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Operation experience with a 1.8 K refrigeration unit during the 2024 LHC physics run at CERN

B Naydenov, L Delprat, M Pezzetti and B Bradu

European Organization for Nuclear Research (CERN), 1211 Geneva, Switzerland

E-mail: boyan.naydenov@cern.ch

Abstract. More than 6'000 hours of nominal cryogenic conditions were provided for the LHC (Large Hadron Collider) physics run during 2024, allowing to reach a record integrated luminosity of 124 inverse femtobarns. The cryogenic system availability during this year was of 96.5% (target 95% to 98%). Out of the total downtime, 80% came from a series of events that led to five trips of the same 1.8 K refrigeration unit. To ensure that a high level of availability is kept as the equipment ages and the luminosity of the machine increases, all failure cases as well as its effects have been thoroughly analyzed. The results together with new consolidation measures aiming at further increasing the reliability and availability to physics are presented.

1 Introduction

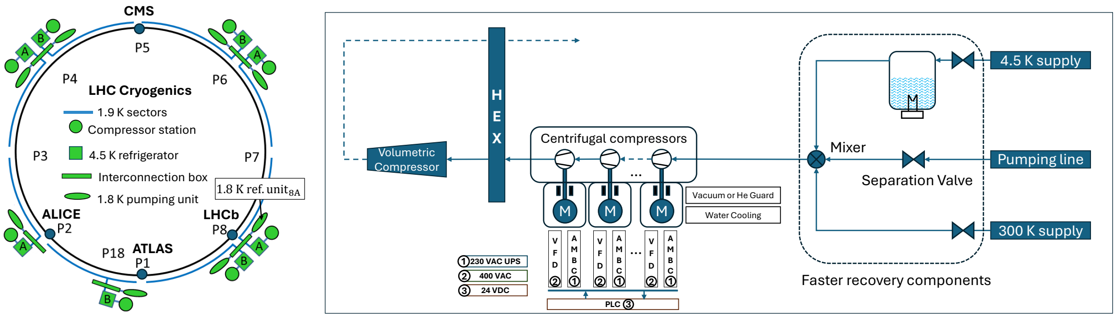
The LHC reached a record integrated luminosity of 124 inverse femtobarns (fm^{-1}) during 2024, almost doubling the previous best year integrated luminosity of 66 fm^{-1} during 2018. In order to achieve this, the cryogenic system had to maintain a record number of hours with nominal conditions. The availability was of 96.5 %, with a 2400 W @ 1.8 K refrigeration unit being the main contributor of 80% of the downtime. Historically [1] [2] this has been one of the main downtime contributors of the LHC cryogenic system, not due to a lower reliability of its components, but because of its higher sensitivity to process variations coupled with an extended time required to restore nominal conditions after a stop. This year, five stops involved one of the four (out of the eight installed) units in operation. For brevity, in the following sections this unit is referred as $1.8Kref.unit_{8A}$[1].

The cryogenic system must keep ensuring a very high level of availability even when the luminosity of the machine is increased, as the latter is of utmost importance for physics production. This aspect is very relevant both for the LHC, which after its planned HL-LHC upgrade (2026-2030) will reach up to 250 fm^{-1} per year, and for any future large particle accelerator. To better improve the availability when the system scales in size, the probability of a failure occurrence as well as the repair and recovery times should be reduced. This paper focuses on understanding the 1.8 K refrigeration unit failure causes, and on addressing the mitigation actions implemented specifically on the $1.8Kref.unit_{8A}$ after the 2024 run.

2 1.8 K refrigeration unit architecture

A generic architecture of a mixed compression cycle [3] 1.8 K refrigeration unit, used in the LHC, is presented in Fig. 1b. It is based on a combination of cold centrifugal compressors in series with a warm sub-atmospheric volumetric compressor. Compared to a fully integral cold compression cycle, a lower number of cold compressors as well as a greater turndown capability is achieved. In the integral cycle, the pressure ratio (PR) needs to be kept constant since both the inlet and the outlet pressures are fixed. Whilst the mass flow rate can vary, the fixed PR limits the operational range of the centrifugal compressors between the stall and the choke conditions. Because of this, the operability of the mixed cycle, with less impellers and a variable pressure ratio, is simpler and more adaptable, coming at the cost of adding more sub-atmospheric equipment with an added leak risk.

