PROCEEDINGS OF SCIENCE

LHC Status - 2023

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The paper summarizes the operation status and highlights of the LHC during the Run 3 period with a focus on the 2023 operation year.

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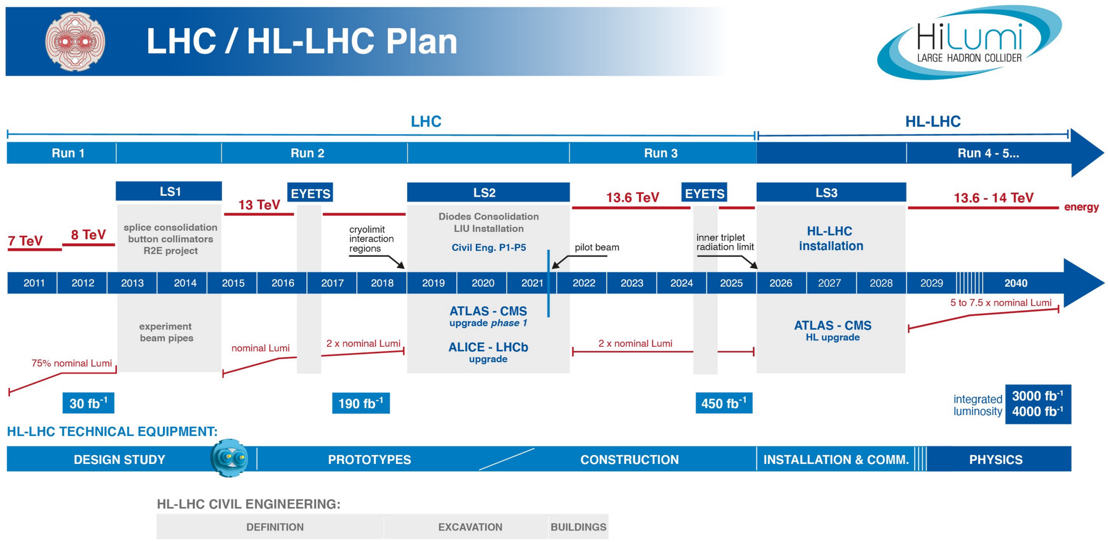

Figure 1: LHC Schedule

1. Introduction

The LHC operation started in 2010 and the LHC is currently in the third run period which is scheduled to last for 4 years from 2022 until 2025 inclusive. Figure 1 shows the overall operation schedule together with the three Long Shutdown [LS] periods which are used for major machine improvements and upgrades.

The LHC performance has steadily improved over the whole operation period and Figure 2 shows the integrated luminosity of the CMS detector over the different operation years. The slope of the data production in Figure 2 increased steadily over time for each operation year and the best performance at the end of the Run 2 operation period in 2018 illustrated that an integrated luminosity of over 70 fb^{-1} is at hand for the LHC. Unfortunately, the performance during the first two operation years of the Run 3 operation period was cut short by technical problems that will be explained in more detail in the following.

2. 2022 Operation Summary

The operation in 2022 was interrupted for about one month due to problems with the superconducting RF system that required a full warm up to room temperature and cool down after the repair. However, apart from this rather long interruption of the operation, the overall machine performance was rather good, providing more than 40% of the scheduled operation time to be spend in stable beam collisions for physics production in the second half of 2022, providing in spite of the short operation period, only about 70 days, an integrated luminosity of $42\, fb^{-1}$ for the ATLAS and CMS experiments each and about $1\, fb^{-1}$ to the LHCb and about $0.03\, fb^{-1}$ to the ALICE experiments.

