THE LHC RUN 2022

D. Jacquet, T. Argyropoulos, E. Bravin, A. Calia, M. Hostettler, E. Métral, D. Mirarchi, D. Nisbet, T. Persson, S. Redaelli, M. Solfaroli, G. Trad, J. Wenninger, CERN, Geneva, Switzerland

Abstract

Following a 3-year shutdown for upgrade and consolidation work, the LHC was re-commissioned in spring 2022, achieving a new record energy of 6.8 TeV per beam. This paper will describe the beam commissioning phase, the electron cloud conditioning, and the intensity ramp-up bringing the machine to a steady production state. The main issues and achievement will be presented, including the fully automated β* adjustment. The limitations for beam intensity and peak luminosity will also be discussed.

INTRODUCTION

Since the LHC [1] start-up in 2009, periods of 3-4 years of operation (runs) alternate with periods of long shut down (LS). After 2 successful runs, the long shut down 2 (LS2) [2] started in 2018. The main purpose of LS2 was the LHC Injectors Upgrade (LIU) [3]. Nevertheless, LHC profited from this period to perform full maintenance of all the equipment, to consolidate part of the machine and to anticipate activities, where possible, of the LHC High Luminosity (HL-LHC) project [4]. For Run3, it was foreseen to run at the LHC design energy of 7 TeV, to be compared to the Run2 value of 6.5 TeV. With this new energy combined with a much brighter beam from the injectors after LIU, the LHC performance for Run3 was expected to be much higher than in Run 1 and 2. This paper describes how the LHC restarted after LS2, with the first promising results of the performance in 2022, auguring well for the rest of the run.

RECOVERY FROM LS2

Originally planned for 18 months, LS2 was much longer than expected for the LHC, with a first beam test only possible in October 2021, 3 years after the start of the shutdown. The delays were attributed to the impact of COVID, in particular for the experiments, and will not be described.

The re-commissioning of the LHC superconducting circuits [5] consists of a series of tests performed on each of the 1700 circuits [6] of the LHC. Most notably, after a thermal cycle, the superconducting magnets with high current need to be 'trained'. This involves repetitive quenches [7] before the target current is reached. For the 1232 main dipoles where the current is the highest (11850A at 7 TeV), the training campaign takes several months, as more quenches are necessary to gain a small intensity step [8]. The LHC dipoles are organised in 8 independently powered sectors that can be commissioned independently. During the training campaign it was observed that the training of the magnets in some sectors was progressing much slower than in others, and it became clear that the 6 months planned for HW commissioning was very tight to achieve the target powering to 7 TeV. In addition, in April 2021 there was a short circuit in one magnet of sector 78, implying a magnet exchange and a full recommissioning of the sector after an additional thermal cycle. In May, a diode short-circuit developed in sector 23, implying an exchange of the diode and consequently a thermal cycle. This second incident was due to a non-conformity of the diode, which turned out to be present in other magnets with the same risk of damage in case of a quench. With the already accumulated delays and the risk to have additional short-circuits, it was decided to target the energy of 6.8 TeV instead of 7 TeV for Run3. At the end of October 2021, the LHC hardware commissioning was completed, the only exception being the training campaign of the main dipoles and quadrupoles of sector 23. It was therefore decided to perform a one-week test with beam, at injection energy. All the systems were successfully recommissioned with beam, but an aperture limitation in sector 23 was discovered due to a bent RF finger [9], not compatible with high-intensity proton operation. The repair required a warm-up of the sector 23 and its full recommissioning. After the additional thermal cycle, the dipole and quadrupole re-training of sector 23 took longer than expected, the reason for which is something that is yet to be clearly understood.

RUN3 START-UP IN 2022

This was not the end of the delays for the start of Run3. Indeed, the conditioning of the RF cavities was just completed when a failure of a control card of a PLC of a ventilation equipment produced the loss of control of the cryogenic system. During the fault recovery, a premature opening of a rupture disk (exchanged during LS2) led to air contamination of the RF cavities [10]. Half of the LHC RF systems needed to be warmed-up to room temperature to avoid the risk of contamination of the cryogenic cooling circuit. They were then cooled down again, with a full cavity reconditioning and low-level set-up, implying 2.5 weeks lost for physics. In August during the physics run, a similar incident occurred, stopping the beam for one month. A task force was established to define and implement mitigation measures for this issue during the 2022-2023 winter shutdown [11, 12].

