ARE WE READY FOR THE 2009 BEAM OPERATION?

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Abstract

In preparation for the 2008 LHC beam operation, commissioning procedures were established by the commissioning team to safely bring up the LHC performance from the initial beam tests to the first 7 TeV physics runs with reduced intensity and intermediate beta* values. The status of the procedures and their usage during the 2008 beam experience is reviewed. The improvements needed for the 2009 operation, in particular as far as the squeeze, luminosity performance, backgrounds and operation at reduced beam energies are concerned, are discussed. The status of procedures for ion operation are also presented.

INTRODUCTION

The operational experience in 2008 was limited to about 4 sector tests [1] and to three days of circulating beam operation [2]. This allowed a partial benchmark of the detailed beam commissioning procedures that have beam established in the past three years in preparation for the beam operation. Even if the beam experience enabled addressing only a minor fraction of the commissioning steps required to achieve physics production at the LHC, this experience gave nevertheless the chance of collecting valuable feedback on the procedure preparations and ideas for possible improvements. In this paper the overall commissioning strategy as of beginning of 2008 and the status of the LHC beam commissioning procedures are reviewed. The feedback from the 2008 operational experience is presented and readiness for the commissioning phases that were not addressed is discussed.

BASELINE FOR 7 TEV COMMISSIONING AND NEW REQUIREMENTS

Procedures for 7 TeV commissioning

The beam commissioning procedures were established for the baseline LHC commissioning to 7 TeV, following the staged approach proposed in [3]. The goal as of the beginning of 2008 was to achieve the Stage A for the 7 TeV early physics runs with up to 156 bunches (no crossing angle required), for a maximum luminosity performance goal of about $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [4]. The list of the commissioning phases for Stage A is given in Tab. 1. In order to make sure that hardware and resources were ready in due time, and that necessary amount of beam time was allocated for the various commissioning steps, the procedures were developed in close collaboration between the operation team, the beam commissioning team and the owners of the accelerator systems.

Table 1: Twelve phases of the commissioning Stage A [5].

Step	Activity
A1	Injection and first turn
A2	Circulating beam
A3	450 GeV - initial commissioning
A4	450 GeV - detailed optics studies
A5	450 GeV - increase intensity
A6	450 GeV - two beams
A7	450 GeV - collisions
A8	Energy ramp
A9	Top energy checks
A10	Top energy collisions
A11	Betatron squeeze
A12	Comm. with experimental magnets

The procedure write-up was under the responsibility of the LHC operation team (LHC engineers in charge and operators took responsibility for a few phases each) and of the accelerator system owners. A web-based repository was chosen [5] to ensure the flexibility required to follow up the evolution of the procedures. On the other hand, a strict approval process was also put in place which relies on the EDMS system [6]. Beam commissioning procedure documents are released for all the phases of Stage A [7] as they were presented and approved at the LHC Technical Committee (LTC) meeting [8]. These documents represent a complete snapshot of the commissioning plans as of beginning of 2008.

After the first training tests of superconducting magnets [9], it became clear that the 7 TeV operation was not within reach in 2008 and therefore a new operational baseline for physics at 5 TeV, with minimum β^* of 3 m in IP1 and IP5, was defined [10]. The implications on the procedures where considered to be minor and, while the preparation for the new operational scenarios was pursued, the documentation of the procedures was not explicitly updated.

New requirements and strategy

The following new requirements become apparent after the 2008 experience:

- the first physics runs will take place at an energy below 7 TeV (the new baseline value will be agreed as an outcome of this Chamonix2009 workshop);

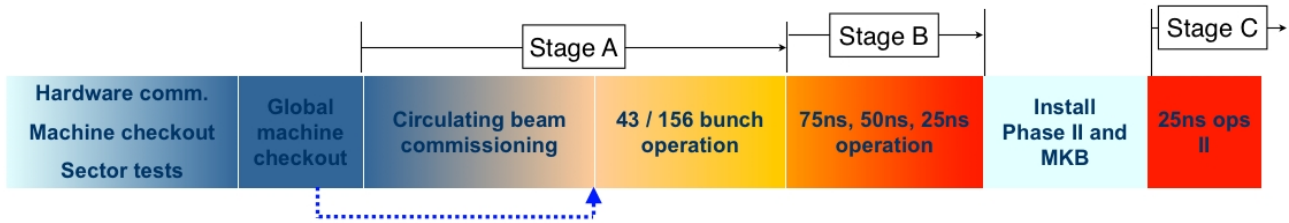

Figure 1: New baseline strategy for the LHC beam commissioning.

