The LHC status, commissioning plans and interface with the experiments

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Abstract

The status of the ongoing Large Hadron Collider (LHC) installation is described with particular attention to the Long Straight Sections around the experiments. A summary of the present beam commissioning schedule is given with some details on the beam conditions during first collisions. The second part of this paper will address the experiment protection system from beam failures (including interlocks) and the exchange of data and control signals between the accelerator and the experiments.

I. STATUS OF THE LHC INSTALLATION (31/8/07)

The LHC [1] is a two-ring superconducting proton-proton collider made of eight 3.3 km long arcs separated by 528 m long straight sections (LSS). While the eight arcs are nearly identical, the straight sections are very different. Four straight sections house physics experiments, ATLAS, CMS, ALICE and LHCb; the latter two also include the beam injection systems. Two insertions are for the beam cleaning systems capturing off-momentum and halo particles, one insertion is for the superconducting RF cavities and beam instrumentation and finally, one insertion is for the beam dump systems to deposit the two beams onto external dump blocks. The LHC architecture allows the commissioning of each of the eight sectors independently from the others, before the installation of other sectors is complete. Therefore, both the LHC installation and the LHC commissioning is organized in sectors.

The installation and commissioning of the cryogenic distribution line (QRL) is now completed. The installation started in July 2003 and finished in November 2006. It suffered a number of delays and problems and Sector 7-8 needed to be dismantled, repaired and re-installed by CERN.

The last magnet was installed in April 2007. In particular, about 1700 cryo-assembles and about 200 warm magnets have been installed. To complete the magnet installation, the transport vehicles had to travel 30000 Km underground at a speed of about 2 Km/h. After installation and alignment, the cryomagnets have to be interconnected [2]. The interconections must ensure the continuity of several functions: vacuum enclosures, beam pipe image current (RF contacts), cryogenic circuits, electrical power supply, and thermal insulation. In the machine, about 1700 interconnections between cryomagnets are necessary. For each interconnection, various operations must be done in the tunnel: TIG welding of cryogenic channels (≈ 50000 welds), induction soldering of main superconducting cables (≈ 10000 joints), ultrasonic welding of auxiliary superconducting cables (≈ 20000 welds), mechanical assembly of various elements, and installation of the multi-layer insulation (≈ 200000 m^2). The interconnections of 3 Sectors have been completed while the remaing sectors are nearly finished.

The LSS consist of a sequence of cold and room temperature (RT) elements. In general, the RT elements are the beam vacuum chambers, collimators, absorbers, experimental devices (like Roman Pots), beam diagnostic devices and RT magnets. Once installed and aligned, the RT elements need to be put under vacuum via permanent and mobile pumping stations. Then all components are baked at a nominal temperature of 250 °C (with a few exceptions at lower temperature). This allows simultaneoulsy the surface degassing and the activation of the Non-Evaporable-Getter (NEG) coatings which provides an additional distributed pumping needed to get the very low pressure required in the LSS. The installation and commissioning of the RT elements in LSS is very well advanced apart from LSS3 (problems in the installation of a few services) and the zones hosting collimators due to the delays in their delivery. Finally, the installation and commissioning of the experimental beam chambers is mainly driven by the installation schedule of the experiments: the installation in ALICE and ATLAS is nearly finished while for LHCb and CMS is still ongoing.

II. STATUS OF THE LHC HARDWARE COMMISSIONING

The Machine Hardware Commissioning [3] consists in the commissioning of a number of systems: magnets, vacuum, cryogenics, power converters, current leads, quench detection and energy extraction systems as well as the associated utility systems such as AC distribution, water cooling, ventilation, access control and safety systems. In the first phase each system and each utility is tested and qualified independently. This is followed by a second phase where most of the equipment in each sector is globally tested together. After the leak and pressure test, the preparation for the cool-down starts (flushing, filling with He, repairs etc) and the electrical quality assurance tests (ELQA) are performed at warm on all circuits. During cool-down, all the circuits go through different electrical quality assurance tests at several temperature levels. The powering tests of the LHC superconducting circuits start as soon as the cryogenic conditions for powering are met, 1.9 K and 4.5 K for the circuits in the arc and the long straight sections respectively. During the power test all power converters are connected to the magnets for the first time and tested up to nominal current.