As a last modification to the schedule, with the energy crisis in Europe, it was decided to stop the 2022 run 2 weeks early to save energy consumption. All these accumulated delays, together with the anticipated end of run, implied a loss of 22.6% of the physics days compared to the original schedule established in December 2021, with an 18% reduction in proton physics and a cancelled ion run.

BEAM COMMISSIONING

After 3 years without beam (except the short, but very useful week of beam test in 2021), a 3 -month beam commissioning program was necessary to bring the LHC from the first pilot beam (10^{10} p/b) at injection to the first 6.8 TeV collisions with nominal bunch intensity (1.2×10^{11} p/b initially then increased to 1.45×10^{11}).

First, the ring trajectory was established through the threading process [13] and the first pilot beam (10^{10} p/b) was circulated, allowing the closed orbit to be corrected. Individual systems were commissioned with beam such as injection and beam dump kickers, injection protection [14], RF low-level and transverse dampers etc... The operational cycle (ramp, squeeze, collisions) was established and fully validated with pilot beam: optics measurement and corrections [15], collimator alignment [16] and validation of their hierarchy with loss maps [17], as well as aperture measurements, were done with the defined reference configuration for nominal bunch intensity. A period of collisions at injection was given for the experimental detector commissioning.

The first beam was injected on the 22nd of April with the first declaration of "stable beam" (stable luminosity production period for experiment data taking) at 6.8TeV on the 5th of July marking the end of the beam commissioning period. A media event was organized to celebrate the first proton collisions at the new world record centre-of-mass energy of 13.6 TeV [18].

SCRUBBING

The build-up of electron clouds (e-clouds) due to secondary electron emission from the beam screens following the passage of high-intensity beams is one of the major performance limitations of the LHC [19]. After LS2, with the machine fully opened, beam screens were exposed to air and fully de-conditioned regarding e-cloud. In order to reduce the e-cloud to an acceptable level before operation with 25ns bunch trains, the machine needed to be scrubbed [20]. The scrubbing process involves a gradual increase of the number of bunches and intensity, keeping the generated e-cloud as high as possible for an efficient conditioning of the vacuum surfaces. 8 days were dedicated to scrubbing at 450 GeV during the beam commissioning period. The scrubbing was very efficient, only limited by the pressure rise in the injection kicker, which nevertheless conditioned rapidly. Most of the sectors quickly recovered the conditions of Run2, apart from sector 78 where the secondary electron yield (SEY) remained unexpectedly high and increased heat load on the cold vacuum surfaces. After the scrubbing period, the quality of the bunch train was good enough to start physics but required high chromaticity and octupoles settings to stabilise the beams. It was anticipated that the conditioning would continue during the intensity ramp-up and physics period, but this proved to proceed much slower than expected.

INTENSITY RAMP-UP

After achieving the first stable beams with a few nominal bunches, the beam intensity was gradually increased. The strategy was first to increase the number of bunches in steps of ~300, then to gradually increase the intensity per bunch once the maximum number of bunches had been achieved. As part of the machine protection strategy, each intensity step needed to be validated with a minimum of 3 successful fills and a total of 20 hours of stable beams. In addition, a team composed of different system experts (the machine protection panel) formally approved that it was safe to proceed to the next step [21]. In 2022, around 1 month was necessary to reach 2400 bunches with 1.2×10^{11} protons/bunch (Fig 1). At this point the intensity ramp-up was stopped due to the e-cloud heat-load limitation in sector 78.

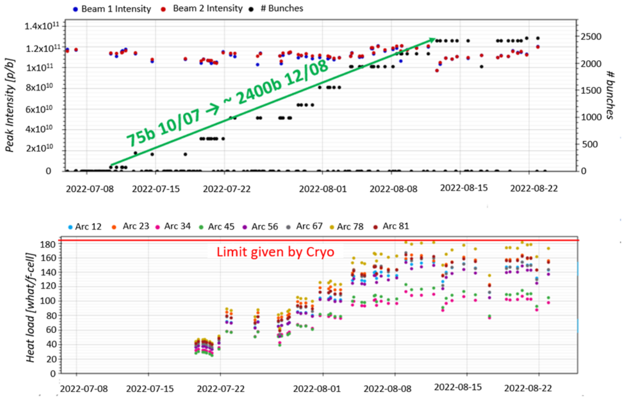

Figure 1: Evolution of bunch intensity and number of bunches during the intensity ramp-up (top) and the corresponding heat-load by sector (bottom).