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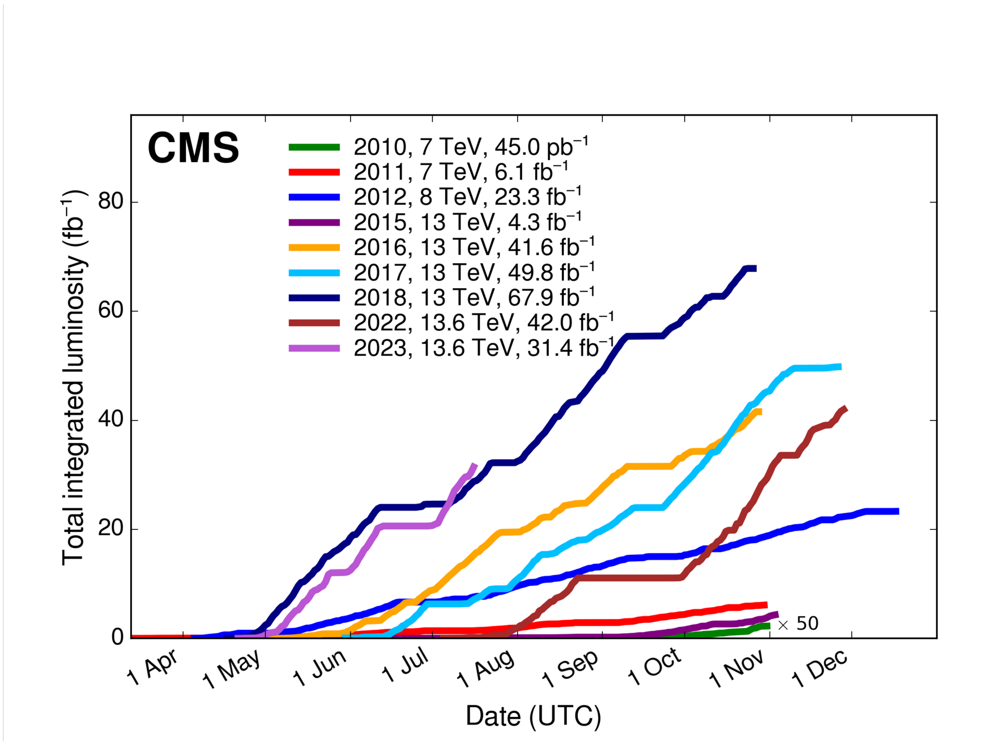

Figure 2: Integrated luminosity recorded by the CMS detector versus time and for the different operation years.

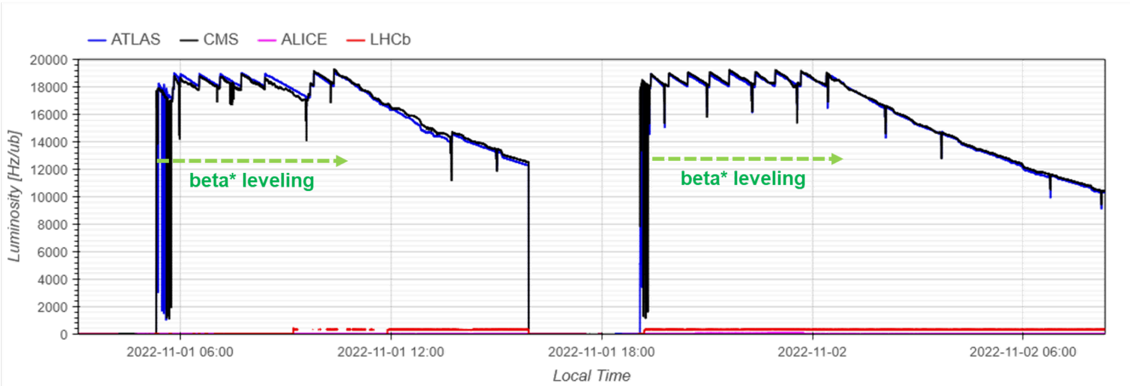

Figure 3: Luminosity levelling over two consecutive physics fills in 2022.

Key ingredients for the high performance level of the LHC in 2022 was the routine use of β^* levelling during the first 5 to 6 hours of stable beam for every physics fill. This novel operation scheme has been developed in preparation for the HL-LHC operation period and features fully automated levelling of the optic functions at the Interaction Points IP1 and IP5 with luminosity jumps of less than 5%. The levelling goal is to keep the number of events per bunch collision at a value of $54 \pm 2.5\%$ and the peak luminosity at around $2 \cdot 10^{34} cm^{-2} s^{-1}$ in order to keep the heat load on the focusing quadrupole magnets left and right of the experiments within the cooling capacity of the cooling capillaries of the magnets.