A. *Sector 7-8*

This first experience with the commissioning of Sector 78 has validated the preparation, the environment, the procedures and tools which had been carefully setup during the last two years. During the commissioning a number of problems have been faced and solved. In particular, during the pressure test (November 2006) the corrugated heat exchanger tube in the inner triplet failed by buckling at 9 bar (external). The reduced-height corrugations and annealing of copper near the brazed joint at the tube extremities accounted for the insufficient resistance to buckling. New tubes have been produced and installed (in situ for the already installed inner triplets) with higher wall thickness, no change in corrugation height at ends, and e-beam welded collars to increase distance to the brazed joint. In the meanwhile, the inner triplet in Sector 7-8 was isolated and the pressure test of the whole octant was successfully carried out to the maximum pressure of 27.5 bar, thus allowing it to be later cooled down.

The sector was successfully cooled-down to nominal temperature and operated with super-fluid helium. A number of problems encountered during this first cool-down (in particular with the cold compressor) have now been fixed. The power test was successful too but limited in number of circuits because of lack of time and limited in current because of electrical non-conformities in some of the main magnets. The sector in now warm for consolidation work (inner triplet repair and a number of non-conformities) and will have to be re-commissioned.

During the warm up, a unexpected problem appeared with the so-called Plug-In Modules (PIM). PIMs are part of the vacuum interconnects whose function is to provide continuity of the beam vacuum inside the beam transport system. These modules must allow for the thermal contraction of the magnet cold masses, for re-alignments of the machine when cold and warm and for the connection of the beam screens with low impedance RF bridges. Therefore, they consists of stainless steel bellows and Cu-Be alloy RF contact fingers. As of today, 10 PIMs have been found with fingers buckled into the beam aperture: 7 PIMs have been wrongly installed and therefore they were working outside the specified range and 3 were non-expected. CERN has decided to go for the systematic check of all PIMs in Sector 7-8: as of 31 August 2007, 238 PIMs have been examined and no additional faulty PIMs have been found (186 still to be done). In the meanwhile CERN is proceeding with the inspection of the damaged PIMs to understand the cause of the problem, with the validation of the design and is exploring all possible means of detection (possibly non-invasive). The strategy for the remaining sectors is still under discussion.

B. Sector 4-5

During the pressure test in Sector 4-5 (March 2007) of the inner triplet with the newly installed heat exchanger tube, the longitudinal fixed points on the “spider” supports of the cold mass broke at 20 bar provoking permanent deformation and rupture of bellows and supports [4]. After analysis, it appeared that the loading conditions resulting from such pressure forces had not been taken into account in the design. Following a complete review of the mechanical design of the Inner Triplets, a few other weak points were reinforced, and repair solutions validated, based on contraction-compensated metallic columns reacting longitudinal pressure forces onto the cryostat outer vessels. As of today, all inner triplets have been repaired and installed in the tunnel. Furthermore, 3 inner triplets have successfully passed the pressure test up to the maximum pressure. In other words, the inner triplet problems are now resolved and no further delay to the LHC schedule is expected related to this.

The sector is actually under cool-down by isolating both the inner triplet and a few leaking circuits. The sector needs to be warmed up to allow the reconnection of the inner triplet and the repair of the found non-conformities.

C. Sector 8-1

Sector 8-1 is presently under leak test. A leak has been detected in a Short Straight Section (SSS is an assembly of the arc quadrupole and the lattice corrector magnets). Several attempts have been made to localize the leak with no success. If the leak is not found, the SSS will have to be replaced with a new one.

III. THE LHC GENERAL SCHEDULE

An updated General Schedule has been submitted and approved by CERN Council in June 2007. The engineering run originally foreseen at end 2007 has been precluded by delays in installation and equipment commissioning. The 450 GeV operation is now part of normal setting-up procedure for beam commissioning to high-energy. The general schedule has been reassessed, accounting for the inner triplet repairs and their impact on the sector commissioning:

- All technical systems will be commissioned to 7 TeV operation and the machine will be closed in May 2008.
- The beam commissioning starts June 2008 and first collisions at 14 TeV c.m. are expected in July 2008.
- The pilot physics run is pushed to 156 bunches for reaching a luminosity of 10^{32} $cm^{-2}s^{-1}$ by the end of 2008.

