and decapole correctors are considered mandatory in order to establish clean conditions for the later setup of Landau octupoles. Although in principle the set values should compensate the predicted errors in the main dipoles. the models of de-tuning with amplitude at 450 GeV were not fully understood in Run 1. The deployed settings might have played against the Landau octupoles.

- ▷ **Optics measurements and corrections down to 40 cm**: As discussed above, a recommissioning of the optics after a period of stable physics conditions can only be deployed efficiently if the optics measurements and correction of the target $\beta^*$ are prepared earlier on. Commissioning down to 40 cm represents a small overhead in time if done during the squeeze setup.

- ▷ **Aperture verification with squeezed beams** should be performed for all $\beta^*$ values reached in the commissioning in order to have all required information.

There is a proposal to use from start-up the pre-squeeze optics of the Achromatic Telescopic Squeeze (ATS) [22]. This optics changes the phase difference between beam dump kicker in IR6 and super-conducting triplet in IR5. In particular, the case of B2 is unfavorable because a phase difference close to 90 deg between dump and the right IR5 triplet is foreseen. This optics, which is being validated under different aspects [23], will require dedicated loss maps and validation tests to probe the triplet protection.

## CONCLUSIONS

Initial thoughts on the first commissioning plans for the LHC Run 2 were presented, addressing the requirements for the first weeks of beam commissioning until the setup of first stable beams is accomplished. In the presence of various uncertainties on the expected performance of the LHC at energies larger than in Run 1, we considered that important goals of the first beam commissioning will be to validate the proposed machine configuration and ensure that the choice of parameters is adequate for the intensity ramp-up in 2015. While several key validations will only be possible later on, during the commissioning of the 25 ns beams, we proposed a number of measurements that can already provide important feedback in earlier commissioning phases, when changes are still possible without major overheads. Other than these additional "decision points", the commissioning will follow the very mature experience of Run 1. Clearly, changes occurred in LS1 must be taken into proper account.

Taking all these constraints into account, and the additional requirements from the experiments that require early on the preparation of various special runs, we consider that the two months scheduled to achieve the first stable beams in 2015 are probably feasible but certainly challenging, even if the LHC will work equally well as in 2012.

A possible way to achieve an efficient commissioning while ensuring a good yearly luminosity performance might be to foresee since the beginning a recommissioning period to squeeze further $\beta^*$ later on in 2015. Ideally, this would take place after an adequate period of stable physics at the maximum intensity, similarly to what was done in 2011. If well prepared, this approach could ease the initial commissioning phase and allow a finer tuning of machine parameters close to the ultimate performance at 6.5 TeV.

## ACKNOWLEDGMENTS

The authors would like to sincerely acknowledge all the colleagues from the BE-OP-LHC, BE-ABP-HSS, BE-ABP-HSC sections who provided useful inputs to the preparation of this paper.

## REFERENCES

[1] M. Lamont, "Closing: Wrap-up and strategy," these proceedings.

[2] R. Bruce, "Collimation and $\beta^*$ reach," these proceedings.

[3] s. Redaelli *et al.*, "Aperture and optics – measurements and conclusions," Evian2012.

[4] G. Iadarola, "Electron cloud and scrubbing," these proceedings.

[5] B. Gorini, "Experiments' expectations," these proceedings.

[6] `http://lhccwg.web.cern.ch/lhccwg/Procedures/stageA/stageA_index.htm`

[7] R. Bruce *et al.*, "$\beta^*$ reach," proceedings. of Evian2012.

[8] R. Tomás *et al.*, "Record low $\beta$ beating in the LHC," Phys. Rev. ST Accel. Beams **15**, 091001 (2012).

[9] Ph. Baudrenghien, "RF: status and plans," these proceedings.

[10] D. Valuch, "ADT: status and plans," these proceedings.

[11] G. Valentino, "Collimation: status and plans," these proceedings.

[12] W. Bartmann, "Injection: status and plans," these proceedings.

[13] N. Magnin, "LBDS: status and plans," these proceedings.

[14] T. Lefévre, "Status of tune and orbit measurement and correction, testing strategy," these proceedings.

[15] G. Trad, "Transverse beam size measurement," these proceedings.

[16] J.E. Muller, "Longitudinal parameters and beam induced heating ," these proceedings.

[17] A. Gorzawski, "Levelling options and strategy," these proceedings.

[18] C. Alabau Pons, M. Giovannozzi, G. Müller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, "LHC aperture measurements," IPAC2010.

[19] N. Mounet, "Impedance and instabilities," these proceedings.

[20] T. Pieloni, "Two beam effects," these proceedings.

[21] R. Bruce *et al.*, presentation at the LBOC meeting of Feb. 25$^{\rm th}$, 2014, `https://indico.cern.ch/event/295934`

[22] S. Fartoukh, presentation at the 179$^{\rm th}$ LMC meeting of April 30$^{\rm th}$, 2015.

[23] D. Mirarchi and R. Bruce, presentations at the Collimation Working Group meeting of June 13$^{\rm th}$, 2014, `https://indico.cern.ch/event/323407/`