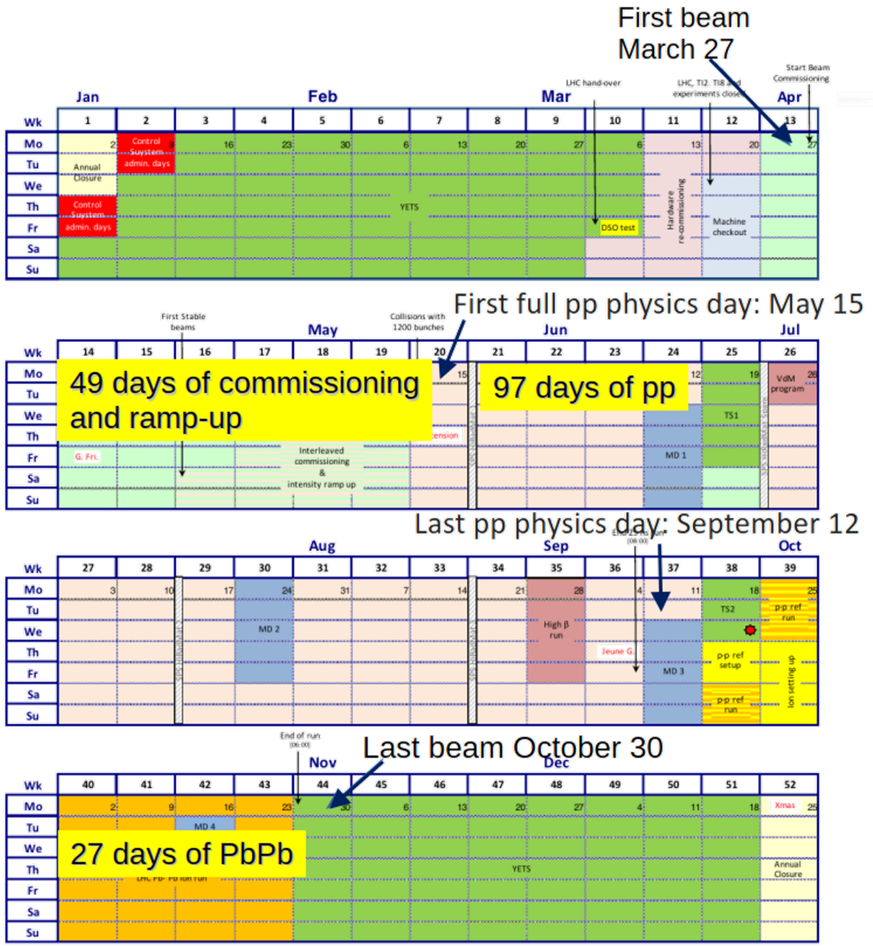

Figure 4: Initial operation schedule of the LHC in 2023.

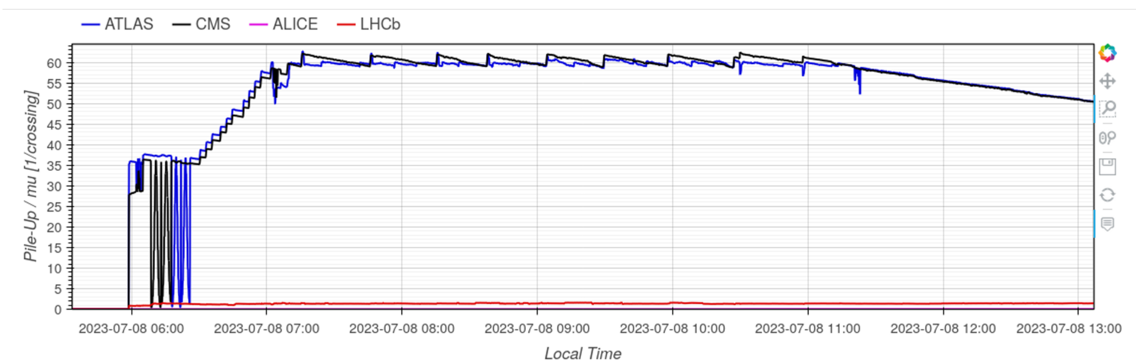

Figure 5: Illustration of the collision levelling orchestration that was implemented for the 2023 operation.

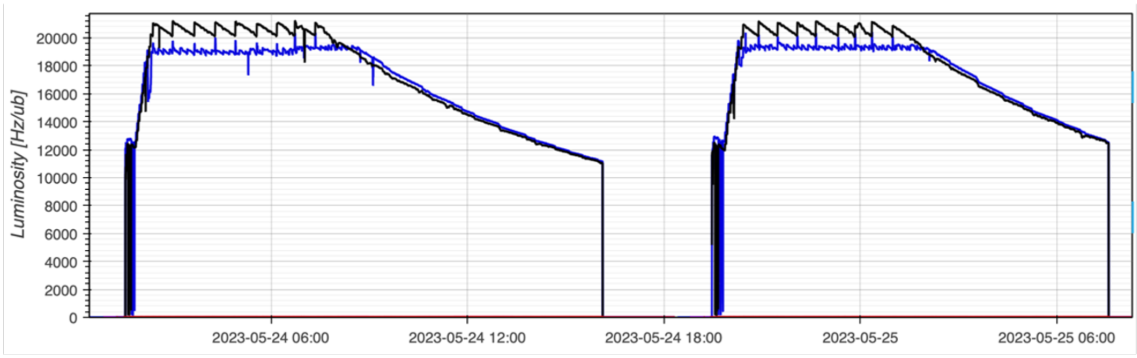

Figure 6: Record physics fills of the 2023 operation.