PERFORMANCE AND LIMITATIONS

Availability

Excluding the downtime due to the RF incidents, the availability in 2022 was good and reached 76% of the allocated operation time. In addition to the usual equipment faults in LHC or in the injectors, there was additional downtime due to magnet training quenches. Despite the long training campaign of the main dipoles and subsequent tests carried out above their maximum operational current, 14 training quenches occurred during beam operation, with a minimum downtime of 8h each time for the cryogenic system to recover. For this reason, during the LHC for RF system issue in September, all dipoles were ramped several times to their nominal current +100A and left there several hours. This was very efficient to anticipate further quenches, with six quenches experienced during this period, and only one additional training quench seen during beam operation in the rest of 2022. Training quenches are therefore not expected to be an issue for the remainder of Run3 (unless a thermal cycle of a sector needs to be performed).

After the machine is exposed to air during a long shutdown, a high rate of Unidentified Falling Objects (UFOs) [22] is expected at start-up. UFOs are believed to be small dust particles that interact with the beam, generating sudden losses that can exceed the thresholds of the beam loss monitoring (BLM) system, causing a beam dump. The biggest UFOs may also induce enough losses to provoke a magnet quench. During previous LHC runs, this happened on average 2-3 times a year.

The UFO rate in 2022 was lower than expected and conditioning faster than in Run2 [23]. Nevertheless, 23 fills were dumped by arc UFOs in 2022, which is twice the number of UFO dumps that occurred during the worse year of Run2. This can be explained by the reduction of the BLM thresholds at the location of the dipoles having a diode non-conformity, as quench on these magnets could lead to damage requiring magnet exchange. After analysis, only 2 or 3 of these dumps really prevented quenches, but the unnecessary dumps and induced downtime are acceptable regarding mitigating the risk of magnet damage. The UFO rate is expected to further condition, even with increased intensity, with a limited number of dumps foreseen for the rest of Run3.

Heat load

As already mentioned, after the scrubbing period, the sector 78 beam screen heat-load remained higher than the other sectors and was not conditioning during the intensity ramp-up, such that the cryogenic system reached its cooling capacity limit. This in turn limited the maximum number of bunches to 2400 instead of the 2750 initially planned. To reduce the e-cloud and optimize the performance for the given the heat load limit [24], the injected beam pattern was modified from 5 trains of 48 bunches to 5 trains of 36 bunches, as the e-cloud is lower when the trains are shorter. It gave enough heat load margin to increase the intensity per bunch to 1.45×10^{11}p/b. Alternative bunch patterns were also tested, like the 8b4e (8 bunches followed by 4 empty slots) beam pattern that is very favourable for e-cloud. [25]. However, as this pattern reduces considerably the total number of bunches that can be stored in the machine, it is not the preferred solution for luminosity production. As a compromise, a hybrid scheme, where some of the 25ns bunch trains are replaced with an 8b4e train was also tested. This gave very good results with the heat-load reduced by 20%, with only a 5% reduction in the total number of bunches that can be stored. This seems to be the best compromise to maximize the integrated luminosity for the rest of Run3.

Maximum Instantaneous Luminosity

The 'triplets magnets' are the quadrupoles responsible for the strong focusing of the beams at the interaction point. As they are longitudinally close to the collision points, they are showered by collision's debris [26]. The higher the luminosity, the more heat-load is induced in the triplets due to the energy deposition from these debris. The cryogenic cooling capacity available to extract this heat load limits the instantaneous luminosity in the experiments.

During 2022, this limit was not reached in operation as the luminosity was limited by the pile-up the experiments could handle. Nevertheless, a dedicated test was performed to define the maximum instantaneous luminosity acceptable by the cryogenic system [27]. A record luminosity was established during the test, at the value of $2.6.10^{34}$ cm^{-2}s^{-1} and it was shown that it is safe to operate reliably up to $2.2.10^{34}$ cm^{-2}s^{-1}, with the possibility up to $2.4.10^{34}$ cm^{-2}s^{-1}.

