LHC OPERATION AT HIGHER ENERGY AND LUMINOSITY

G. Papotti, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) at CERN (Geneva) was commissioned and operated in the years 2009-2013 up to a beam energy of 4 TeV. A peak luminosity of $0.77 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was reached and an integrated luminosity of around 29 fb^{-1} was delivered to both ATLAS and CMS. This performance allowed the discovery of a scalar boson. The LHC is presently in a shutdown phase dedicated to consolidation and maintenance that will allow the restart of beam operation in early 2015 at an increased beam energy of 6.5 to 7 TeV. Maximum acceptable pileup, effectiveness of electron-cloud scrubbing, and fast loss events are some of the issues that will shape the choice of operational parameters, cycle setup, and the commissioning strategy. The baseline choices and options for the restart after the shutdown are presented. In addition the roadmap for future performance upgrades is sketched.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is a 27 km long circular accelerator and collider based on superconducting two-in-one magnets and designed for a beam energy of 7 TeV [1]. It features 8 straight sections: 4 Interaction Points (IPs) are reserved for accelerator equipment and 4 house particle physics experiments. IP3 and 7 are dedicated to the collimation system, IP4 houses the RF system and most of the beam instrumentation, IP6 the beam dump system. IP1 and 5 contain ATLAS and CMS, the high luminosity experiments, while IP2 and 8 accommodate ALICE and LHCb, together with beam injection.

Initial commissioning with beam was re-started at the end of 2009, and first collisions at 3.5 TeV were achieved on 30 March 2010. The decision to limit the energy to 3.5 TeV was taken in order to reduce the risk of repeating events similar to the 2008 incident, when a highly resistive splice combined with a non-continuity in the copper stabilizer caused localized over-heating and an accidental release of the 600 MJ that were stored in the sector. After two years of successful running at 3.5 TeV with no accidental beam-induced quench at high energy, the decision was taken to run at 4 TeV per beam (in 2012 and 2013) until the start of the first Long Shutdown (LS1) during which the machine is being consolidated to run safely at 7 TeV.

The few weeks in 2009 and the year 2010 were dedicated to gaining the first operational experience. Initially, operation was with "pilot" bunch intensity (few 10^9 ppb), to commission the first squeeze. In June 2010 the bunch intensity was increased to "nominal" ($\approx 10^{11}$ ppb) and the summer was a period of steady running at $\approx$1 MJ to gain experience with intense beams and Machine Protection. In September the injection of bunch trains was commissioned (150 ns bunch spacing) and by mid-October the yearly target of an instantaneous luminosity of 10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ was achieved.

Operation in 2011 started with 75 ns beams, and 50 ns beams were used only after a scrubbing run. With 50 ns beams, the number of bunches was slowly increased to 1380, then luminosity production was improved by reducing the transverse emittance, by squeezing further (from beta star 1.5 m to 1 m) and finally by gently increasing the bunch intensity. Squeezing to 0.6 m in 2012 allowed the production rates to increase even further and the year culminated with the discovery of the Higgs boson on 4 July 2012. The main machine and beam parameters are recalled in Table 1 for 2010-2012 and for the Design Report [1] for comparison. Operation with lead ions was also very successful [2, 3], but is not discussed here.

LONG SHUTDOWN 1

In the morning of 16 February 2013 the last LHC beam of run 1 was dumped and the LS1 started. The duration of the LS1 is planned to be approximately 20 months, and first beam is supposed to be back in the LHC in early 2015. This is to be compared to the winter shutdowns of 2010, 2011, 2012, that were as short as a couple of months and during which only fundamental maintenance was carried out.

The LS1 [4] firstly addresses the need to consolidate the interconnections between the LHC main magnets (soldered joints of two superconducting cables, splices, stabilized by a copper bus bar) to allow the LHC to operate at the nominal centre-of-mass energy of 14 TeV. It additionally targets consolidation activities to guarantee reliable operation of the LHC and its injectors until the next long shutdown (presently foreseen for 2018). Quality controls are performed on the splices and, in case of failure, the splices are remade. Consolidation activities include also the installation of shunts to improve electrical continuity and insulation boxes that provide mechanical restraints in addition to dielectric strength.