In addition, the 2022 operation featured the demonstration of viability and efficiency of the Crystal Collimators for ion operation during the LHC Run 3 and HL-LHC operation periods and the readiness of the dispersion suppressor protections for proton operation with HL-LHC beam intensities.

3. 2023 Operation

The remaining Run 3 operation period after 2022 foresees a reduced operation time in 2023 as part of the energy saving measures that were implemented by the CERN directorate after the energy crises that appeared in 2022. Figure 4 shows the initial LHC operation schedule in 2023. The original 2023 operation year featured already only 31 operation weeks, while the years 2024 and 2025 feature 33 and 36 weeks of operation respectively. The baseline for the start of the Long Shutdown period LS3 is still set for 17^{th} November 2025.

The 2023 LHC operation started well with first stable beams established on 21^{st} April ahead of the original schedule in Figure 4. It featured a further improved luminosity levelling that combines now β^* levelling with crossing angle tuning and separation levelling. Figure 5 illustrates the orchestration of the collision levelling that was implemented for the 2023 operation. It features first β^* adjustment for a pile-up [number of events per bunch crossing] of 58 in ATLAS, followed by a crossing angle tuning in order to reduce the pileup in ATLAS with respect to that in CMS. The main levelling period features then a combined β^* and beam separation levelling plus a reduction of the crossing angle once β^* reaches 30cm. Once the levelling stops being effective in the ATLAS detector, the operation continues without parallel separation of the two beams in ATLAS until the end of the physics fill.

The peak performance in this operation mode achieved an integrated luminosity of $1.2fb^{-1}$ within 24 hours and two fills for physics. Figure 6 shows the two corresponding consecutive fills, each with a peak luminosity of $2 \cdot 10^{34} cm^{-2} s^{-1}$ and peak pileups of 63 and 59 in the ATLAS and CMS detectors respectively. The maximum energy per beam at the start of stable beams reached a new record value of 425MJ with 2464 bunches and $1.59 \cdot 10^{11}$ particles per bunch [from an initial intensity of $1.61 \cdot 10^{11}$ particles per bunch at injection] underlining the steady intensity and performance increase over the LHC operation period. The overall machine efficiency, measured by percentage of the scheduled time for physics operation that has actually been spent in stable beams, increased during the 2023 operation period from initially 41% in May to 60% in July, underlining the impressive performance potential of the LHC machine during the Run 3 period.

Unfortunately, a power cut incident brought the 2023 proton operation run to an early stop. A fallen tree caused a power glitch on 17^{th} July 2023 and triggered a beam dump in the LHC. The tree fell on two 125kV lines of the Romandie Energie provider which were attached to the same support tower. After the beam dump, the power glitch resulted in the quenching of several magnets in the tunnel when the power converters still tried to compensate for the drop of current in the magnet system. The heat wave generated by the quench of the triplet quadrupole magnets left of Point 8 [RQX.L8] caused the tripping of the IP8 cold compressor, resulting in an interruption of the cooling of the triplet and matching section magnets. An inspection in the tunnel showed the formation of ice around the triplet cryostats and extending up to D1 dipole magnet and the electrical feedbox. But the amount of ice at the D1 magnet and the feedbox was clearly less than at the triplet magnets, indicating an insulation vacuum problem originating at the triplet magnets. Further inspections pointed to a vacuum problem in the magnet interconnection next to the Q2 quadrupole magnet and it was decided to open the interconnection for further inspections. The opening showed a fault of one of the Edge-Welded bellows next to the Q2 auadrupole. Fortunately, the bellow was installed at the so called M-Line of the magnet interconnection, a line that is used for diagnostic cables and that could be opened and repaired without too much overhead. The cryogenic system needed to remain off during the repair work, implying that the temperature of the magnets without active cooling would increase during the intervention. In order to avoid a too long re-qualification procedure after the repair work, it was mandatory that the temperature of the affected magnets remained below 80K. Above 80K the warm up would imply larger mechanical deformations that would require a full electrical re-validation of all maget circuits after the intervention.

The intervention could be finished when the maximum temperature in the arcs reached 80K and the re-cooldown could be started just in time. The machine operation could start again in September, securing the planned end-of the year ion operation. But the lost time implied that the proton run in 2023 was prematurely ended in July, limiting the integrated luminosity for proton operaton in 2023 to $31.4 fb^{-1}$.

