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First results of the cryogenics operation from the LHC physics Run 3 at the increased energy to 6.8 TeV

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Abstract. Back in 2018, LHC completed its Run 2 physics period. Consolidation, maintenance, and upgrade activities performed during the subsequent Long Shutdown 2 period (LS2), based on a data-driven approach, allowed for full potential availability of the LHC cryogenics infrastructure before tackling the 2021 magnet quench training campaign, preparing the whole machine for operation at the increased energy of 6.8 TeV. This paper will first give a summary of the main upgrades, consolidations and maintenance performed during the LS2. Magnet training of the machine to the increased energy of 6.8 TeV will be addressed. Results of the first year (2022) of Run 3 physics will be presented, achieving high cryogenic availability in a heavily sustained operational context of the accelerator (beams energy increase, induced heat load, peak & integrated luminosity). Helium inventory management aspects will be discussed, with a particular highlight on the necessary operational adjustments taken to cope with the present supply market evolution. Implementation of several operational modes for cryogenic plants will be presented, towards significant electrical power savings while maintaining nominal physics production at the highest availability rate.

1. Introduction

During Run 2 period from 2015 to 2018 inclusive, the LHC was operated at the energy of 6.5 TeV with intensity up to 3.2 10^{14} protons/beam, while the peak luminosity reached the level of 2.2 10^{34} cm^{-2}/s, well above the 10^{34} cm^{-2}/s value of the LHC Design Report. Entering its second major maintenance period – Long Shutdown 2 (LS2) – in early 2019, the cryogenic system went through a necessary major overhauling, consolidation, and upgrade program of one year, allowing for full restoration of its potential and preparation for the operation of the accelerator at the increased energy of 6.8 TeV, through dedicated magnet quench training campaign.

Prior to that, necessary rebuild of the LHC helium inventory was performed in a limited time-window of 4.5 months, from mid-July to end of November 2020. It represented 83 tons of liquid helium to be recovered, to which 50 tons of new molecules were added, thus allowing the cryogenic infrastructure to get back to its operational stock of 150 tons by the end of 2020, before resuming operation at nominal conditions.

The cooldown sequence of the LHC sectors and its associated nitrogen logistics thus started in October 2020 and lasted one year. The LHC machine being cryogenically sectorized in eight independent sectors, six encountered issues (dealing with magnets, protection diodes, short-circuits and cryostats alignment) directly impacting the cooldown planning. An earth fault was detected in sector 81 (S81) in early December 2020, followed by a magnet re-alignment in S56 in January 2021, a short-circuit in S67 in February 2021, a dipole replacement in S78 in May 2021 and a diode replacement in S23 in June 2021. Later in the year, the “RF ball” test allowed for the early detection of a default on a RF finger (flexible metallic connector maintaining the electrical contact between LHC magnets and ensuring beam pipe continuity) in S23 in November 2021, triggering for a repair in December 2021 and a re-cooldown of the sector in January 2022. Year 2021 was very dense in terms of operation, mainly dedicated to the sectors cooldown, the multiple above-mentioned repairs, and the quench training campaign for the preparation of the machine to run at 6.8 TeV, from March to November 2021. Beam recommissioning followed right after, with the proton physics starting in May 2022 and ending up in late November 2022, to enter the year end technical stop before resuming proton physics in March 2023.

Figure 1 gives a global overview of the LHC cold masses average temperatures from the beginning of LS2 in 2019 down to summer 2023, displaying the main encountered issues by the cryogenic system of the LHC to reach its nominal temperature.