- hardware commissioning, cold-checkout tests and sector tests with beam are not separated in time as originally foreseen but might co-exist;

- the global machine cold-checkout and the commissioning of the machine protection systems might take place after the initial circulating beam commissioning.

In addition, updated estimates of the electron-cloud effect [11] suggested that the 75 ns operation is not anymore a mandatory step of the beam commissioning but has rather to be considered as a natural intermediate step of the intensity increase commissioning.

A modified version of the overall commissioning strategy, derived from [3] and updated to take into account the new boundary conditions, is proposed, see Fig. 1. The 75 ns operation is no longer listed as a dedicated commissioning stage but is put together with the 50 ns and 25 ns in a stage that requires operation with crossing angles. Based also on [13, 14], the bunch filling scheme should be seen as a parameter, chosen to optimize the luminosity performance for given total beam intensity, single bunch intensity and β^*. The commissioning stages are defined as

(A) simplest machine configuration (no crossing schemes, limited total beam intensity and moderate squeeze) to achieve as soon as possible relevant physics milestones (same as in the previous baseline);

(B) nominal machine configuration for the commissioning towards the intensity limit of the machine, e.g. as imposed by the cleaning performance of the phase I collimation system (combined Stages B and C of previous baseline);

(C) commissioning of nominal and ultimate LHC performance, only possible after a long shut-down for hardware update [1] (previous Stage D).

Within each phase, the commissioning approach remains obviously the same: operation will start with machine configuration as simple as possible and the key parameters (bunch intensity, number of bunches, β^* values and amplitude of crossing angle) will be progressively pushed to the limit within the boundaries of the stage (see also [13]).

[1] Note that the mentioned hardware modifications do not refer to the upgrade of the insertion regions for luminosity increase.

2008 COMMISSIONING EXPERIENCE

Steps covered and role of sector tests

The commissioning steps addressed, at least partially, by the 2008 beam operation are listed in Tab. 2. This comprises essentially the first three phases of Stage A (A.2 and A.3 could be done only for beam 2) and a few additional steps such as beta-beating measurements and initial tests with the dump system. The LHC beam commissioning would have been very different without the numerous sector tests that took place in the weeks before Sep. 10th [12]. Not only these tests allowed to advance the commissioning of the LHC injection, beam instrumentation and and application software, which proved to be crucial for a quick establishment of circulating beams, but also gave the chance to perform dedicated measurements that were foreseen for subsequent commissioning phases (polarity checks, dispersion, aperture measurements). It is likely that the 2009 commissioning will also rely on sector tests of some sort before completion of the hardware commissioning. In the following, an attempt is made to summarize the sector tests activities that could be included in a dedicated 'A0' commissioning phase. This is obviously based on the programs for the sector tests that appeared on the agenda of the LHC in the last years [15].

A0.1 Commissioning of injection region
Region downstream of TED with TDI closed
Timing synchronization of MKI
SPS-to-LHC timing aspects

A0.2 Single-pass threading in LHC sectors

A0.3 First BPM calibration and optics response matrices
First polarity checks of BPM
Timing of BPM acquisitions

A0.4 First commissioning of additional BI:
Screens, BLM's
BCT if possible (beam 1 to IP4)

A0.5 SPS/LHC energy synchronization (LHC master)
Dispersion measurements

A0.6 Aperture measurements
Injection region
Arcs / IR's / dump line

A0.7 Polarity checks

Table 2: Steps of the first phases of the commissioning Stage A. The 'X' symbol indicates which steps have been – at least partially – addressed for beam 1 (B1) and beam 2 (B2) during the 2008 operation.