4. Main Limitations and Obstacles for the 2023 Operation

The performance during the 2023 LHC operation year indicated three potential limitations for the performance reach of the LHC:

- Equipment heating from wakefields and impedance
- Electron Cloud
- Faulty bellows

4.1 Equipment Heating

Figure 7 shows the temperature evolution of the deflecting injection kicker elements MKI versus time. The MKI elements use Ferrites to absorb a significant portion of the beam-induced

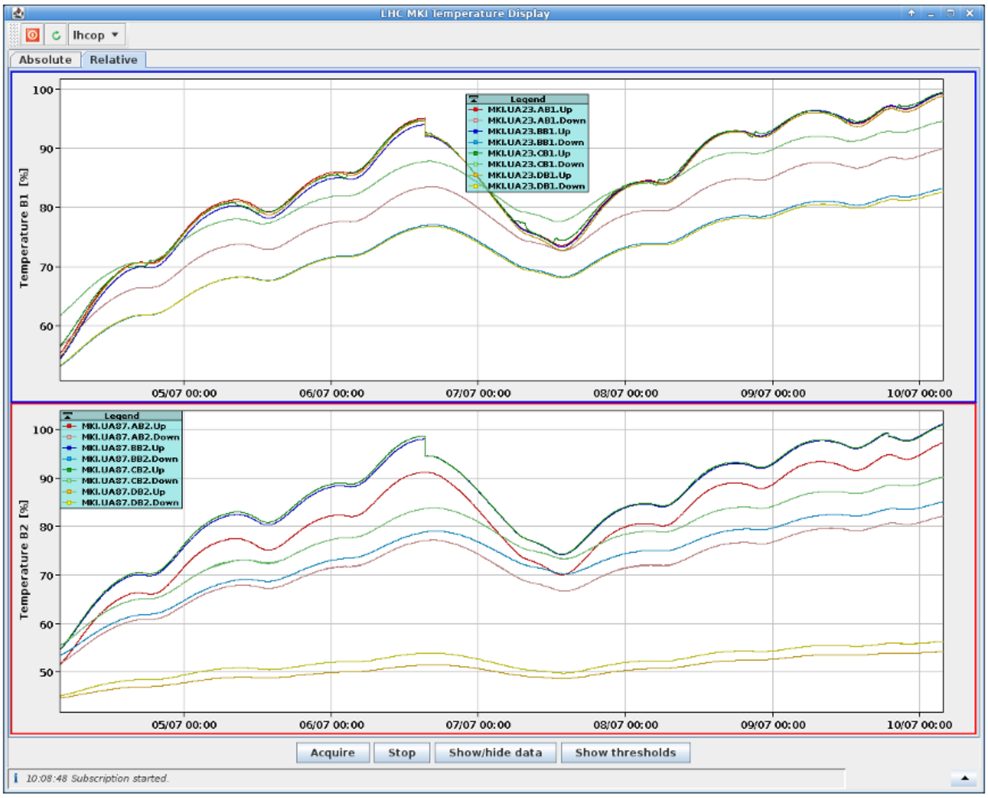

Figure 7: Temperature evolution of the deflecting injection kicker elements MKI versus time.

heating, thus reducing the heating of the magnet's yoke. For all elements to function properly, the temperature of the Ferrites needs to stay below the Curie temperature.

One clearly sees in Figure 7 that the temperature of the MKI Ferrites increases steadily with time when high intensity beam is circulating in the machine and drops only slowly during periods without beam in the machine. A similar effect occurs in the injection absorber tank TDIS.4R8 on the right side of Point 8. Here, the temperature increases to values of up to 147 degrees Celsius which came quite close to the interlock limit of 150 degrees Celsius. For the intensities of $1.6 \cdot 10^{11}$ particles per bunch and 2464 bunches this was not yet a performance limitation during the 2023 operation. But it clearly will be a limitation once the beam intensities are pushed higher, in particular for the HL-LHC operation period where it is planned to operate with bunch intensities of up to $2.2 \cdot 10^{11}$ particles per bunch with up to 2760 bunches per beam. Upgrades are already being prepared and it is planned to replace the MKI elements in the LHC with actively cooled versions of the kicker elements, called MKI-Cool. They are planned to be installed during the Year-End-Technical-Stop [YETS] 2023 / 2024.