It should be noted that in this success-oriented schedule there is no provision for major mishaps, e.g. for additional warm-up/cool-down of a sector. Finally, a new updated schedule is under preparation: it will take into account the highly probable replacement of the SSS in Sector 8-1, the PIMs problem and the helium inventory in 2008 (more than 6 sectors have to be cool-down in parallel and each sector needs ~ 17 tons of helium). It should be noted that the impact on the actual schedule is expected to be minimal.

IV. PLANS FOR BEAM COMMISSIONING

Both the machine and the experiments will have to learn how to stand running at nominal intensities. An early aim is to find a balance between robust operation (i.e. avoiding quenches and at all costs damage) and satisfying the experiments by delivering a significant integrated luminosity minimizing the event pile-up. The performance estimates are based on the standard luminosity equation:

$$L = \frac{N^2 k_b f \gamma}{4\pi \varepsilon_n \beta^*} F$$

where N is the number of protons per bunch, k_b the number of bunches per beam, *f* the revolution frequency, γ the relativistic factor, ε_n the normalised emittance, β^* the value of the betatron function at the interaction point, and F the reduction factor caused by the crossing angle.

To avoid quenches two parameters are considered: higher β^* to avoid problems in the delicate part of the beta squeeze and lower the total current either by reducing the number of bunches or the bunch intensity or both.

With lower currents in mind, two important machine systems will be staged. For the collimators, a phased approach will be adopted which will provide the necessary protection but will require higher beta functions or lower currents. For the beam dump, 4 out of 10 dilution kickers will be installed for each beam, which will restrict the total circulating intensity to around 50%.

The resulting proposal for early proton running is to aim for a pilot physics run with a few tens of bunches per beam, and the commissioning strategy has been developed with this in mind. Following this, attention will shift to many-bunch operation, first with 75ns spacing and later with 25ns spacing [5].

A. Stage A – pilot physics run

The aim here is to bring two moderate intensity beams to high energy and to collide them for physics. The target is 43 on 43 bunches of 3 to 4 10^{10} protons at 7 TeV. In order to provide collisions in LHCb (IP8 is shifted by 11.25 m), 4 bunches in one beam will be displaced by 75ns. It should be noted that the 4 displaced bunches will produce collisions in the remaining IPs shifted by 11.25 m.

Initial physics will be with the injection optics. Once this has been achieved the squeeze will be partially commissioned. The commissioning phases to achieve this are summarized in Table 1 [6].

Table 1: Commissioning phases for the pilot physics run.

Phase A.1	**First turn:** injection commissioning; threading, commissioning beam instrumentation. Ring 1, Ring 2.
Phase A.2	**Circulating pilot:** establish circulating beam, closed orbit, tunes, RF capture, …
Phase A.3	**450 GeV initial commissioning:** system commissioning: instrumentation, beam dump,...
Phase A.4	**450 GeV optics:** beta beating, dispersion, coupling, non-linear field quality, aperture,...
Phase A.5	**450 GeV increasing intensity:** prepare the LHC for unsafe beam.
Phase A.6	**450 GeV, two beam operation.**
Phase A.7	**450 GeV, collisions.**
Phase A.8	**Snap-back and ramp:** single beam.
Phase A.9	**Top energy checks.**
Phase A.10	**Top energy, collisions.**
Phase A.11	**Squeeze:** Commissioning the betatron squeeze in all IP's.

Taking into account the machine availability for physics, it will take about 2 months from first injection to first collisions at top energy.

The luminosities expected for this pilot run can be found in Table 2 and Table 3. In this mode it is possible to increase the number of bunches to 156 per beam with a corresponding 4-fold increase in luminosity, still without the need for a crossing angle to avoid parasitic collisions. This should achieve a luminosity of 2 10^{31} $cm^{-2}s^{-1}$ in the high luminosity experiments. The insertion in IP8 could be tuned to increase the luminosity for LHCb.

