ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC17

OPERATION OF THE LHC DURING THE 2023 PROTON RUN

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

Abstract

In 2023 the LHC restarted after the yearly winter shutdown with a new machine configuration optimized for intensities of up to $1.8 \cdot 10^{11}$ protons per bunch. In the first two months of the 2023 run the bunch intensities were pushed up to $1.6 \cdot 10^{11}$ ppb, until a severe vacuum degradation, caused by a damaged RF bridge, occurred close to the ATLAS experiment. Following repair, the decision was taken to stop the intensity increase. After a period of smooth operation, a leak developed between the cold mass and insulation vacuum of a low-beta quadrupole, leading to an abrupt stop of the LHC. Thanks to a rapid intervention, the leak could be repaired without warming up large parts of the machine, and the LHC was ready for beam again in early September. Special runs at very large beta* were completed in the remaining time, before switching to lead ion operation. The performance and limitations as well as the issues that were encountered over the year will be discussed in this paper.

INTRODUCTION

Every winter of a Run, the LHC is shutdown for a minimum period of 15 weeks, the so-called Year End Technical Stop (YETS), for maintenance and minor upgrades of the machine and of the experiments. The 2022-2023 YETS officially ended on the 9th of March 2023, with the successful completion of the access system safety tests.

The proton physics objective for 2023 was to collect an integrated luminosity of $75\,\mathrm{fb}^{-1}$ at an energy of 6.8 TeV, with the bunch intensity gradually increasing to reach $1.8 \cdot 10^{11}$ ppb. 97 days were allocated on the planning for proton physics. This contribution will focus on the proton physics part of the LHC 2023 Run.

HARDWARE COMMISSIONING

Before commissioning the LHC with beam, all LHC systems are tested and validated. Powering tests of the more than 1700 superconducting circuits of the LHC [1] are the main activity of the Hardware commissioning phase, which lasted 16 days in 2023. During this phase, particular attention is put on the circuits of the 1232 main dipoles with the highest stored magnetic energy. With the same target energy of 6.8 TeV as in 2022, no dipole magnet training quench [2] was observed. The powering test campaign for 2023 concluded successfully with over 10000 tests performed and analysed.

In parallel with powering tests, all the LHC Individual System Tests (ISTs) are performed: RF (including conditioning of the cavities), injection kickers, dump system, transverse dampers, collimators and beam instrumentation.

BEAM COMMISSIONING

During the beam commissioning phase the machine is setup and optimized for physics production. The first step is to steer the beams down the SPS-LHC transfer lines and to establish a closed orbit after threading the beam around the ring, a step-wise steering process done by limiting beam circulation using collimators [3]. First circulating beam was established on 28th of March 2023. The first phase of the beam commissioning is performed with only a few pilot bunches with an intensity of around 10^{10} ppb. The beam optics is corrected from injection to collisions, the collimation system is setup and the aperture of the machine is checked. During this phase, it was verified that vertex detector of the LHCb experiment (VELO) did not pose an aperture bottleneck, which was particularly important following an incident with its RF foil [4] at the beginning of the year.

Once the optics is corrected and the orbit setup and machine configuration established, a campaign of loss maps is performed. This involves the controlled blowup of individual bunches to ensure that beam losses are well contained within the collimation sections. Asynchronous beam dumps are simulated with low intensity beams by de-bunching the beam, thus populating the abort gap.

The first fill with stable collisions was performed on 21st of April 2023, starting the 2023 physics production.

INTENSITY RAMP-UP

During the intensity ramp-up the number of bunches in the beams is gradually increased from 3 to 2400 bunches per beam in steps of 400-600 bunches. Additionally, the bunch intensity was also increased from around 1.4×10^{11} ppb to 1.6×10^{11} ppb. For each intensity step, at least two fills totalling at least 15 hours with stable collisions are required. Once a step is completed, system experts fill a checklist, assess the status of their systems and give the green light for the following step.

A limitation during the intensity ramp-up is the presence of electron cloud (e-cloud) due to secondary electron emission from the beam screens caused by the passage of high intensity beams at 25ns spacing [5]. The vacuum chamber surfaces condition to a certain extend when operating with high intensity beams. To accelerate the conditioning, 2 days of dedicated conditioning sessions at injection energy (called "scrubbing" [6]) were scheduled, where an increasing number of 25ns bunch trains are injected to "scrub" the surface of the vacuum chamber.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC17

MAJOR ISSUES

RF Disk Rupture

During beam commissioning, a power glitch in LHC Point 4 led to the loss of cryogenic conditions and a subsequent pressure increase of helium in the RF cavities. Even though the pressure release valves correctly opened, the pressure increase was too high and the cavity rupture discs burst. The fast reaction of the RF team as well as the improvement of the safety system implemented in 2022 [7], allowed the downtime due to this incident to be reduced to 2 days. This event led to further mitigation measures being implemented in YETS 2023-2024 to avoid future incidents.