At the time of writing, the shutdown activities are progressing well. The consolidation activities spread across most of the machine, with hte interconnections being opened in sectors 12 and 23 being opened, the electrical

ISBN 978-3-95450-138-0

Table 1: Main Beam and Machine Parameters for Design Peport, 2010, 2011, 2012 and Options for 2015

Parameter	2010	2011	2012	Nominal	2015 (50 ns)	2015 (25 ns)
collision energy [TeV]	3.5	3.5	4	7	6.5	6.5
N_b [10^{11} ppb]	1.2	1.45	1.6	1.15	1.6	1.15
k	368	1380	1380	2808	1260	2508
bunch spacing	150	75/50	50	25	50	25
stored energy [MJ]	25	112	140	362	210	300
tr. emittance [μrad]	2.4	2.4	2.5	3.75	1.6	1.9
beta star (β^*) [m]	3.5	1.5, 1	0.6	0.55	0.4	0.5
L [cm^{-2}s^{-1}]	$2 \cdot 10^{32}$	$3.5 \cdot 10^{33}$	$7.7 \cdot 10^{33}$	$1 \cdot 10^{34}$	$2 \cdot 10^{34}$	$1.5 \cdot 10^{34}$
pile-up μ	8	17	38	26	120	44

quality of the old splices being tested in sector 81, shunts and insulation boxes being installed in sectors 67 and 78. The activities in sector 56, the first to be opened, are completed apart from few non-conformities, and the first vacuum leak tests gave positive results.

The activities have so far accumulated a delay of 3 weeks with respect to the initial schedule. This can be traced back to a few causes: a few technical issues (which are being solved), the summer vacation period and the consequent slow down of activities, and the fact that more splices than expected are to be redone (15% was expected, while 30% failed the quality tests so far, on 40% of the machine). A few bad surprises were also discovered, e.g. damaged bellows in the cryogenic system and in the electrical feed boxes, for which the repair is under study.

PREPARATION FOR RESTART

At the end of the shutdown activities a number of tests are performed on a sector by sector basis: electrical quality assurance tests are performed at room temperature, followed by flushing and cool down to cryogenic temperatures, further electrical quality tests and a full campaign of powering tests.

The hardware commissioning powering tests verify correct behaviour of the superconducting circuits and the associated protection systems, and are currently foreseen for the second half of 2014. All circuits but the main ones are tested up to the 7 TeV equivalent current values. Concerning the main circuits, the current baseline is to train them to 6.55 TeV (for which about 100 quenches are expected to be needed [5]), to allow to initially operate at 6.5 TeV beam energy.

In parallel to the powering campaigns, the other accelerator systems are also tested in "dry runs", so to verify the equipment control from the central control room (e.g. beam dump, RF, injection kickers, etc.). Also, in parallel to the end of the powering tests, a "sector test" with beam is foreseen for the end of 2014. It plans the injection of beam from point 8 to point 7 to the dump in point 6. It requires the readiness of sectors 67 and 78 and many other systems, and allows verifying system-wide integration and pre-commissioning many key procedures.

Finally, a global machine checkout takes place, in which the integration of all systems is verified, including interlocking functionality. The goal is to run the machine through the full cycle without beam.