Another temperature related fault occurred on the bellows of the large aperture beam pipe that is common to both beams. Figure 8 shows a sharp increase in the beam vacuum at the start of the ramp with high beam intensity operation. Radiological inspection of the affected region showed that the RF-fingers of the large bellows lost contact with the metallic beam pipe ends, interrupting the electromagnetic continuity of the beam screen in that area. Opening of the affected area showed clear indications of heating and sparks that can explain the observed sudden rise in the

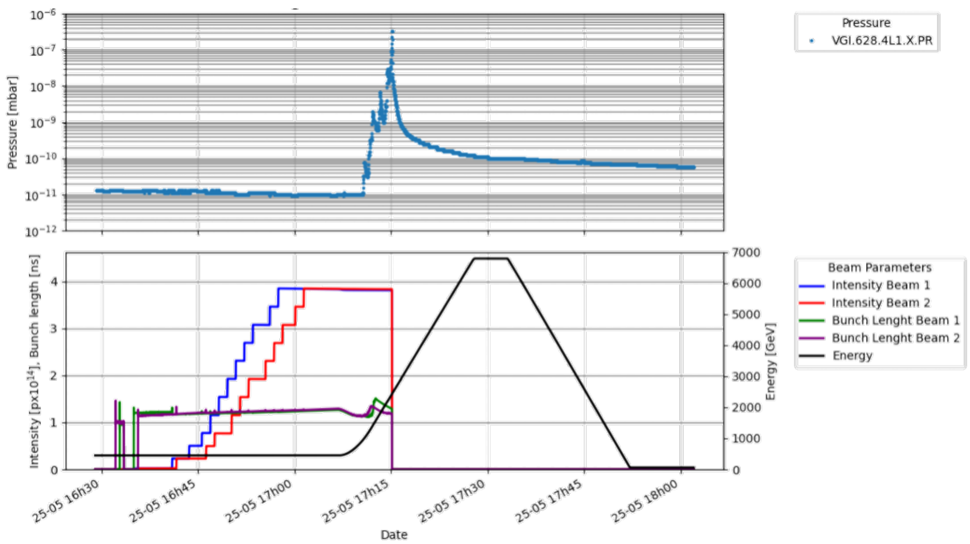

Figure 8: Beam vacuum evolution versus time left of Point 1 for a high beam intensity fill.

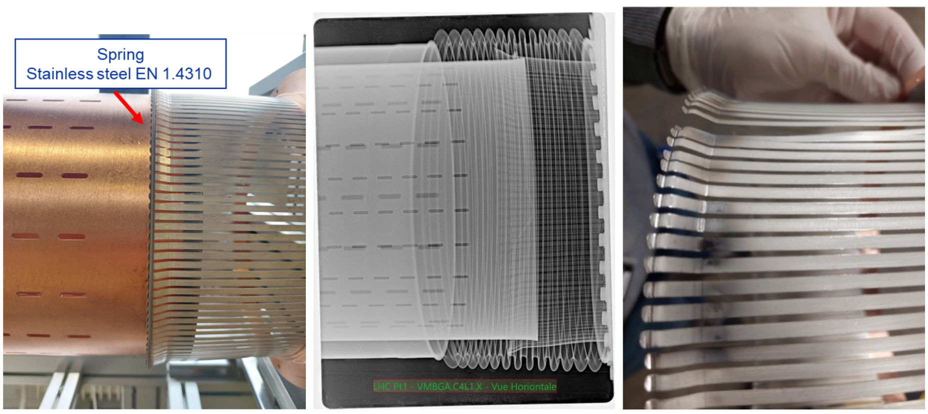

Figure 9: The large aperture bellows of the common beam pipe left of Point 1. Left: the nominal RF fingers of the bellows. Center: X-ray picture of the damaged bellow with clear signs of loss of contact of the RF fingers with the metallic surrounding. Right: Picture of the damaged RF fingers with signs of electric sparks and heating.

beam vacuum. Figure 9 shows how the RF fingers of the large bellows should look on the far left, the X-Ray picture showing the loss of contact of the RF fingers with the surrounding in the middle picture, and tips of the RF fingers with clear signs of sparks and heating, in the picture on the right.

The observed fault confirmed the need to systematically replace all bellows of this design in the machine before the beam intensities can be pushed higher and triggered the imposition of a limit on the bunch intensity of $1.6 \cdot 10^{11}$ as long as not all large bellows have been replaced with a new version that features improved designs for the RF fingers.

4.2 Electron Cloud

The electron cloud effect describes the build up of electrons inside the beam vacuum chamber. Initial electrons are generated by the absorbtion of synchrotron radiation photons and the photoelectric effect that generates the emission of low energetic, typically a few MeV, electrons inside the vacuum chamber. For the LHC bunch spacing of 25ns, these photon generated electrons can remain inside the vacuum chamber long enough to experience the passing of the following proton bunch. The low energetic photo-electrons can come quite close to the center of this trailing proton bunch can now be accelerate to energies of a few keV. These higher energetic electrons will then in turn eventually impact again on the surface of the beam screen, where they will generate secondary electrons and the whole process repeats and adds additional electrons to the photo-electrons that are generated by the trailing bunch. The number of generated secondary electrons per impacting primary electrons is called the Secondary electron Emission Yield [SEY]. If the SEY is larger than one, this process leads to a continuous increase of the electron density inside the LHC beam vacuum system until the electron density is large enough to shield the electromagnetic field of the positively charged proton bunches, at which level newly generated electrons are no longer accelerated by passing proton bunches.