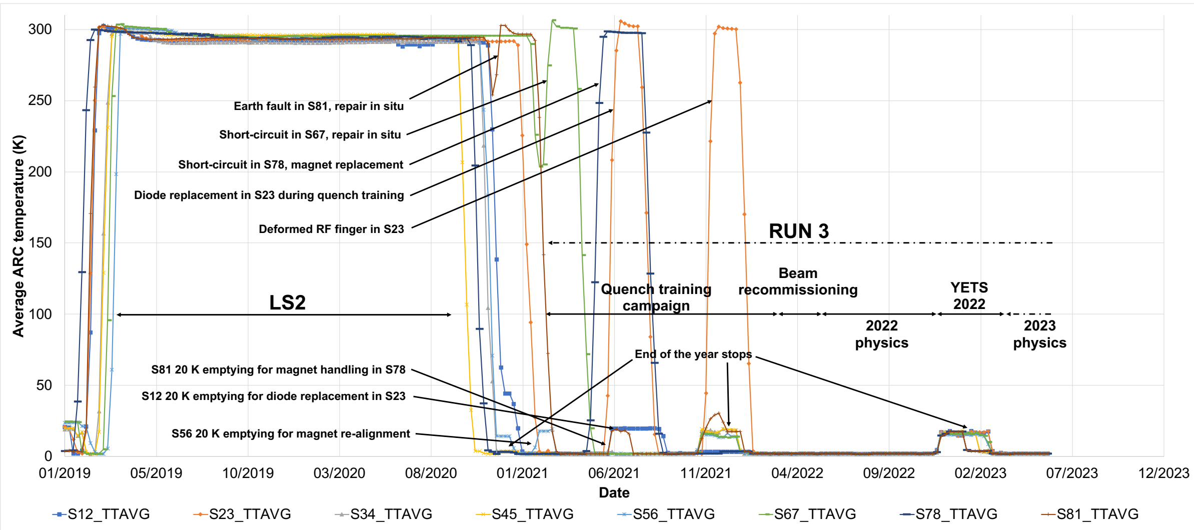

Figure 1. Evolution of average temperatures in LHC sectors during 2020 cooldown.

2. Main upgrades, consolidations and maintenance performed during LS2

Continuous operation of the LHC at the energy of 6.5 TeV during Run 2 from 2015 to 2018 induced an expected ageing of its cryogenic system, and the need for planned and extended period of maintenance, allowing for the full restoration of its potential before resuming physics operation at the increased energy of 6.8 TeV. Implementation of availability calculation tools as well as the use of a fault tracking system on cryogenics equipment, has allowed the CERN cryogenics team to gain valuable experience and data to drive maintenance and consolidations. Major maintenance tasks and a comprehensive consolidation program have been planned during the LS2 based on a data driven approach [1].

Adopted methodology consisted in measuring the performance of the cryogenic infrastructure operation throughout the Run 2 period, listing, and categorizing all the occurred faults and their inter-dependencies (namely when issued from a technical service or a user of the cryogenic system), to act by priority on all the faults with a root cause associated to cryogenics. This fault tracking approach, which was made possible by the systematic follow-up of all operation interruptions, ended up in the creation of a prioritized list of actions to be performed during the related maintenance window. Those actions were regrouped in three main domains: a consolidation program, a process review (essentially evaluating oil removal performance on compressor stations) and a procedures and operators training update (with a focus on critical restart of cryoplants in case of major failures).

Among the consolidation program, distinction was made between reliability improvement measures and treatment of components subject to end of life. While the first concerned in majority actions taken on the compressor stations, the second dealt with a significant number of PLCs that needed upgrades.

Focusing on the maintenance plan, condition-based monitoring allowed to dress up a list of actions to be taken on the cryogenic equipment, prioritizing them from the Run 2 maintenance history, the previous technical stops lessons learned, the predictive maintenance data and the operation process data. In total, it generated 4 000 work orders for preventive and corrective maintenance for 26 000 field working hours. It triggered the calibration of 20% of the cryogenic instrumentation, the check of 28% of the vacuum gauges, the replacement of 32 coalescing filters, and the cleaning of 40% of the water-cooling heat exchangers based on temperature deviation measurement.

Finally, as part of the High-Luminosity LHC project and to anticipate the increase in related beam-induced heat loads in the arcs in parallel to the existing RF accelerating cavities loads, former LEP cryogenic plant reallocated to LHC cryogenic infrastructure in point 4 was upgraded with an additional refrigeration capacity equivalent to 2 kW @ 4.5 K with respect to the existing plant capacity of 16.5 kW @ 4.5 K. The upgraded refrigerator was successfully commissioned from summer 2020 to summer 2021, covering the assessment of the newly installed turbines efficiency and the verification of the global performance of the cryogenic plant, evaluating it to 18.8 kW i.e., slightly above the project requirement of 18.5 kW [2].