BEAM COMMISSIONING

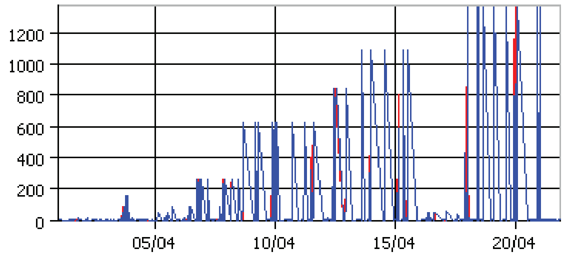
The LHC commissioning with beam starts after a successful machine cold checkout. The breakdown of the beam commissioning into phases to build the nominal cycle is rather standard. Traditionally, the first injections are used to "thread" the beam around the machine: with the smallest intensity detectable by the beam position monitors, the trajectory is corrected one sector at a time, and the beam stopped on collimators. When a closed orbit is established, the setup of the RF system can start, allowing to capture the beam. Injection of a bunch of nominal intensity is used to record a flat orbit reference and setup primary collimators, beam instrumentation, transverse damper, etc.

The first energy ramp and beta star squeeze require the commissioning of orbit, tune and radial feedback, then optic measurements and corrections are also performed. Then, crossing and separation bumps are added throughout the cycle, allowing further measurements of aperture and beta star. Finally, collisions are established in all interaction points and RF cogging is performed to align the collision in the center of the experiments. Note that the protection by the collimators is verified by performing controlled tests of losses at injection, flat top, after squeeze and in collisions.

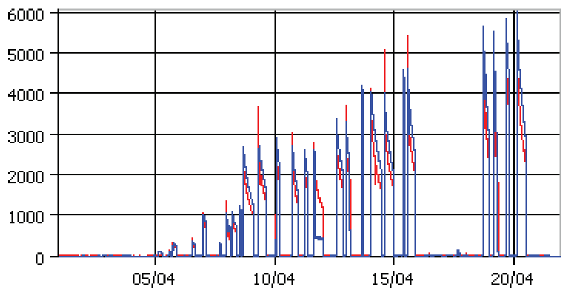
A total of about 2 months in the beginning of 2015 is required for completing these steps, including testing thoroughly all machine protection systems. While in this initial phase everything is performed with at most 2-3 nominal bunches in the machine, the injection of many bunches at a time (bunch trains) and the increase of intensity in the machine is performed in steps, i.e. "intensity ramp-up".

Intensity Ramp-up

The intensity increase from few nominal bunches to a full machine is staged in steps. Some fills with limited number of bunches allow verification of the nominal cy-



(a) Number of bunches per fill in April 2012.



(b) Luminosity per fill in April 2012 [10^{30} cm^{-2}s^{-1}].

Figure 1: Intensity ramp-up in April 2012.

cle and the procedures, e.g. scaling of losses. Fills with more bunches allow approaching intensity (or luminosity) related problems slowly, e.g. effects on vacuum or heating of machine components. This procedure took about one month in April 2012 and it was divided in 7 steps: 2-3 fills and 4-6 hours each with 48, 84, 264 and 624 bunches for cycle validation, and 3 fills for a total of at least 20 hours with 840, 1092, 1380 bunches for intensity-related problems. The resulting number of bunches and luminosity are shown in Figure 1.

For the restart in 2015, the uncertainty on the duration of the intensity ramp-up is dominated by the effectiveness of electron-cloud scrubbing.

OPEN QUESTIONS

Three effects that are expected to shape beam commissioning in 2015 are recalled next: electron cloud effects and their scrubbing, the so-called Unidentified Falling Objects (UFOs) and beam stability. Additionally the issue of radiation effects on electronic components is included.

Electron-cloud and Scrubbing

The operation of an accelerator with closely spaced proton bunches can give rise to local accumulations of electrons inside the vacuum chamber depending on beam structure and properties of the chamber (e.g. the Secondary Electron Yield, SEY). In particular if the SEY is higher than a threshold value, an avalanche effect can take place and cause vacuum pressure rise, increased heat load on the cryogenic system, increased beam emittance, and single and multi bunch instabilities.