[1]Located at the LHC point 8 and associated with the 4.5 K refrigerator A (see Fig.1a)



(a) (b)

Figure 1: (a) LHC Cryogenics Layout. Blue dots represent collision points and each cryogenic island is composed of two cryoplants, A and B. $1.8Kref.unit_{8A}$ is indicated. (b) A 2400 W @ 1.8 K LHC refrigeration unit architecture, including main process lines, the centrifugal compressors, the motor, the Variable Frequency Drive (VFD), the Active Magnetic Bearing Controller (AMBC) and the Programmable Logic Controller (PLC). The return to the 4.5 K refrigerator is omitted to keep the diagram generic.

At CERN, the two chosen suppliers for LHC [4] proposed slightly different mixed architectures with many aspects remaining very close, with both choosing the usage of electrical motor drives with active magnetic bearings working at room temperature, axial-centrifugal impellers and fixed-vane diffusers. A Variable Frequency Drive (VFD) is used to drive the motors between 200 and 800 Hz, and an Active Magnetic Bearing Controller (AMBC) is used to keep the shaft well aligned and levitating, ensuring no mechanical contact. In order to retain a capability to reconnect a stopped unit to a client that is still below 400 mbar, a separation valve, a phase separator supplied by the 4.5 K refrigerator, a 300 K Helium supply and a mixer are included (Faster recovery components in Fig.1b). With those, it is possible to match the conditions at the inlet of the first cold compressor, to the ones in the pumping line even below the minimum pumping pressure of the volumetric warm compressor, allowing for a faster re-connection. Once the conditions are matched, the separation valve is opened and the client pumping is restarted.

Mitigation operation actions can be performed to preserve the conditions with reduced heat loads for most cryogenic systems failures. However, an undesired stop of the cold compressor unit can not be directly mitigated. As soon as it occurs, the client isolates and start building up in temperature and pressure. The fastest recovery after a unit stops takes about 6 h, while in average it takes 12 h, directly depending on the time to restart. Without the re-connection capability, the 1.8 K refrigeration unit would have to pressurise the clients and restart at about 320 mbar every time, which is the lowermost suction pressure for the volumetric warm compressor at the needed mass flow rates. Such operation would increase the total recovery time by up to 80%. In other words, the availability of 2024 would have been decreased by about 2% without the faster recovery components.

Each of the four cryogenic islands covering the entirety of the LHC has two independent 1.8 K refrigeration units - see Fig.1a. Due to a lower than design 1.8 K heat load [5], one unit is enough to cover two sectors, whilst the other can stay in standby, in case of a failure with the active unit. This arrangement impacts negatively the recovery time, but it allows to increase the effective cooling capacity in nominal conditions, allowing to cope for the higher than expected beam screen heat loads [5]. In most LHC cryogenic islands, a swap could be considered[2] towards the 20 K standby 1.8 K refrigeration unit in case of a severe damage and long expected repair time. However, it is currently not fully possible to count on such redundancy at P8, where $1.8Kref.unit_{8A}$ is located. Presently, the two sectors attached to P8 (S78 and S81) have the highest beam-induced heat loads, reaching values twice as high as the design values. In order to cope with those, an optimised configuration of the cryoplants and the 1.8 K refrigeration unit is required [6]. Changing this configuration would require to change the beam parameters, leading to a lower integrated luminosity. Therefore, during the problems that occurred with the $1.8Kref.unit_{8A}$, it was not possible to swap to the other 1.8 K refrigeration unit from point 8 without impacting the accelerator luminosity production.

A last important particularity of $1.8Kref.unit_{8A}$ is that it is the only one out of the 8, that is located in an experimental cavern next to an interaction point, in this case, to the LHC beauty (LHCb) experiment (See Fig. 2). This translates to a higher radiation exposure, increasing the failure probabilities of the different subsystems. This, together with the distribution of the beam-induced heat loads described above, make the $1.8Kref.unit_{8A}$ currently the most critical cryogenic system in the LHC.

[2]For restart times lower than ≈6 h, a swap should not be considered due to the interconnection lines thermalisation time. This is needed because the standby unit has been kept isolated from the interconnection box. See Sec.4.2.

3 Failures analysis and risk mitigation

Focusing on the 2024 events, two $1.8Kref.unit_{8A}$ stops occurred after a trip of the AMBC4 without an apparent reason. After the first trip, the unit was replaced. In both cases the trip occurred as particle collisions were being produced in LHCb, the detector located in the same cavern as $1.8Kref.unit_{8A}$. The cumulated luminisoity was 7.6 fm^{-1} and 10.1 fm^{-1} on the first and the second AMBC4 trip, respectively. FLUKA simulations on the location of the AMBC4, located nearby the cavern, indicate a fluence of 7×10^7 HEH/cm^2 for 10 fm^{-1} as shown in Fig. 2 [7]. From previous studies [8] related to an initial displacement needed after the Long Shutdown 1, it is known that an AMBC failure is expected every 1×10^8 HEH/cm^2. After an exhaustive check of all other potential sources for such trip, a Single Event Upset (SEU) was considered the most probable cause for the two trips. In both cases, there was no error message on the AMBC and, following a simple power recycle, they restarted working again, which is a typical behavior observed after a SEU. The mitigation measures consisted in displacing the cabinet 80 cm further away from the radiation source and adding additional iron shielding on the freed space.