Performance

Figure 2 shows the peak and integrated luminosity of 41fb^{-1} achieved of in 2022, which was much beyond the original target of 25 fb^{-1}, Table 1 lists the machine parameters used in 2022. In addition to a very good availability towards the end of the run, sometimes reaching to 60% of time in stable beams over a week of operation, the integrated luminosity was maximized during stable beams thanks to the β* levelling process [28] that was used for the first time in operation in 2022. This starts with a β* of 60 cm, which with a bunch intensity of 1.4×10^{11} p/b, means that ATLAS and CMS are already at their maximum pile-up μ=54. This target pile-up is kept within a 5% margin, as the intensity decreases, by automatically changing the optics to reduce the β*, so reducing the beam size at the collision point. The process stops when β* reaches 30 cm.

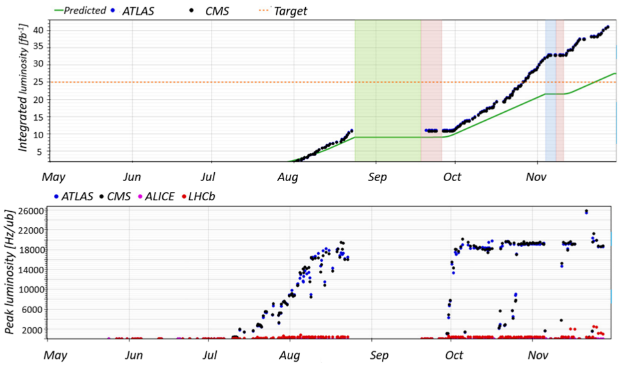

Figure 2: 2022 Peak luminosities(bottom) in all IPs and integrated luminosity in ATLAS & CMS (top)

Table 1: LHC Parameters in 2022

Beam energy	6.8 TeV
Max Bunch Intensity	$1.46\text{x}10^{11}$ p/b
Max number of bunches	2462
Max stored energy per beam	~400 MJ
Transverse Emittance in collision(H&V)	1.75 µm
β* range for levelling	60cm-30cm
Peak luminosity (ATLAS&CMS)	$1.9.10^{34}$ cm^{-2}s^{-1}

CONCLUSION AND OUTLOOK FOR 2023

After 3 years without physics, 2022 was expected to be a challenging year for the LHC with a higher collision energy and brighter beams from the injectors. Despite the difficulties encountered, the performance was beyond all the most optimistic expectations. A lot was learned regarding the intensity limitations in the LHC as well as in the injectors [29]. The heat-load will be one of the main challenges going forward, but using bunch patterns favourable for reduced e-cloud should nevertheless allow a bunch intensity increase up to $1.8.10^{11}$ p/b, the limit for the current LHC due to robustness issues with the beam dump system. With the new operational cycle configuration for 2023 [30], the β* levelling range will be extended from 1.2 m to 30 cm. In addition, the acceptable pile-up in ATLAS and CMS will be increased to $\mu = 65$. It is therefore expected that the machine performance will allow for an integrated luminosity of 75 fb^{-1} in 2023.

REFERENCES

[1] L. Evans and P. Bryant, “LHC Machine”, Institute of physics publishing and SISSA, August 2008, CERN, Geneva, Switzerland.

[2] K. Hanke *et al.*, “The LHC Injectors Upgrade (LIU) Project at CERN: Proton Injector Chain”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 3335-3338. doi:10.18429/JACoW-IPAC2017-WEPVA036

[3] J. Ph. G. L *et al.*, “The Second LHC Long Shutdown (LS2) for the Superconducting Magnets”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 240-243. doi:10.18429/JACoW-IPAC2018-MOPMF056

[4] B. Alonso, L. Rossi, “The HiLumi LHC Technical Design Report”, CERN-ACC-2015-0140, 2015.

[5] A. Apollonio *et al.*, “Summary of the Post-Long Shutdown 2 LHC Hardware Commissioning Campaign”, in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 335-338. doi:10.18429/JACoW-IPAC2022-MOPOPT040

[6] M. Zerlauth, A. Jimeno, G. Morpurgo, and R. Schmidt, “The Electrical Circuit Description for the LHC”, in *Proc. EPAC'02*, Paris, France, Jun. 2002, paper MOPDO014, pp. 2058-2060.

[7] A. Siemko, “Magnet quench process”, presented at the 11th LHC Chamonix workshop, Chamonix, France, 2001. https://cds.cern.ch/record/567209/files/7-4-as.pdf

[8] A. Verweij, “Training campaign analysis & quenches during operation”, presented at the LHC Chamonix Workshop 2023, Chamonix, France, 2023. https://indico.cern.ch/event/1224987/contributions/5153711

[9] E. Métral *et al.*, “Lessons Learned and Mitigation Measures for the CERN LHC Equipment with RF Fingers”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper TUPWA042, pp. 1802-1804.