Electron cloud effects were observed in the LHC as soon as bunch trains were injected, with 150, 75, 50 and 25 ns bunch spacing. Scrubbing runs took place in 2011 and 2012 as dedicated periods during which the electron cloud generation is enhanced so to “clean” the vacuum chamber walls, and thus decrease the SEY and effectively improve beam quality for physics operation. Additionally, Machine Development time was allocated for electron cloud studies for 25 ns beams. In particular, in December 2012, a short run was dedicated to study 25 ns beams to assess the evolution of the SEY and other possible differences compared to 50 ns beams [6]. After an initial improvement of heat load and beam lifetime, a sharp slow down of the scrubbing process was observed in the studies at 450 GeV (see Figure 2). This lead to the conclusion that, at restart in 2015, at least one week of scrubbing will be required for 50 ns running, an additional week for 25 ns running, and that coexistence with electron cloud will be probably inevitable in the first part of the physics run (so that physics will be performed with degraded beam parameters). The understanding of the observations and underlying physical phenomena is progressing well at the moment of writing, and this could impact positively on the above statements.

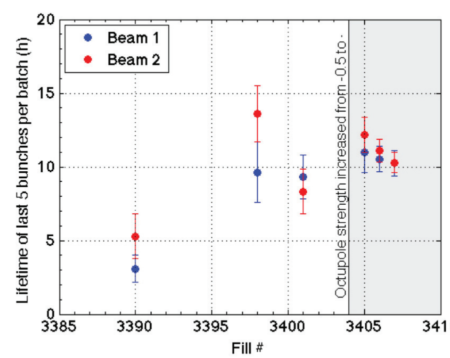


Figure 2: Single beam lifetime during the December 2012 scrubbing run.

Unidentified Falling Objects

UFOs are micrometer size dust particles that, when interacting with the beam, produce fast beam losses (approximate duration of about 10 turns). Such events were observed since 2010 and caused a non negligible number of beam aborts (about 5% of the total number of dumps above injection energy, or ≈20 dumps/year).

The occurrence of such events has been thoroughly studied [7]. There is evidence for a “scrubbing” effect over the course of 2011 and 2012, e.g. the rates in 2011 decreased from 10 to 2 events/hour. There is also evidence for deconditioning after periods without beam as technical stops, e.g. an increase of a factor 2.5 after the 2011-12 winter stop. Because of this, an increase in rates is expected after LS1. Additionally, during the 25 ns studies, UFO rates increased by a factor 10 at 4 TeV. This, combined with the

ISBN 978-3-95450-138-0

energy dependence of UFOs, indicate that they might be a major source of beam dumps (extrapolations indicate over 100 dumps per year). In a very pessimistic scenario they might impose to start with 50 ns beams, or at a lower beam energy.

Beam Stability

Many instabilities were observed during run 1, in all phases of the operational cycle, and many different countermeasures have been deployed to cure them (see for example [8]). Transverse instabilities caused emittance blow up at injection (2010 and 2011) and were cured by increasing the octupole strength for increased Landau damping. "Dancing bunches" (longitudinal dipolar and quadrupolar motion) are observed at high energy for low longitudinal emittance, and are cured by controlled emittance blow up by phase noise since 2010. Lack of Landau damping was also observed in 2012 for beams colliding only in LHCb, and was solved by changing the filling scheme to have additional collisions in ATLAS and CMS for these bunches so to increase the tune spread by the beam-beam interaction. A transverse instability was reproducibly observed at the end of squeeze in 2012 and caused mostly emittance increase: it was not fully understood, but it could be mitigated by high chromaticity and high transverse damper gain.

Beam instabilities are expected also at 6.5-7 TeV and will shape many operational choices. The option to collide the beam already during the squeeze is being considered to profit from Landau damping by head-on beam-beam force. The amount of opening of collimator jaws is still under discussion as it compromises between cleaning efficiency and machine impedance. The high setting of chromaticity and transverse gain will be kept if needed, the efficiency of the octupoles might be limited by the available hardware current and the small emittance.

Radiation to Electronics

The Radiation To Electronics project (R2E) aims at limiting the Single Event Effects so to reduce the R2E induced beam dumps and the impact on machine availability [9]. A thorough analysis allows identifying which beam dumps are likely to be caused by radiation effects, correlate them with radiation levels in the tunnel and integrated luminosity. The systems that were the most sensitive in 2012 operation were the Quench Protection System and an auxiliary power supply of 600 A Power Converters, followed by cryogenics and vacuum equipment.