Commissioning step	B1	B2
First turn (A.1)		
Comm. of the last 100 m of TL and injection	X	X
First commissioning of beam instrumentation	X	X
Set-up trajectory acquisition and correction	X	X
Beam threading (first turn)	X	X
Closing the orbit	X	X
Circulating beam (A.2)		
Establishing closed orbit		X
Additional BI: BPM intensity acquisition		
Orbit, tune, coupling and chromaticity		X
Obtaining circulating beam (≈thousand turns)		X
SPS-LHC energy matching		X
Commissioning of RF capture		X
Initial commissioning at 450 GeV (A.3)		
Commissioning of beam instrumentation		X
Improving lifetime		X
Rough optics checks		X
Initial commissioning of beam dumping system		X
Detailed measurements at 450 GeV (A.4)		
Beta-beat measurements		X
Initial commissioning of beam dump		X

A0.8 Beam-induced quench tests

A0.9 First commissioning of the dump line

A0.10 Initial beam tests with collimators (BLM calibration, vacuum and temperature measurements, controls)

The activities listed above are partially covered by the existing procedures. On the other hand, many activities are done differently with single-pass injection than with circulating beam (for example, the techniques to measure the ring aperture or the dispersion). Therefore we propose to elaborate a dedicated procedure to cover all the above.

Feedback from operation

The procedure preparation was found to be a very good and useful exercise for the commissioning team. It helped in defining for each commissioning step clear goals and milestones, agreed upon by all the teams involved and then used by the LHC coordination team to steer the commissioning plans. It also pushed the commissioning teams to elaborate in advance a clear commissioning plan, which was crucial to follow-up in due time the readiness of the hardware required for the various phases.

On the other hand, the procedure documents were not directly used by the operation crew in CCC as an on-line documentation for commissioning. This is mainly due to the fact that most of the systems were not yet fully handed over to operation, as foreseen for the initial commissioning phases. In addition, the preparation for the various activities was mainly done off-line prior to beam tests by the teams of people who elaborated "their own" procedures, making the on-line usage un-necessary. The fact the details of the procedures were mainly used by the people who prepared them should be taken into account for the future follow-up and maintenance: the maintenance of very detailed procedures is difficult and time consuming but necessarily useful for a large number of people. Focus should rather be put on the requirements ("Entry conditions") and on the expected outcome ("Exit conditions") that help defining the overall commissioning structure.

As foreseen, flexibility is essential to proceed efficiently with the commissioning: changes "on the fly", as determined by the immediate requirements and priority changes, should be envisaged and possibly built into the procedure. This was done by defining a priority ranking and "optional" steps (*nice to do but not strictly needed until step 'x' is reached*). Typical examples are the commissioning of the BPM intensity mode and of the movable BLM - only to be done if required - and the BPM/corrector polarity check - that can be done more efficiently with circulating beam but could also be performed routinely with injected beam during night shifts when experts of other top-priority activities were not available. A review of the optional steps and of their inter-links between different phases, based on the experience gained so far, will be done.

For the future there is a clear need to improve the traceability of commissioning steps. For the moment there is no well defined environment that allows to consistently monitor the progress of the various steps and to follow-up the open actions. A web-based follow-up page was set-up by the LHC coordination team [16] but this needs to be improved in preparation for phases more complex than the ones covered so far and for a systematic tracing of machine protection related activities. Various options, such as a database-based repository or an MTF directory structure similar to the one used for the approval procedure [6], are being investigated

READINESS FOR 2009

The phases of Stage A that were not covered in 2008 and additional critical operational aspects are reviewed. When possible, the hardware readiness is also commented upon. This status summary is largely based on the results of the cold-checkout tests performed in 2008 in preparation for the beam operation.