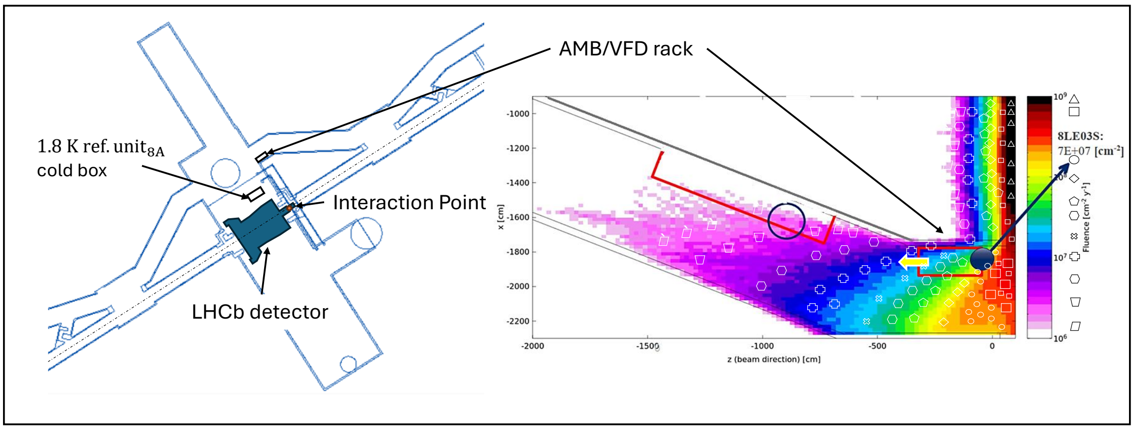


Figure 2: High Energy Hadron (HEH) fluence on $1.8Kref.unit_{8A}$ AMBC location for 10 fm^{-1} accumulated during Run 3. Displacement of 80 cm, indicated by an arrow, expected to reduce the fluence by a factor 2. [7]

Two other stops happened due to a failure in a pressure sensor measurement used by the control system. The onsite diagnostic suggested that the fault was not coming from the acquisition chain, indicating the sensors themselves as the probable source. Therefore, both sensors were replaced. One of the affected sensors measures the pressure at the inlet of the second cold compressor, CC2, directing impacting the control system. When the unit is cold, this area is at subatmospheric pressures and the pressure transmitter needs to be located in a helium guard [9]. Its replacement with the unit at cold has not been done before during operation, as it is not trivial due to the pollution risk. It required several conditioning actions to prepare the process before and after the intervention. Out of the 8 units, only this 1.8 K refrigeration unit suffered from sensor issues, which strengthens the hypothesis that the sensors may be experiencing a faster ageing due to a stronger exposure to radiation. Nevertheless, this hypothesis is difficult to prove with the available data. A stricter preventive maintenance plan is set up for the critical sensors, that is, those used by the control system.

Finally, a stop of the $1.8Kref.unit_{8A}$ occurred due to a VFD trip following a Static Var Compensator (SVC) restart. The SVC is needed to improve the network power factor by compensating the reactive power. During the restart of the SVC, the 400 VAC network, which also supplies the VFDs, experiences temporary perturbations. The most loaded VFD, i.e., the VFD4 due to the higher rotation speeds of CC4, could end up tripping in overcurrent, depending on the load of the VFD and the load of the electrical network itself. Following tests performed in the laboratory, it was found that the internal DC power supply that regulates to maintain the required voltage during a 400VAC perturbation, causes an overvoltage and eventually an overcurrent, after the perturbation ceases. A leakage current can also appear due to this and trip the VFD. The inductance of the motor cables as a function of their length, the motor impedance and, the $\frac{dV}{dt}$ at the output of the VFD influence this phenomenon. Several tests were performed during the Year End Technical Stop (YETS) concluding with the installation of higher protective inductors at both inlet and outlet of the VFD, as indicated in Fig.3. The main goal of this consolidation is reducing the current variation following an SVC restart and, hence, avoiding the VFD trip.