3. Magnets training of the machine to the increased energy of 6.8 TeV

After the LHC machine cooldown at 1.9 K and the qualification of all electrical circuits performed after the LS2, an intense quench training campaign was performed between March 2021 and April 2022. LHC was operating at 6.5 TeV during the Run 2 and the aim of this training session was to allow the LHC to operate at a higher energy for the Run 3. During this training, about 600 quenches occurred on the LHC main dipoles across the eight LHC sectors. Three sectors where qualified at the nominal energy of 7.0 TeV (S12, S34 and S45) whereas the five others were qualified to operate at 6.8 TeV, energy finally retained for the Run 3 operation [3].

In anticipation of this exercise, a new quench recovery control logic was implemented in the LHC cryogenic control system, based on the experience of Run 2, to optimize the recovery sequence and to alleviate the operator duties, mainly by using the heat exchanger bypass valve instead of the standard Joule-Thomson (JT) valve at the beginning of the quench recovery. This new logic proved to be very efficient and most of the quenches were recovered faster than expected. Figure 2 displays 600 quench recovery times, being plotted as function of the quench released energy. In average, main dipole quenches were releasing about 14 MJ with an associated cryogenic recovery time of about 8 hours.

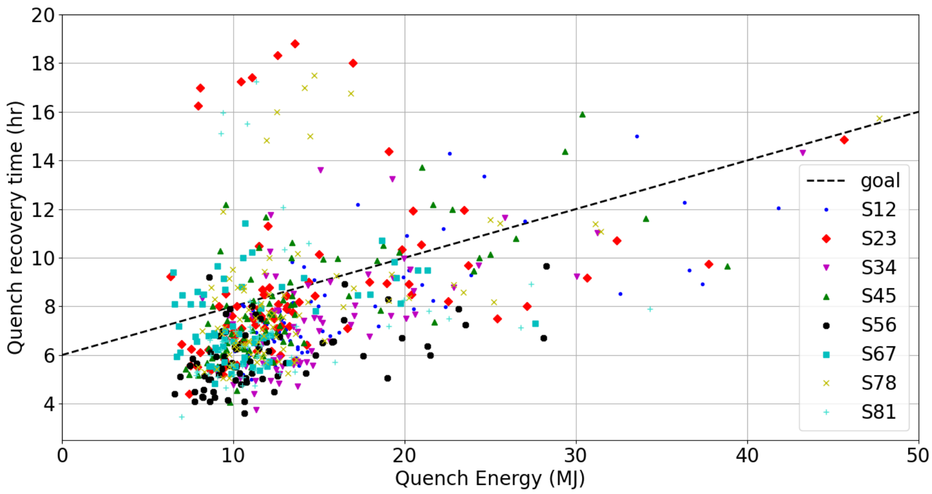

Figure 2. Cryogenic recovery time as function of the quench released energy in 2021 and 2022.

4. Beam operation and dynamic heat load

4.1. Beam screen heat loads

Significant changes in the LHC beam operation were implemented between Run 2 and Run 3, with four of them being of interest to the LHC cryogenic system and its beam screens, inserted inside the LHC beam pipes and intercepting the beam induced heat loads between 5 K and 20 K.

The LHC energy first, was slightly increased from 6.5 TeV to 6.8 TeV, inducing more synchrotron radiations to the beam screens as it varies with the power fourth of the energy.

A major upgrade of the LHC injectors (LIU project) took place during the LS2 and the LHC beam intensities could almost be doubled for the Run 3, thus inducing more heat loads to the beam screens: image current, synchrotron radiation and electron-cloud.

During the LS2, some beam screen surfaces demonstrated degradations, inducing more electron-cloud in the corresponding areas of the LHC ring when compared to the Run 2 [4].

New bunch filling schemes have been setup in the LHC injectors to mitigate the electron-cloud effect without impacting too much the beam and luminosity performances. Since then, injectors can provide the LHC with a "*hybrid filling scheme*", where 25% of the bunches are presenting empty buckets (8b+4e scheme) to reduce the electron-cloud effect with its associated heat loads [4].