R2E mitigation actions consist of equipment relocation from critical to safer areas or addition of shielding to reduce the exposure to radiation, and equipment upgrades or redesign to improve radiation hardness. These measures already improved the number of dumps from 12 dumps/fb^{-1} in 2011 to 3 in 2012, and a major campaign during the LS1 aims at reducing the rate further to 0.5 dumps/fb^{-1}.

EXPECTED PEAK PERFORMANCE

The main machine and beam parameters for 2015 operation are shown in Table 1. With a baseline beta star of 40 cm, peak luminosities of 1.5 to $2 \cdot 10^{34}$ are within reach with 25 ns and 50 ns beams. The excessive pile-up that characterizes the 50 ns beams makes 25 ns the preferred choice for having cleaner physics events. Electron cloud scrubbing might be slow or impose initial physics operation with degraded beam parameters, but would be an investment until LS2 (2018).

Conversely, 50 ns beams are the fallback plan in case in of insurmountable problems with 25 ns beams, e.g. electron cloud or UFOs. The higher brightness that can be provided by the LHC injectors for the 50 ns beams allows achieving higher luminosity with less stored energy in the machine, but would impose the need for luminosity leveling at ATLAS and CMS.

UPGRADES

The present LHC will reach the end of its usefulness in the early 2020s, when the running time necessary to halve the statistical error in the measurements will be more than 10 years, making a substantial increase in luminosity necessary to maintain scientific progress. At the same time, the triplet and cleaning insertion magnets will reach the end of their lifetime due to radiation, and the limit of cooling and cryogenics systems will be reached (at $\approx 1.75 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. A novel machine configuration, called High Luminosity LHC (HL-LHC), will be installed during the LS3 to overcome these limitations.

High Luminosity LHC

The High Luminosity LHC (HL-LHC, [10]) is an approved project aiming at obtaining 3000 fb^{-1} within ten-twelve years of operation. This translates to the goal of an integrated luminosity of 250 fb^{-1} per year, i.e. about ten times the present LHC, which can achieved with peak luminosities of $5 \cdot 10^{34}\,\mathrm{cm^{-2}s^{-1}}$, leveled down from higher, "virtual" luminosities.

These specifications require a number of equipment upgrades. Large aperture magnets are needed for the IP quadrupoles to accommodate for very low beta star. Crab cavities are also needed to profit from the small beta star despite the large crossing angle. Additional dispersion suppressor collimators remove cleaning bottlenecks, but require the use of high field dipoles to free up space longitudinally to allow their installation. Additional cryogenics plants for P1, P4, P5 will provide the same cooling power in all arcs. The use of new, super-conducting links (300-700 m long) allow power converters to be moved to surface, effectively reducing radiation-induced risks and increase availability (critical aspect when working with leveled luminosities). Additionally, an upgrade of the LHC Injector Chain is foreseen that will help both beam brightness and availability, and an upgrade of the high-luminosity experiments will allow them to cope with higher pile-up density (i.e. 140 events per crossing).

Options for the Farther Future

The HL-LHC will also reach the end of its lifetime after 10-12 years of operation, i.e. in the mid-2030's. For the LHC, the lead time was about 25 years, so that similarly the design phase of a new accelerator should start now for it to be operational few years after the end of HL-LHC. A number of new designs are being studied at present at CERN, to take advantage of the existing accelerator complex and infrastructure.

Studies aiming at very high field magnets (16-20 Tesla) are ongoing [11], and would allow a High Energy LHC [12] to be installed in the LHC tunnel, that could reach center of mass energies of 26-33 TeV. With similar, high field magnets, and a tunnel with larger circumference (84-104 km), a Very High Energy LHC could be installed with center of mass energies of 100 TeV (see for example [13]).