[10] D. Boussard and T. Linnecar, “The LHC superconducting Rf system”, presented at the 1999 Cryogenic Engineering and International Cryogenic Materials Conference (CEC-IC-MC'99), 12-16 July 1999, Montreal, Canada.

[11] W. Venturini *et al*., “RF burst disk task force status report”, presented at the LHC machine committee, Geneva, Suisse, August 2022, https://indico.cern.ch/event/1184331/contributions/4984264

[12] W. Venturini *et al*., “RF burst disk task force status report”, presented at the LHC machine committee, Geneva, Suisse, December 2022, https://indico.cern.ch/event/1228297/contributions/5168375/

[13] H. Grote, “Beam Threading in the LHC”, in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper THP05B, pp. 1277-1279.

[14] W. Bartmann *et al.*, “Beam Commissioning of the Injection Protection Systems of the LHC”, in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper TUPEB067, pp. 1674-1676.

[15] F. Carlier *et al*. “LHC Run3 Optics Corrections” presented at the 14th International Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper MOPL015, this Conference.

[16] G. Azzopardi, B. Salvachua, and G. Valentino, “The Automatic LHC Collimator Beam-Based Alignment Software Package”, in *Proc. ICALEPCS'21*, Shanghai, China, Oct. 2021, pp. 659-664. doi:10.18429/JACoW-ICALEPCS2021-WEPV016

[17] A. Frasca *et al.* “Collimation performance at the 400MJ LHC beam at 6.8 TeV” presented at the 14th international Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper TUPM119, this Conference.

[18] Live from Cern, recorded the 5th of July 2022, CERN, Geneva, https://www.youtube.com/watch?v=06kFq1QF5-s

[19] G. Rumolo *et al.*, “Electron Cloud Effects at the LHC and LHC Injectors”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 30-36. doi:10.18429/JACoW-IPAC2017-MOZA1

[20] L. Mether *et al*. “Electron cloud observations and mitigation for the LHC Run 3” presented at the 14th international Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper WEPA091, this Conference.

[21] D. Wollmann, R. Schmidt, J. Wenninger, and M. Zerlauth, “Machine Protection at the LHC - Experience of Three Years Running and Outlook for Operation at Nominal Energy”, in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPEA046, pp. 3246-3248.

[22] B. Lindstrom *et al.*, “Results of UFO Dynamics Studies with Beam in the LHC”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2914-2917. doi:10.18429/JACoW-IPAC2018-THYGBD2

[23] D. Jacquet *et al.*, “The LHC cycle, settings and efficiency”, presented at the LHC Chamonix Workshop 2023, Chamonix, France, 2023, https://indico.cern.ch/event/1224987/contributions/5153318

[24] G. H. I. Maury Cuna, G. Iadarola, G. Rumolo, and F. Zimmermann, “Simulation of electron-cloud heat load for the cold arcs of the large hadron collider”, in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper MOPPC001, pp. 115-117.

[25] H. Bartosik, G. Rumolo, “Beams from the injectors”, in *Proc. 7th Evian Workshop on LHC beam operation*, Evian-LesBains, France, Dec. 2016, pp. 233-238.

[26] E. Y. Wildner *et al.*, “Energy Deposited in the High Luminosity Inner Triplets of the LHC by Collision Debris”, in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper WEPP031, pp. 2587-2589.

[27] B. Bradu *et al.*, “Cryogenics,2022 experience and options for the future”, presented at the LHC Chamonix Workshop 2023, Chamonix, France, 2023, https://indico.cern.ch/event/1224987/contributions/5153545/

[28] M. Hostettler *et al*. “Operational beta* levelling at the LHC in 2022 and beyond” presented at the 14th international Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper MOPL045, this Conference.

[29] C. Zannini *et al.* “Beam induced heating mitigation of the SPS kickers: a crucial upgrade to move towards HL-LHC beam intensities” presented at the 14th international Particle Accelerator Conf. (IPAC'23), Venice, Italy, May 2023, paper WEPL157, this Conference.

[30] S. Fartoukh *et al.*, “LHC Configuration and Operational Scenario for Run 3”, Tech. Rep. CERN-ACC-2021-0007, CERN, Geneva, Switzerland, 2021, https://cds.cern.ch/record/2790409