To monitor these heat loads, an energy balance is performed in each of the 585 beam screen half-cells (one half-cell represents a 53 m beam screen cooling loop), using available cryogenic instrumentation [5]. It is also important to note that these heat loads calculations were fully validated at the beginning of Run 3 in 2022 by using extra instrumentation (Coriolis flowmeters and Cernox thermometers) installed during the LS2 in some half-cells [6]. The Figure 3 depicts the average heat loads measured in each LHC sector during typical LHC physics fills in 2018 (3e14 protons/beam), 2022 (3.65e14 protons/beam) and 2023 (3.75e14 protons/beam) with the corresponding beam screen cryogenic capacity for each sector. One can see that 2022 was the more "loaded" year with beam screen heat loads measured at 180 W/half-cell in sector 78 and 160 W/half-cell in S81, reaching almost the maximum limits in these two sectors. Therefore, the LHC used this new *hybrid filling scheme* in 2023 to reduce the electron-cloud while having more intense beams to stay below the LHC cryogenic capacity limits. The aim for the rest of the Run 3 will be a continuous increase of the beam intensities until reaching the cryogenic limits to maximize the luminosity production.

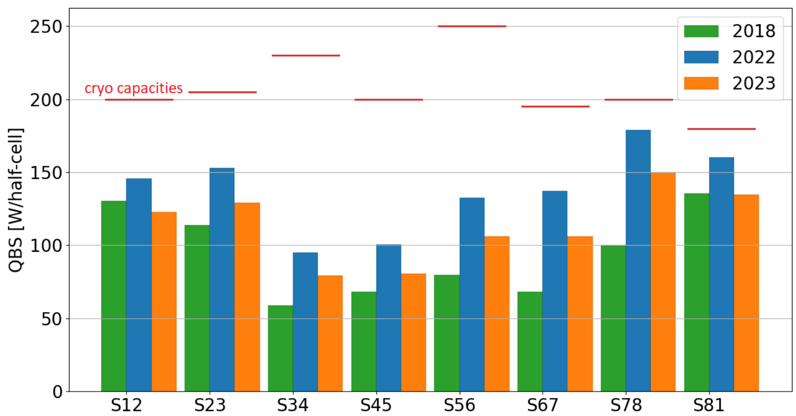

Figure 3. Typical beam screen average heat loads in each LHC sector in 2018, 2022 and 2023, with associated beam screen cryogenic capacities.

4.2. Inner Triplet cryogenics

Inner triplets are the final focusing quadrupoles located on each side of the LHC interaction points. The LHC cryogenic system must handle the dynamic heat loads induced by the collision debris intercepted by these magnets maintained below 2 K. For the Run 3, thanks to the LHC injectors upgrade, the luminosity in ATLAS and CMS experiments could theoretically be increased but one of the limitations was the local heat extraction capacity of these magnets by the so-called bayonet heat exchanger. To better understand this limitation, additional instrumentation was installed on one inner triplet during the LS2, and dedicated capacity tests were organized in 2021. Finally, the local heat extraction capacity of inner triplets was re-evaluated from 270 W at 2 K to 325 W at 2 K, corresponding to a maximum achievable luminosity of 2.4e34 $cm^{-2}.s^{-1}$, value confirmed with a real test in ATLAS and CMS in November 2022 [7].

5. Key Performance Indicators

Run 3 physics started on May 18th, 2022, with LHC resuming operation after LS2 completion, quench training campaign and beam recommissioning. While this first year allowed for an operation time for physics with beam of 4 465 hours, down to November 28th, 2022, and the beginning of Year-End Technical Stop (YETS), it showed excellent results with an availability of the cryogenic system of 99.5%, calculated based on the cryogenic interlock allowing the superconducting magnets of LHC to be electrically powered – the Cryo Maintain (CM).

5.1. LHC cryogenic availability

Operation at the increased energy of 6.8 TeV brought a significant amount of magnet quenches, which disturbed the overall availability of the accelerator. Thirty quenches had to be recovered during the physics run, for a total of 194.5 hours of downtime. The two other main categories of availability losses originated in technical services failures and cryogenic operation related issues.