Similarly to the LEP/LHC experience, where the same tunnel was reused for two different machines, lepton-proton collisions could be explored in the LHC tunnel with LHeC [14], or e+e- in the 84-104 km tunnel with TLEP [15.

CONCLUSIONS

The LHC is presently in a shutdown phase and operation with beam resume in early 2015 at a higher beam energy, the present baseline is 6.5 TeV. The use of 25 ns beams is imposed by the need to limit the pile-up and provide clean physics events to the experiments, but might bring other important issues along, as degraded beam parameters due to electron cloud effects or impaired machine availability due to excessive UFO rates. Work is already ongoing to prepare the High Luminosity upgrade of the LHC, that is supposed to start operating in about 10 years, and studies are taking place to devise what the next circular accelerator might look like.

ACKNOWLEDGEMENTS

The author would like to acknowledge the whole LHC team whose work was summarized in this paper, in particular G. Arduini, T. Baer, V. Kain, W. Herr, G. Iadarola, E. Metral, M. Pojer, L. Rossi, G. Rumolo, G. Spiezia, L.Tavian, J. P. Tock, F. Zimmermann. Additionally, a special mention goes to M. Lamont and J. Wenninger.

REFERENCES

[1] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, "LHC Design Report", CERN-2004-003-V-1.

[2] J. Jowett et al., "First run of the LHC as a heavy-ion collider", Proceedings of the 2nd International Particle Accelerator Conference (IPAC11), San Sebastian, Spain, 4-9 September 2011, TUPZ016.

[3] J. Jowett et al., "Proton-nucleus collisions in the LHC", Proceedings of the 4th International Particle Accelerator Conference (IPAC13), Shanghai, China, 12-17 May 2013, MOODB201.

[4] F. Bordry et al., "The First Long Shutdown (LS1) for the LHC", Proceedings of the 4th International Particle Accelerator Conference (IPAC13), Shanghai, China, 12-17 May 2013, MOZB202.

[5] E. Todesco et al., "Energy of the LHC after the 2013-2014 shutdown", Proceedings of the Chamonix 2012 Workshop on LHC Performance, Chamonix, 6-10 February 2012.

[6] G. Iadarola et al., "Electron cloud and scrubbing in 2012 in the LHC", Proceedings of the LHC Beam Operation workshop, Evian, 17-20 December 2012.

[7] T. Baer et al., "UFOs: observations, statistics and extrapolations", Proceedings of the LHC Beam Operation workshop, Evian, 17-20 December 2012.

[8] E. Metral et al., "Review of the instabilities observed during the 2012 run and actions taken", Proceedings of the LHC Beam Operation workshop, Evian, 17-20 December 2012.

[9] G. Spiezia et al.,"R2E - experience and outlook", Proceedings of the LHC Beam Operation workshop, Evian, 17-20 December 2012.

[10] L. Rossi, O. Brüning, "High Luminosity Large Hadron Collider A description for the European Strategy Preparatory Group", CERN-ATS-2012-236.

[11] P. Ferracin, "Review of Superconducting Magnet (LTS and HTS) Developments for Accelerator Applications", these proceedings, FRYAB1.

[12] O. Brüning et al., "High Energy LHC Document prepared for the European HEP strategy update", CERN-ATS-2012-236.

[13] O. Dominguez, F. Zimmermann, "Beam parameters and luminosity lifetime evolution for an 80-km VHE-LHCVHE", Proceedings of the 4th International Particle Accelerator Conference (IPAC13), Shanghai, China, 12-17 May 2013, TUPFI042.

[14] O. Brüning et al, "Overview of the LHeC Design Study at CERN", Proceedings of the 4th International Particle Accelerator Conference (IPAC13), Shanghai, China, 12-17 May 2013, MOZB201.

[15] M. Koratzinos et al., "TLEP: a high performance circular e+e- collider to study the Higgs boson", Proceedings of the 4th International Particle Accelerator Conference (IPAC13), Shanghai, China, 12-17 May 2013, TUPME040.

ISBN 978-3-95450-138-0