Damaged RF Bridge

RF bridges are structures that ensure electrical field continuity between the interconnections of the different parts of vacuum chambers and in vacuum-equipment [8]. For room temperature vacuum chambers, the current implementation is based on flexible structures (so-called "RF fingers") kept in place via metallic springs. Degradation of these structures can lead to beam impedance-induced local heating. During the intensity ramp-up, at $1.6 \cdot 10^{11}$ ppb and 2358 bunches, vacuum spikes were observed in sector 4L1 close to ATLAS experiment. The degraded vacuum resulted in significant losses in the machine, leading to beam dumps. High intensity operation had to be interrupted for investigation. The intervention revealed a damaged RF bridge which was quickly exchanged before the area was re-conditioned with beam for a few days and nominal operation could resume. The same RF bridge design is present in around 100 room temperature interconnects of the LHC. Consequently, it was decided to limit the bunch intensity to $1.6 \cdot 10^{11}$ ppb for 2023 to limit the risk of further issues. A campaign to replace as many similar RF bridges as possible was undertaken during YETS 2023-2024.

Low-Beta Triplet Magnet Incident

On the 17th of July, during proton physics production, a short electrical network interruption triggered the quench heaters of several LHC magnets. The LHC Quench Protection System (QPS) can be affected by such small electrical perturbations, given the required sensitivity to voltage changes necessary to safely detect a magnet quench. In this event it included the low-beta quadrupole triplet (IT) on the left side of point 8 near the LHCb experiment. Due to the large heat generated by the magnet quench, the pressure inside the cold masses increased to 18 bars. Although the system is designed to cope with this, in this case the pressure inside the insulation vacuum started to rise, reaching atmospheric pressure in about 8 hours. After a thorough investigation, a leak was identified between the Helium filled magnet assembly and the insulation vacuum, on an edge-welded bellow of a magnet interconnection.

After a remarkably fast and precise intervention, the interconnection bellow was removed and a spare component welded in situ. The cryogenic team implemented a novel procedure for isolating the entire sector while keeping the temperature within the access safety and thermal cycle threshold limits [9]. This avoided the need for a full thermal cycle of the sector affected by the intervention, allowing the LHC to be ready for beam after a stop of only 6 weeks.

Vacuum Leaks on Injection Protection Device

The injection protection device (TDIS) is an absorber composed of three modules, each with two vertical jaws, aimed at protecting LHC equipment in the event of a failure of the injection kickers.

At the end of August a continuous vacuum degradation in the TDIS in Point 8 (injection of beam 2) was observed and was traced to two vacuum leaks on vacuum bellows. The leaks were varnished and two TDIS modules were blocked open to avoid additional stress on these bellows. Due to the reduced protection provided in such conditions, high intensity proton operation had to be stopped. Only operation for special proton physics at very large β^* and low intensity and lead ion operation was considered acceptable for the remainder of the year [10]. The TDIS for both beams where exchanged during YETS 2023-2024.

PERFORMANCE AND LIMITATIONS

Availability

The availability of the LHC for proton operation in 2023 was strongly affected by the three major faults described previously. Excluding those stops, the LHC achieved 75.9% availability for proton physics with 51.6% of the time spent with colliding beams. These figures are in line, if not better, than in previous years.The contribution of short faults (<24 hours) is significant, their total downtime amounts to 15.9% of the scheduled run time [11]. However, the contribution of short faults is practically constant during Run2 and Run3, indicating no sign of degradation of the various LHC systems. Both the 2022 and 2023 availability was, nevertheless, dominated by a few large faults (>24h) [12].

Electron cloud heat load

Heat-load deposited by electron cloud in the LHC beam screen is one of the limiting factors of the LHC performance, as this must be absorbed by the LHC cryogenic system.

The e-cloud impact on LHC was not significant in 2023, thanks to the conditioning effect of beam and the use of a filling scheme mixing a standard beam comprised of trains of 36 bunches spaced by 25 ns and a special beam, called 8b4e, consisting of 8 bunches spaced by 25 ns followed by 4 empty 25 ns bunch slots [6]. The "empty" spaces in the filling scheme reduce the build-up of e-cloud over the 8b4e beam, considerably reducing its impact. This configuration comes at the price of a reduced number of bunches due to these empty slots, an increased workload in the injectors to maintain two LHC beam types and a reduced quality of the beam, with a less homogeneous bunch by bunch distribution. With this filling scheme the heat-load was not a limiting factor in

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC17

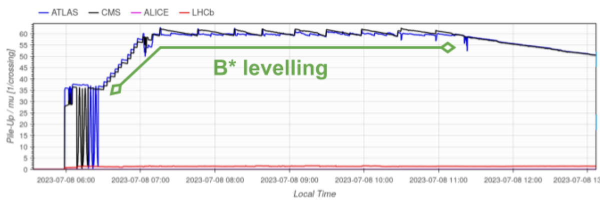

Figure 1: Luminosity evolution for a typical fill in 2023. The β^* levelling, highlighted in green, starts the beams are colliding and an emittance scan is performed. It lasts several hours and maintains the desired target pile-up. The fast β^* descent from 120 cm to 60 cm can be seen at the start.