Representing 61% of the total downtime related to the technical services faults, a major water-cooling failure on a LHC point ended up in the complete stop of related cryogenic installations for 38 hours. 18 additional hours of downtime were provoked by the failure of static VAR compensators (SVC), inducing twice the stop of 1.8 K pumping units. In total, technical services failures accounted for 62 hours of downtime.

A total of 21.2 hours of downtime were generated by cryogenic operation related issues, out of them 12.3 hours were caused by the clogging of a filter on a 1.8 K pumping unit, and by an instrumentation failure on a warm compressor station.

As a result, 277.7 hours of downtime were shared between the users (194.5 hours for magnet quenches recovery), the technical services (62 hours for utilities failures) and cryogenic related issues (21.2 hours), with corresponding calculated availability being presented in Figure 4.

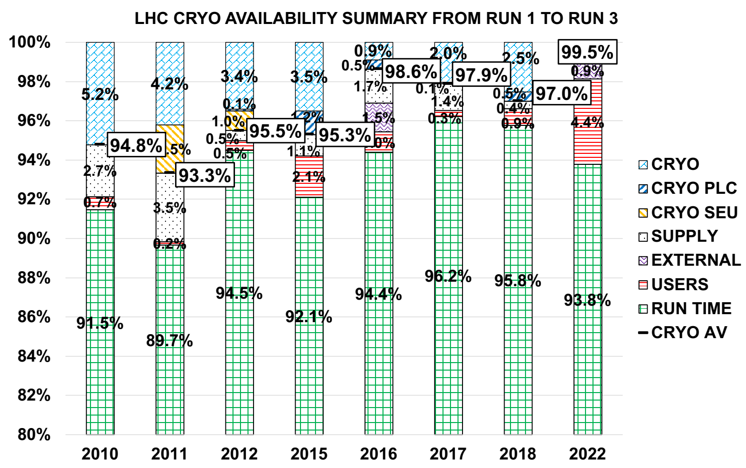

Figure 4. LHC cryogenics availability since 2010.

5.2. Updated helium inventory management constraints

Thanks to the lessons learned from the experience gained through the completion of two consecutive physics runs and long shutdowns, helium management strategy of the LHC has reached maturity.

A repetitive scheme can be drawn around the alternance of maintenance and operation periods. With no specific contingency, LHC cryogenics requires the supply of 7 ISO-containers of 4.5 metric tons of liquid helium each to run during a standard physics year. A total of 19 ISO-containers is externalized during the first year of a long shutdown period, while 30 trailers are to be supplied during the last year of this same period. During beam recommissioning (and eventually magnets training) occurring on the preceding year, with overall rather low helium consumption, 5 ISO-containers are required to ensure reliable operation.

During the YETS, helium management strategy has systematized the emptying of all LHC sectors and maintaining them at 20 K, which accounts for 104 tons of helium to be removed from underground and stored at surface. Considering the total storage capacity of LHC cryogenics of 130 tons (shared between 83 tons in liquid and 47 tons in gas), and given the operational inventory value of 150 tons, it induces the necessary use of external storage for about 20 tons. Thus, during YETS 2022, to cope with the present helium market supply evolution and secure the inventory for an early restart of the cryogenic infrastructure in 2023, the usual strategy has been refined. CERN Cryogenics group decided to maintain the entire LHC helium inventory on CERN premises by renting 4 additional ISO-containers from the industry to store during eight weeks the helium that could not be contained in the installed facilities. Dedicated and adapted logistics was put in place, to monitor the evolution of the inner pressure of the vessels while ensuring the regular refill of the nitrogen guards when needed. All rented trailers demonstrated a very good autonomy in terms of inner pressure raise, in the range of three weeks, with a filled rate of 90% and no connection to the helium process. This strategy allowed to get through the two weeks of CERN annual closure without the need for nitrogen refill. It also ensured a smooth transition to the sectors filling, with no delay as the molecules were already available at CERN.