Energy ramp

The LHC energy ramp will be done by playing preprogrammed time-dependent functions for power converters, RF and collimators. The functions will be loaded into the hardware during the injection *plateau* by the LSA [17] control system, possibly incorporating discrete setting changes performed at injection. The function execution is driven by the timing system, which is then responsible for the overall synchronization of the various system. The baseline is that the LHC ramp will be performed without

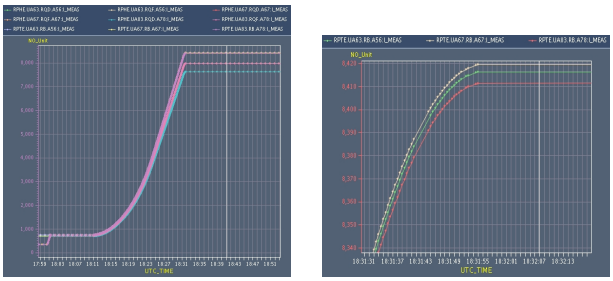

Figure 2: Result of simultaneous 5 TeV ramp tests on the main dipole and quadrupole circuits of sectors 56, 67 and 78. The measured current versus time is given.

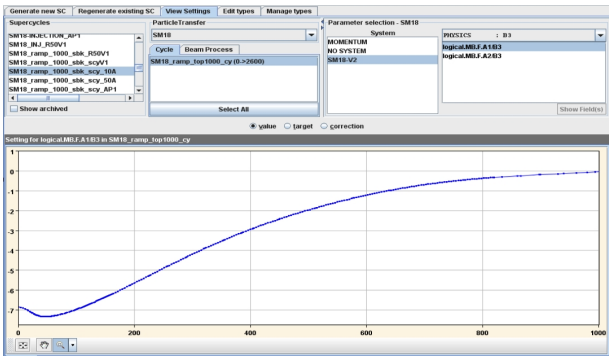

Figure 3: Example of generation of the snap-back of the sextupole field component (b_3) as generated by the LSA TRIM application using the FiDeL magnetic model of the LHC.

intermediate stopping point. On the other hand, LSA offers all the flexibility to generate "beam processes" at intermediate energy values and this will be used for the first tests of magnetic field snap-back. For a given top energy, the total ramp time is determined by the power converter parameters, optimized at the beginning of the ramp to minimize snap-back effect. This is then used to define the beam momentum function versus time, then used to generate parameters for all the other systems (RF frequency, collimator gaps, etc.).

Ramp tests were performed throughout the commissioning period. Figure 2 shows an example of synchronous ramp to 5 TeV for three LSA sectors, performed as a part of the beam dump energy tracking system. Dedicated tracking tests of the main circuit show an overall good performance [18]. The numerous tests performed on various circuit types allowed to validate the power converter parameters used during hardware commissioning and to define a set of operational parameters for the beam commissioning.

A first implementation of the FiDeL corrections of field decay and snap-back were also deployed and tested in 2008. An example of estimated snap-back of the sextupole field component, as generated by the LSA trim application, is shown in Fig. 3. Clearly the model implemented for these complex phenomena require a validation based on beam measurements but the dynamics of the corrections

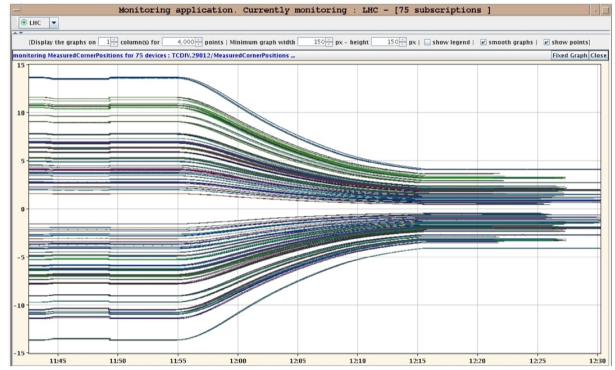

Figure 4: Synchronous execution of nominal 7 TeV ramp functions for 75 collimators in the LHC ring and in the transfer lines (300 stepping motors). The positions of left (positive values) and right (negative) jaws in [mm] are shown versus time.

can be handled by the system. More tests will be performed in particular to efficiently incorporate the fill-to-fill corrections.

An example of a ramp of the LHC collimators is shown in Fig. 4. Typically, a nominal ramp to 7 TeV was used during the collimator tests because at higher energy the required gaps are smaller and hence more critical in terms of position accuracy. All the 75 collimators of type TCP, TCSG, TCLA, TCT, TCLI, TCDI installed in the LHC ring and transfer lines, corresponding to 300 degrees of freedom (4 motors per collimators) followed the ramp functions that are generated to scale the collimator gaps as a function of the beam size during the energy ramp. The different collimators have different initial gap settings to match the local beam sizes. For the purpose of accuracy tests, also the collimators that are not moved during the ramp (like the injection protection devices) were actually "ramped". The system shows a very good position accuracy and the function-driven collimator control, deployed for the first time in 2008, will insure the required flexibility for all the LHC commissioning phases.