B. Stage B – 75 ns operation

Once the pilot physics run is complete, a period of operation with 75ns spacing in proposed. There are several advantages to this:

- The reduced number of parasitic beam-beam encounters allows a relaxed crossing angle. This would be exploited, moving to the full crossing angle only in preparation for 25ns operation
- Electron cloud is not expected to be a problem
- Total beam intensities and power are increased in an incremental way, allowing the machine protection systems to adapt.

Initial operation at 75ns would be with the β^* achieved in the pilot physics run, say 2m, and a crossing angle of 250μrad. Typical performance expected is given in Table 2 and Table 3. It should be noted that the luminosity at IP2 should not exceed ~ 5 10^{30} $cm^{-2}s^{-1}$: this is achieved detuning the insertion from β^* = 10 m to β^*= 50 m [7].

C. Stage C – 25 ns operation I

During this mode, a luminosity of 10^{33} cm^{-2} s^{-1} for the high luminosity experiments is within reach. Luminosities in IP8 are now fairly optimal with the injection optics, while in IP2 detuning and transverse beam separation will be required. Typical performance expected is given in Table 2 and Table 3.

Table 2: Suggested evolution of parameters for 2008/2009.

Parameters			Rates in IP1 and IP5	
k_b	N	β^* (m)	Luminosity ($cm^{-2}s^{-1}$)	Events/ Crossing
43	4 10^{10}	11	1.1 10^{30}	<<1
43	4 10^{10}	2	6.1 10^{30}	0.76
156	4 10^{10}	2	2.2 10^{31}	0.76
936	4 10^{10}	11	2.4 10^{31}	<<1
936	4 10^{10}	2	1.3 10^{32}	0.73
2808	4 10^{10}	2	3.8 10^{32}	0.72
2808	4 10^{10}	2	5.9 10^{32}	1.1
2808	4 10^{10}	1	1.1 10^{33}	2.1

Table 3: Suggested evolution of parameters for 2008/2009 (see text for the comments on the β^*).

Parameters			Rates in IP2 and IP8	
k_b	N	β^* (m)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
43	4 10^{10}	10	1.2 10^{30}	0.15
43	4 10^{10}	10	1.2 10^{30}	0.15
156	4 10^{10}	10	4.4 10^{30}	0.15
936	4 10^{10}	10	2.6 10^{31}	0.15

936	$4\ 10^{10}$	10	$2.6\ 10^{31}$	0.15
2808	$4\ 10^{10}$	10	$7.9\ 10^{31}$	0.15
2808	$4\ 10^{10}$	10	$1.2\ 10^{32}$	0.24
2808	$4\ 10^{10}$	10	$1.2\ 10^{32}$	0.24

D. Stage D – 25 ns operation II

Once the installation of the full complement of beam dump dilution kickers and of the Phase II collimators is completed, bunch intensities will be progressively increased toward nominal and nominal performance can be achieved.

V. DATA AND SIGNALS EXCHANGE BETWEEN THE LHC ACCELERATOR AND THE EXPERIMENTS

The data and signal exchange between the LHC accelerator and the experiments, both at the hardware and software levels, has the aim of communicating information on the state of the machine and experiments, as well as providing a means to understand the causes of error by acting as a recording and diagnostic tool [8]. The data and signals are mainly exchanged via the following systems:

- *CERN Data Interchange Protocol (DIP)[9]:* this system allows relatively small amounts of soft real-time data to be exchanged between very loosely coupled heterogeneous systems. All signals regarding the quality of beam collisions, data from beam instrumentation, and the operation status (mode) of the LHC are exchanged via this system. It should be noted that this system is highly flexible and data and signals to be exchanged may be added as the experience with the experiments and accelerator operation develops.
- *Timing, Trigger and Control (TTC)[10]:* provides for the distribution of synchronous timing, level-1 trigger, and broadcast and individually-addressed control signals, to electronics controllers with the appropriate phase relative to the LHC bunch structure, taking account of the different delays due to particle time-of-flight and signal propagation.
- *Beam Synchronous Timing (BST):* developed using the TTC technology to provide a means of supplying the LHC beam instrumentation with 40 MHz bunch synchronous triggers and the 11 kHz LHC revolution frequency. In addition to these two basic clocks, the BST system also provides a message which can be updated on every LHC turn. This message will mainly be used by the LHC instrumentation to trigger and correlate acquisitions, but it will also contain the current machine status and values of various beam parameters. This latter information will be provided also to the LHC experiments [11].
- *General Machine Timing (GMT):* this system synchronizes all CERN accelerators. In particular, it distributes:
  - The LHC telegram: it represents a snap shot of the machine state and it is updated each second. Among the various parameters, it sends out the Safe Beam Parameters which are essential for building the interlock signals.
  - LHC Machine events: an event is sent punctually when something happens that affects the machine state. Some are asynchronous that come from external processes, e.g. post-mortems, while others are produced from timing tables corresponding to running machine processes.
  - The UTC time of the day
- *Beam Interlock System (BIS) [12,13]*: it provides a hardware link from a user system to the LHC Beam Dumping System, to the LHC Injection Interlock System and to the SPS Extraction Interlock System. The role of this system is to ensure safe operation with beam. More details are given in the following paragraph.

A. The LHC experiments beam interlock system

The LHC experiments beam interlock system (BIS) is described in [14]. The LHC BIS is split into a system for beam1 and a system for beam2 and carries the two independent BEAM_PERMIT signals, one for each beam. The BEAM_PERMIT is a logical signal that is transmitted over hardware links and that can be

- TRUE
  - Injection of beam is allowed
  - With circulating beam, beam operation continues.
- FALSE
  - Injection is blocked.
  - If a beam is circulating and the signal changes from TRUE to FALSE, the beam will be dumped by the Beam Dumping System.

The individual user systems must provide USER_PERMIT signals for beam1 and/or beam2 that are collected by the BIS through the Beam Interlock Controller (BIC) modules. The USER_PERMIT is a logical signal that is transmitted over hardware link and that can be

- TRUE
  - The user is ready and beam operation is allowed according to the user.
- FALSE
  - Beam operation is not allowed according to the user.

To obtain permission for beam operation, i.e. BEAM_PERMIT=TRUE, all the connected USER_PERMIT signals must be TRUE. This condition is somewhat relaxed for the maskable user signals, where the USER_PERMIT signal may be masked when the beam intensity is safe, i.e. below the damage threshold. Currently, the beam is considered safe if:

- Beam intensity is below 10^{12} protons at 450 GeV and nominal emittance.

- Beam intensity is below 10^{10} protons at 7 TeV and nominal emittance.

The LHC experiments are non-maskable users.

The delay between reception of an interlock (USER_PERMIT to FALSE) and the moment where the last proton is extracted on the dump block varies between 100 and 270 µs depending on the location of the USER and the precise timing with respect to the beam abort gap position in the ring.

A special attention is paid to the interlocking of the movable devices since they are supposed to be positioned between 10-70 σ from the beam axis. Therefore, a wrong operation of these devices may lead to important damage of both the devices themselves and the machine. In general, the movable devices are authorized to leave their garage position only during collisions.

It should be noted that the experiments will use the actual BIS only to dump the beam. In order to inhibit injection, they have asked to get an independent system which would not dump the beam at the same time. In fact, the injection inhibit will be based on the state of the detectors and it will not depend on the data from the experiment's protection system. The design of this new system looked not compatible with the LHC startup schedule. Therefore, it has been agreed to use the already existing Software Interlock System (SIS) to send the experiments' injection inhibit during the early LHC operation.

Finally, a number of handshaking signals have been agreed between the machine and the experiments aiming at improving the communication during the LHC operation. This should ensure a more efficient and safer beam operation. The handshaking signals will be sent through the DIP system.

VI. CONCLUSIONS

The LHC installation is nearly finished while the Hardware Commissioning phase has started at full speed. Problems have been encountered during the commissioning of the first sectors but none of them has resulted in a show-stopper. Therefore, the beam commissioning phase is approaching and all communication channels between the machine and the experiments need to be functioning to ensure an efficient and safe commissioning and operation with beam.

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