2023, being consistently below 150 W/half − cell for a cryogenic cooling capacity limit of around 200 W/half − cell.

Performance

The LHC peak luminosity is limited by the cryogenic cooling capacity of the low-beta triplet quadrupoles to around $2.5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$. The luminosity should be maintained roughly 10% below that maximum for stable operation. A second limitation arises from the experimental event pile-up, which corresponds to the number of overlapping proton collisions for each bunch crossing. The LHC high luminosity experiments, ATLAS and CMS, are limited to pile-up values between 60 and 65.

Because the LHC peak luminosity at the lowest achievable β^* of 30 cm largely exceeds both peak luminosity and pile-up limits, the luminosity must be levelled. This operation has been performed since the start of LHC on both low luminosity experiments, ALICE and LHCb, by means of transverse beam offsets. Since Run3, β^* levelling has become the primary technique to keep a steady level of luminosity production for the high luminosity experiments ATLAS and CMS. After the energy ramp to 6.8 TeV and a small squeeze segment, the beams are collided at a β^* of 1.2 m. With colliding beams, the $\beta^*$is lowered in 10 steps to 30 cm, see Fig 1.

The optics, collimation system and cycle of the LHC for 2023 were optimized for a bunch intensity of $1.8 \cdot 10^{11}$ ppb [13], which was set as a target for 2023. Given the limitation of $1.6 \cdot 10^{11}$ ppb following the vacuum module issue, the peak pile-up is not reached for β^* 1.2 m. The first steps of β^* levelling could be transitioned over, until the peak pile-up was reached around 60 cm β^*, see Fig. 1.

The evolution of the LHC peak luminosity is shown in Fig. 2, with record values during 2023 production. The stored energy in each beam reached a new record of 430 MJ.

The long faults described previously severely impacted the proton run performance. The best production period in 2023 covered the two weeks from 4th to 17th July [14] (just before the triplet incident). Over this period, the average daily production reached $0.79\,\mathrm{fb^{-1}}$, Fig. 3, with a new record production over 24 hours of $1.2\,\mathrm{fb^{-1}}$ [15]. The integrated luminosity produced in 2023 amounted to $32\,\mathrm{fb^{-1}}$, corresponding to 49% of the goal. At this average production rate, without the three major incidents, the LHC would have achieved the production goal of $75\,\mathrm{fb^{-1}}$ within the scheduled days.

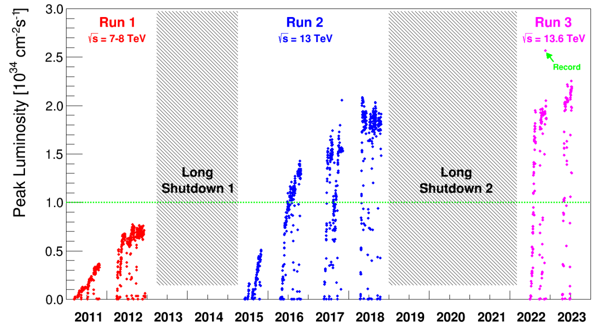

Figure 2: LHC peak luminosity between 2011 and 2023.

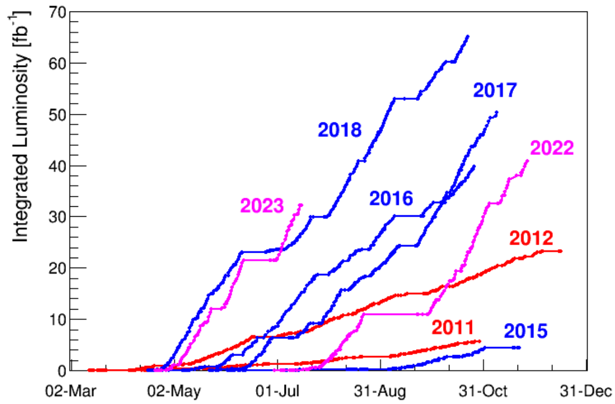

Figure 3: The luminosity production of the LHC.The average daily production in 2023 was $0.79\,\mathrm{fb^{-1}}$.