The settings for the RF frequency were also fully implemented in LSA and tested in 2008 (see Fig. 5). The system worked well. The distribution of the beam RF frequency to the LHC experiments was also successfully tested. For 2009, the implementation of the frequency generation for ion acceleration has to be done. In addition, there is also the need to improve the operational diagnostic tools from the CCC.

Betatron squeeze

The betatron squeeze will be performed similarly to the energy ramp, by pre-loading setting functions to the equipment concerned (power converters and collimators) and by triggering them with timing events. The squeeze functions are generated for the magnets in the matching sections by using optics matched points with intermediate β^*

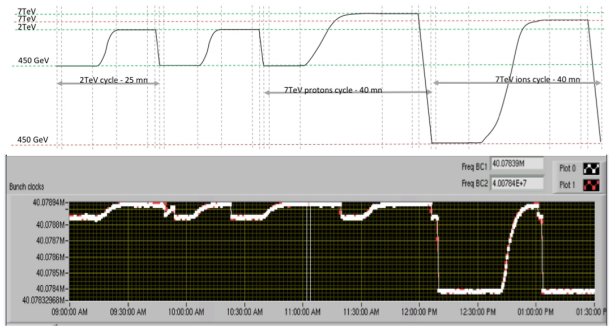

Figure 5: The RF frequency for protons and ions was generated and sent to the RF system. The top plot shows the RF frequency measured with the functions that were played. This information will be broad casted to all experiments. This link was also tested. The bottom graph shows the frequency signal received by ATLAS. Courtesy of RF team and D. Jacquet.

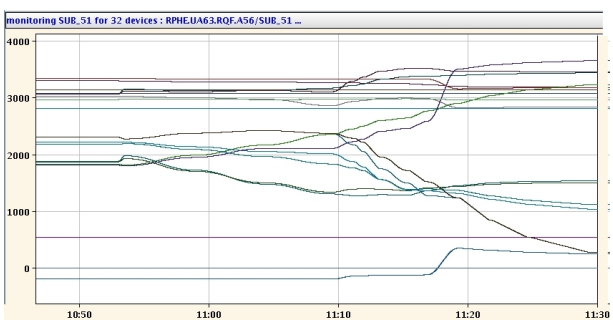

Figure 6: Example of synchronous execution of the current functions required for the nominal betatron squeeze. Current levels in A are given as a function of time for 32 power converters in the matching section left of IP5. These tests were performed on June 24th, 2008.

values, provided by the accelerator physics group (ABP). The squeeze is a critical manipulation that with take place at high energy with dangerous beams. The possibility of interrupting the squeeze function and of stopping at intermediate β^* is therefore incorporated. In case the dynamic behaviour during the transition between matched points is not under control, additional matched points can be easily added to reduce the steps until the variations are kept under control. This will be determined by the operational experience with beam. An example of the current change of the matching quadrupoles left of IP5 during a nominal betatron squeeze is shown in Fig. 6.

The protection devices in point 6 and close to the inner triplet magnets will also be moved to the protection setting of the "next" betatron step in order to ensure safety during all phases. For this purpose, it will be possible to adjust the collimator settings by using the different optics at the available matched points. An example with the calculated beam sizes at a tertiary collimators is given in Fig. 7.