Through a constant on-line follow-up coupled to systematic checks of calculation accuracy and regular verifications of leak-tightness of storage facilities, the overall consumption of helium was maintained at the level of 900 kg/month for the whole LHC during 2022, which represents between 3 and 4 kg per day and per running cryoplant. Figure 5 presents the LHC cryogenics helium consumption over the past sixteen years.

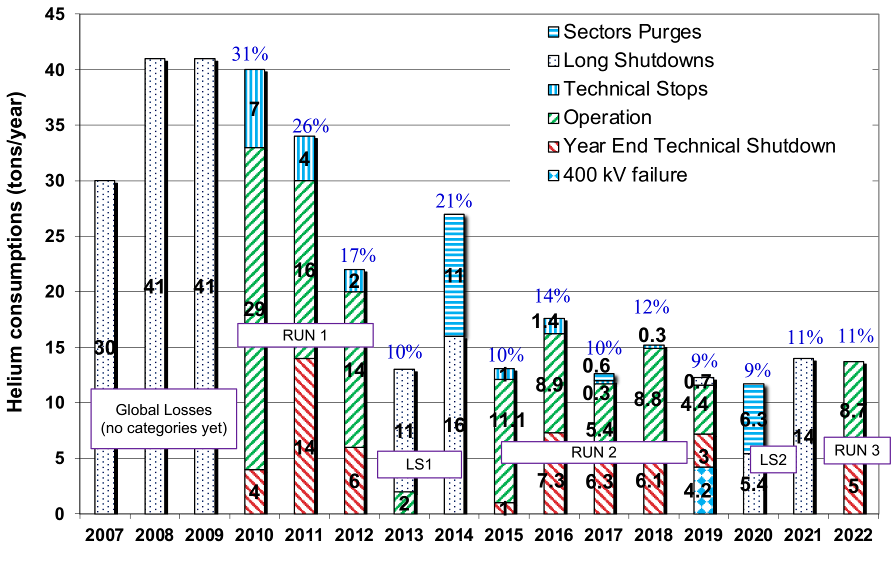

Figure 5. LHC cryogenics helium consumption since 2007.

6. Cryogenic plants operation and related electrical power savings

During the first year of the Run 3 operation in 2022, 271 GWh have been consumed for the LHC cryogenics over the 537 GWh used for the entire LHC machine (without experiments). Hence, the cryogenics represents roughly 50% of the LHC consumption and 25% of CERN total consumption during the beam operation years. It is therefore important to figure out how some electrical power savings can be achieved by optimizing the LHC cryogenics, while ensuring reliable LHC operation.

During the standard proton physics operation for the Run 3, the beam induced heat loads are significant and all LHC cryoplants must run at their full power to handle the dynamic heat loads [8]. Note that in the past, during the Run 2, some compressors were switched-off due to the relatively lower heat loads in S56 and S67, but these savings are no longer possible due to the heat load increase in these sectors in the Run 3. Nevertheless, there are significant time periods where the dynamic heat loads are very low such as during the hardware or beam commissioning, the technical stops, the ion runs, and the special runs at low beam intensities.

Considering these low heat load periods, the idea consists in setting-up an *economic mode* whenever it is possible thanks to the possibilities of “crossing” the two cryoplants on each LHC cryogenic island supplying two adjacent sectors. While one 18kW @ 4.5 K refrigerator is used at its full power to supply the magnet and the beam screen cooling loops over the two adjacent sectors, consuming about 4.5 MW of electrical power, the other 18 kW @ 4.5 K refrigerator is running in degraded mode at 50 K to supply the thermal shields between 50 K and 80 K in the two adjacent sectors, consuming about the half of its usual power (about 2.5 MW).

With this economic mode on the four LHC cryogenic islands, the LHC cryogenic consumption can then drop from 36 MW to 26 MW, representing a significant electrical power saving of 10 MW. Note that to go into this mode from the physics mode, the cryogenic operation team needs about 24 hours to reconfigure and stabilize the entire cryogenic system. In agreement with the LHC coordination, it was then decided to regroup as much as possible the “low heat load periods” in the LHC planning to use the LHC economic mode as much as possible and to minimize the number of cryo reconfigurations over the year. As result, in 2022, LHC cryogenics operated during seven months in economic mode and five months in physics mode, as shown in Figure 6. The economic mode was also used in August, following an unexpected burst disk rupture of RF cavities that forced the LHC to stop for one month.