HIGH BETA RUN

Dedicated forward physics runs are scheduled periodically in the LHC. Forward physics requires very low divergence beams at the collision points with very high β^* values ranging from 90 m to 6 km [16, 17].

In September 2023 the last dedicated high β^* run planned for the LHC was successfully completed. The run used a special optics to record data at 3/6 km β^*. Crystal collimators were used during this run to achieve the required low background levels [18]. Integrated luminosities of $300/329\,\mathrm{ub^{-1}}$ were delivered to the TOTEM and ALFA experiments, respectively, over 70 hours of physics production.

CONCLUSIONS AND OUTLOOK FOR 2024

The LHC 2023 run was challenging. Major incidents significantly reduced the available physics production time. Nevertheless, the last planned High β^* run was successfully performed, the average daily proton physics production met expectations, and a peak luminosity record was achieved. Novel β^* levelling techniques were tested to reach this peak performance and they will be part of the operational cycle in 2024.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC17

REFERENCES

[1] 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.

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

[3] H. Grote, "Beam Threading in the LHC", in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper THP05B, pp. 1277–1279.

[4] R. Ferreira, "LHCb VeLo vacuum recovery and vacuum safety system for 2023", presented at the 233rd Machine Protection Panel Meeting for LHC - Joint meeting with CollWG, Meyrin, Switzerland, Mar. 2023. https://indico.cern.ch/event/1261512/contributions/5298521/

[5] 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

[6] L. Mether *et al.*, "Electron cloud observations and mitigation for the LHC Run 3", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2850–2853. doi:10.18429/JACoW-IPAC2023-WEPA091

[7] W. Venturini *et al.*, "RF burst disk task force status report", presented at the LHC Machine Committee, Meyrin, Switzerland, Dec. 2022. https://indico.cern.ch/event/1228297/contributions/5168375/

[8] D. Ramos, "Modeling of the RF-shield Sliding Contact Fingers for the LHC Cryogenic Beam Vacuum Interconnects Using Implicit and Explicit Finite Element Formulations", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper TUPD035, pp. 1503–1505.

[9] B. Bradu, "LHC Cryogenic Status and Scenarios", presented at the LHC Machine Committee, Meyrin, Switzerland, Jul. 2023. https://indico.cern.ch/event/1298992/contributions/5510270/

[10] A. Lechner, "TDIS Limitations and Implications on Filling Schemes", presented at the LHC Machine Committee, Meyrin, Switzerland, Sept. 2023. https://indico.cern.ch/event/1299139/contributions/5583565/

[11] G. Trad, "Overcoming performance limitations for LHC proton operation: strategy and configuration for Run 3", presented at the LHC Chamonix Workshop, Chamonix, France, Jan. 2024. https://indico.cern.ch/event/1343931/contributions/5672249/

[12] L. Felsberger, "LHC availability in 2023", presented at the Joint Accelerator Performance Workshop, Montreux, Switzerland, Dec. 2023. https://indico.cern.ch/event/1337597/contributions/5634959/

[13] F. Van der Veken, R. Bruce, M. Hostettler, D. Mirarchi and S. Redaelli, "LHC Beam Collimation During Extended β*-Levelling in Run 3", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2138–2141. doi:10.18429/JACoW-IPAC2022-WEPOTK034

[14] M. Solfaroli, "Summary of LHC operation: issues and prospects for Run 3", presented at the Joint Accelerator Performance Workshop, Montreux, Switzerland, 2023. https://indico.cern.ch/event/1337597/contributions/5634011/

[15] T. Persson, "Status of the Accelerator", presented at the 154th LHCC Meeting, Meyrin, Switzerland, Jun. 2023. https://indico.cern.ch/event/1284315/contributions/5396300/

[16] TOTEM Collaboration *et al.*, "First determination of the ρ parameter at $\sqrt{s}$ = 13 TeV – probing the existence of a colourless three-gluon bound state", *Eur. Phys. J. C*, vol. 79, no. 785, Feb. 2019. doi:10.1140/epjc/s10052-019-7223-4

[17] I. Efthymiopoulos, D. Mirarchi, M. Solfaroli, S. Redaelli, S. Fartoukh, T. Persson, "Evolution of special LHC optics configurations: Run 3 update", presented at *Proc. IPAC'24*, Nashville, USA, May 2024, paper MOPC16, this conference.

[18] D. Mirarchi *et al.*, "Reducing Beam-Related Background on Forward Physics Detectors Using Crystal Collimation at the Large Hadron Collider", *Phys. Rev. Appl.*, vol. 14, no. 6, Dec. 2020. doi:10.1103/PhysRevApplied.14.064066