The electron cloud build up has two major detrimental impacts on the LHC operation: 1) it generates a source for surface heating of the beam screens which eventually limits the maximum attainable proton bunch intensity once the cryogenic cooling capacity has been reached. 2) it creates a mechanism for coupling the motion of different proton bunches and can drive beam instabilities if the coupling becomes too strong. Both effects are clearly visible in LHC operation.

The electron cloud build up was first observed for the positron beams of the B-Factories at SLAC and KEK. Unfortunately the effect was recognized too late as a potential limitation for the LHC and too late in the design stage of the LHC to be mitigate the effect via changes in the beam screen design. Instead, the LHC relies on a continuous conditioning of the beam screen surface that reduces the secondary electron emission yield over time with accumulated electron dose. This surface conditioning was well observed during the first and second running periods of the LHC, before and after the LS1 operation stop, and is often referred to as 'beam scrubbing' of the beam screens.

However, at the beginning of the Run 3 operation period, after the operation was stop during the 3 years of LS2, it was observed that the electron cloud effect worsened with respect to the effect during the Run 2 period before the LS2 stop and that the beam scrubbing conditioning was saturating at a higher level as compared to the operation before LS2. Figure 10 shows a comparison of the electron cloud heat load in the cryogenic system before and after LS2 for the different LHC sectors. The heat load from before LS2 is shown in blue bars and the heat load after LS2 in orange bars.

The upper bars show the total heat load on the LHC beam screen per half-cell and the lower bars show the heat load normalized to the beam intensity. The measurements clearly show that the normalized heat load per half cell during operation after LS2 is significantly larger than that before LS2 for the sectors ARC56, ARC67 and ARC78, showing an increase in the normalized heat load of about 50%. The time evolution of the heat load over the scrubbing run after LS2 is shown in Figure 11, clearly illustrating the saturation of the normalized head load, and thus of the surface conditioning. The observed heat loads are still compatible with the beam operation during the Run 3 operation period. But they would limit the beam intensities for the HL-LHC period, that plans to increase the bunch intensities from $1.6 \cdot 10^{11}$ particles bunch to $2.2 \cdot 10^{11}$ particles per bunch. Furthermore, it can not be excluded at this stage that the normalized head load might not deteriorate

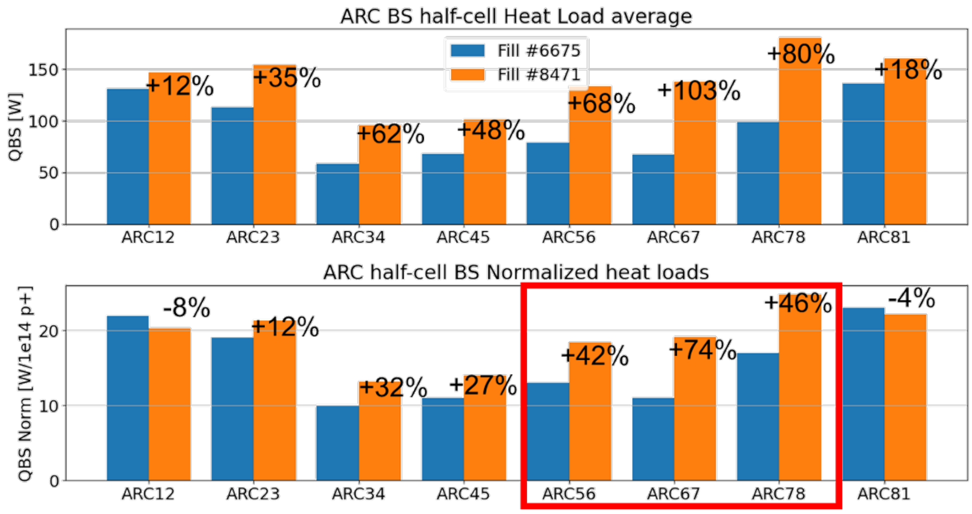

Figure 10: Comparison of the electron cloud related heat load on the LHC cryogenic system before and after LS2 for the different LHC sectors. The heat load from before LS2 is shown in blue bars and the heat load after LS2 in orange bars.