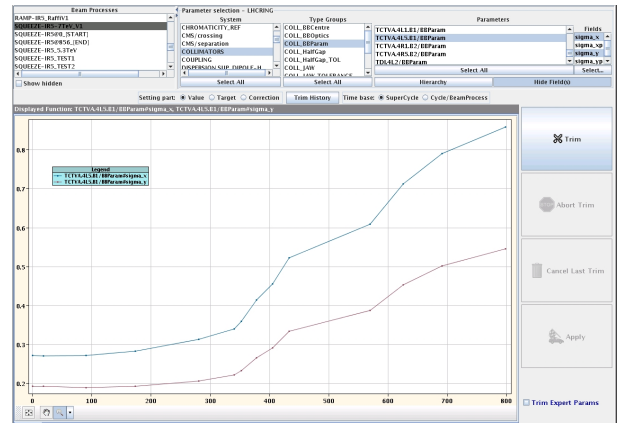

Figure 7: Horizontal and vertical beam sizes at the vertical tertiary collimator TCTVA.4L5.B1 on the left of IP5 for a squeeze beam process. Sizes in [mm] are given as a function of time in [s] from the beginning of the squeeze. Each point correspond to a "matched" optics and can be used as stopping point. In reality, the beam-based sizes and orbit positions will be used. The settings will be optimized to ensure the protection of the triplet.

Machine protection commissioning

The commissioning plans for the machine protection (MP) systems are discussed in detail in [19] and are not reviewed here. The elaboration of the commissioning procedure for the MP systems is followed-up by the Machine Protection Panel (MPP). The operations team will be involved early on in the commissioning tests of these system in preparation for the 2009 operation. On the other hand, the MP procedures must be systematically included in the existing beam commissioning procedures. This will be done as soon as the MP documents will be available for all the critical systems.

Detector background issues

Detector background issues are a concern for the LHC because there are no specific layout elements designed to optimize background in the experiments. The tertiary collimators at either side of the IP's could be used for background optimization purposes but their primary function is to protect the supercondicting triplets. LHC background issues were discussed in a workshop on Experimental Conditions and Beam-Induced Detector Background, held at CERN on April 2008 [20]. While it was re-iterated that beam-induced background is not expected to be an issue for the high-luminosity experiments, a number of potential issues were identified. For example, it was stressed that a consistent definition of background signal should be defined and agreed among the experiments and be provided to the machine for background tuning. An LHC Background Study (LBS) group has been started at the beginning of 2009 to address the open points identified in [20] and to provide support to the operations team for background re-

lated issues.

Luminosity optimization

The optimization of the luminosity performance will be of primary importance for the LHC. This must rely, amongst others, on an accurate and reliable measure of the luminosity in the various experiments. In addition to the measurements provided by the experiment themselves, for the 2009 operation also the machine measurements from the BRAN's will be available in all points [21]. Tools are being developed following the specification document [22] to perform luminosity scans using all the relevant sources of information such as luminosity, background, beam losses and orbit measurements in the IPs. A tool for automatic luminosity scans is being developed and the first tests look promising [23].

Procedures for ion operation

The commissioning plans for ions are discussed in a paper in this section [24]. Separate commissioning procedures that cover all the twelve phases of the proton beam commissioning are being established. A dedicated document with the ion commissioning procedures, which addresses the specific ion aspects of all the phases in Tab. 1, is being prepared and will be circulated for approval.

CONCLUSIONS

In this paper the status of the LHC beam commissioning procedures and the readiness for 2009 have been reviewed. The procedures for the 7 TeV operation have been thoroughly thought through in preparation for the 2008 operation. The main aspects that are not yet documented in details are the operation with crossing angles and with more than 156 bunches (operation with crossing schemes). In addition, the aspects of machine protection procedures relevant for beam operation remain to be built into the beam commissioning procedures. These aspects will be addressed with high priorities as soon as the operational beam parameters for 2009 will be defined, which is expected as an outcome of this workshop.

The first beam commissioning experience covered a minimum fraction of the procedures. The feedbacks have been collected and will be taken into account for the upgrade of the procedures. An important aspect that will be addressed is the traceability of commissioning steps, which needs to be improved in view of tackling complex procedures and machine protection related activities.

A review of the system readiness, based on the results of the cold-checkout tests performed in 2008, has been presented and used to identify activities that need further follow-up. This process will be eased by the fact that the operations team responsible for the elaboration of the procedures is also deeply involved in commissioning tests with and without beam. Overall, we believe that the key accelerator systems and the procedures for their operation are ready for the 2009 operation. A long series of "Dry" tests performed during 2008 made us confident that critical operational aspects are under control but clearly only the real beam operation can confirm that.

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