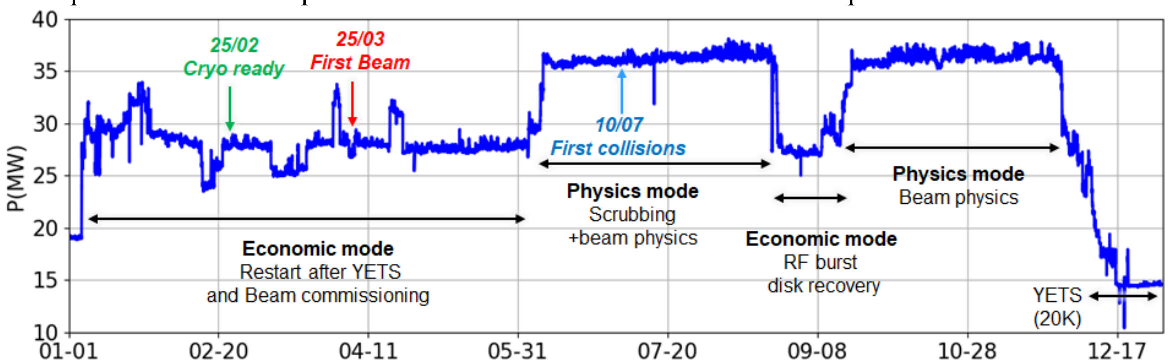

Figure 6. Evolution of the LHC cryogenic electrical consumption during 2022.

Total electrical power saving on the LHC cryogenics in 2022 was estimated at about 20 GWh with the adoption of this configuration. In 2023, this saving will be even more important as the economic mode will be applied on the four cryogenic islands and due to the relatively long ion run period at the end of the year. Figure 7 is showing the LHC cryogenic electrical consumption during the Run 2 and the Run 3 with corresponding energy saving (previsions for 2023).

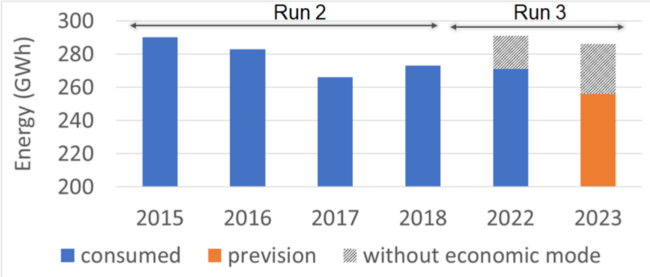

Figure 7. LHC cryogenic electrical consumption during the Run 2 and the Run 3.

7. Conclusions and perspectives

LS2 has allowed to restore the full potential of LHC cryogenic infrastructure. A comprehensive series of maintenance, consolidation and upgrade activities paved the way to the specific quench training campaign for the LHC, successfully completed in 2021 as the necessary prelude to the Run 3 operation with beam at the increased energy of 6.8 TeV.

Results of the first year of operation at this level of energy were fully satisfactory, with an achieved cryogenic availability over the 2022 run of 99.5%, in a heavily sustained operational context of the accelerator with an energy saving configuration operationally implemented.

To address the increased beam induced heat loads – consequence of the successful completion of the LIU project during LS2 – which were pushing the cryogenic system to its limits, LHC used a new hybrid filling scheme to reduce the electron-cloud and increase the beam intensity.

While ensuring the supply of the cryogenic conditions to the accelerator teams to allow for physics production, a new cryoplants operation mode was set up to cope with the increase in the price of energy on the market, allowing for a significant electrical power saving of about 20 GWh, being around 7% of the annual consumption for the whole cryogenic infrastructure.

On the cryogens market side, a new strategy was developed and implemented, allowing to maintain the entire LHC helium inventory on CERN premises during year end technical stops.

All these strategies put in place allowed for a safe and reliable operation for the first year of Run 3 and will therefore be maintained for the rest of the run till end of 2025 while continuing to increase the beam intensities until reaching the limits of the cryogenic system, to maximize the luminosity production.

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