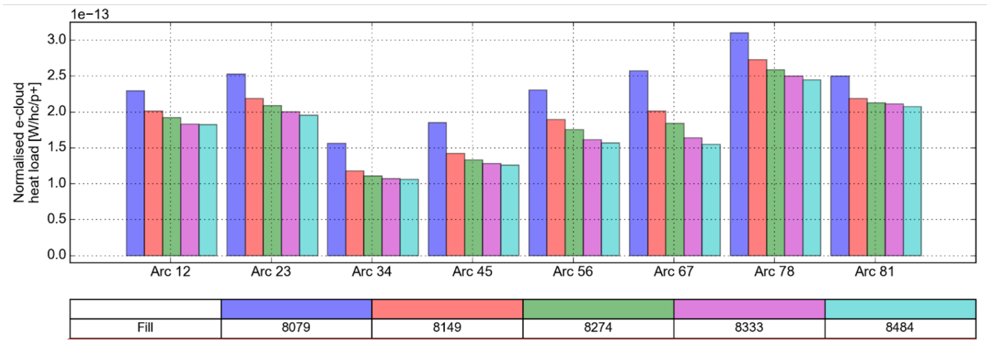

Figure 11: The time evolution of the heat load over the scrubbing run after LS2 for different fills in the LHC.

further over the Long Shutdown 3 period. One way to mitigate the electron cloud effect in the LHC is to introduce long enough gaps in the bunch trains so that the electron cloud can decay in between bunches before it reaches the maximum saturation level. One effective filling scheme is to leave out 4 consecutive bunches in every train of 12 bunches that is generated in the PS. This scheme is referred to as the 8 bunches, 4 empty scheme, or 8b4e. This filling scheme fully mitigates the electron cloud effect for the LHC and HL-LHC eras. However, it does so at the price of reducing the number of bunches in the machine by 30%. This reduction in the number of bunches can be partially compensated by introducing higher bunch intensities. But this will have detrimental effects on the experiments by increasing the event multiplicity, or pileup, per bunch crossing and will eventually be limited by beam instabilities in the SPS and LHC. The LHC operation team is therefore studying so called Hybrid schemes, where trains of 8b4e are mixed with regular bunch trains at 25ns bunch spacing. The mixing ratio of these Hybrid schemes can then be tailored to keep the electron cloud related heat load in the beam screens at the acceptable limit of the existing cryogenic infrastructure. Combining 56 8b4e trains with 5 sets of 3 regular 12 bunch trains shows the most promising potential. It is referred to as the Hyb-36 scheme.

The root cause of the surface deterioration and the resulting increase of the electron cloud related beam screen heating has been linked to the introduction of airborne Cu Hydroxide [$Cu(OH_2)$] inside the beam vacuum system during the opening of the LHC vacuum system during LS2. With electron bombardment, the Cu Hydroxide creates CuO on the beam screen surface that features an increased SEY. A critical question for the HL-LHC operation period is therefore how the introduction of Cu Hydroxide into the beam vacuum system can be excluded during LS3 and how a further degradation of the beam screen surface conditions and a resulting increase of the electron cloud activity can be avoided for the HL-LHC operation period. The most promising approach seems at the moment to eliminate the electron cloud problem at the root cause and to implement a surface treatment of the most strongly affected sectors during LS3. Two options are currently pursued for such a surface treatment: 1) Plasma Assisted CuO reduction and carbon recovery [PE-CVD] and 2) Carbon coating (10-20nm) by sputtering (PVD). Both methods will be tested for in-situ treatment in the tunnel and a final intervention plan during LS3 is being developed for LS3.

4.3 Faulty Bellows

The incident in July 2023 indicated a weakness of the Edge-Welded bellows in the triplet area. Two more incidents in 2023 showed similar problems with this type of bellows in other areas of the machine, namely the newly refurbished TDIS [injection protection devices]. As edge-welded bellows are used in all triplet magnets and many of the collimator movable absorber installations, the CERN teams have launched a general revision of the quality of these devices in the machine and on the spare parts storage. A redesign and systematic replacement of these types of bellows might be necessary during LS3 and studies to this end are still ongoing.

5. Summary

In spite of the premature ending of the 2023 proton run, the operation in 2023 has underlined the superb performance potential of the LHC machine. The 2023 proton operation has validated and implemented in routine operation all required leveling tools for the HL-LHC era. In spite of the complex operational gymnastics, the LHC has achieving a luminosity efficiency of 60% [60% of the schedule physics time spent in stable beams physics runs] with stored peak beam energies of up to 425MJ in 2464 bunches. The total accumulated integrated luminosity of the LHC in proton operation amounts to $237 fb^{-1}$ so far. With over $70 fb^{-1}$ per year at hand for the remaining 2 years of proton operation in the LHC, the LHC machine has the prospect of delivering in excess of $400 fb^{-1}$ by the end of the LHC Run3 period in 2025, clearly exceeding the nominal deign goal of $300 fb^{-1}$ of the LHC.