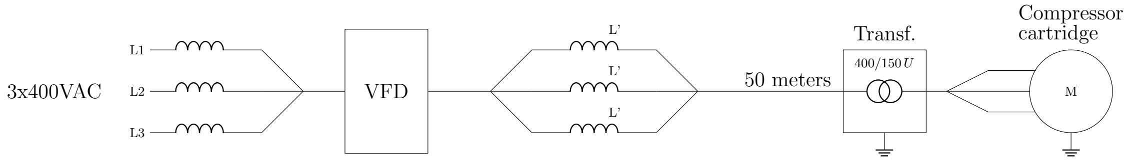


Figure 3: VFD control of the cartridge motor, including the new inductors. L1, L2 and L3 upgraded from 1.47 mH to 2.3 mH in order to better protect the VFD from the SVC-restart-induced perturbations on the 400 VAC supply. The L' inductors are set to 170 µH. The voltage needs to be lowered to 150 VAC to avoid arcing due to the lower breakdown voltage in the helium environment present in the motor.

4 Repair and recovery time

The recovery time, and hence the unavailability, is directly proportional to the stop duration or repair time. One way to improve the repair time is to ensure a safe stop of the system whenever a failure occurs. At each failure, it is necessary to safely slow down the CCs impellers before stopping their levitation. A safe stop allows for a quick and smooth restart of the system as soon as the source of the primary issue is understood and corrected. On the other hand, an unsafe stop, can provoke further damage and multiply the overall repair time. Considering the specific nature of this system, neither spare management nor repairs or replacements are simple or quick tasks.

The choice of active magnetic bearings for the cold compressors is justified due to its excellent MTBM of 100.000 hours [2], the high rotation speed needs, the very low operation temperature of the impellers, as well as its active vibration damping characteristics. However, it comes with an added complexity cost. Focusing on the stop of the impellers, three types of scenarios can occur from normal operation, when the shaft is kept levitating by the magnets of the bearings:

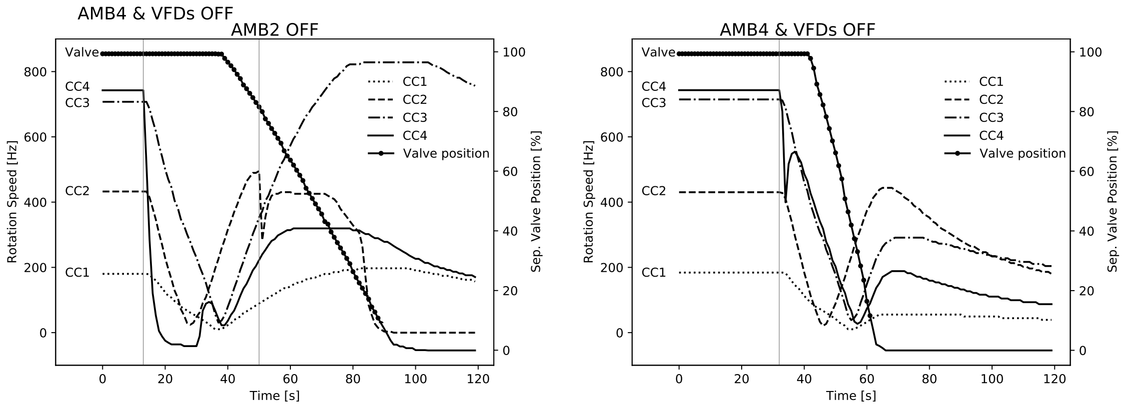
- A controlled stop. The VFDs decrease the rotation speed to their idle speed. From there, they are slowed down further, and only when they are almost not spinning, the AMBC stops the levitation. At that point, the shaft lands smoothly on a ceramic touch down ball bearing depicted in Fig.5a.
- An AMBC trip. The impeller lands on these touch down ball bearings while spinning at its nominal speed, i.e., hard-landing, adding a risk of damaging the ceramic bearing and, potentially, the impeller or the shaft.
- A VFD interlock. The impellers go into free-wheeling, without any active braking. At that point, the impellers are exposed to reverse flow back into the clients risking reaching an overspeed condition. Such a condition arises when the cold compressor spins excessively fast, creating centrifugal forces beyond what the magnetic bearing can counteract. If that condition is reached, the AMBC switches off and a hard-landing is produced.

After every hard-landing, an onsite calibration check is required to ensure the shaft clearance in all directions. If the check is not passed, the unit needs to be dismounted for maintenance. Table 1 summarises the events that affected the $1.8Kref.unit_{8A}$ during the physics run 3 until the end of 2024.

Table 1: Summary of hard landings of $1.8Kref.unit_{8A}$ during Run 3 until the end of 2024. CC2 was replaced at the end of 2024 after 5 events, following an unsuccessful calibration check.

Hard landings $1.8Kref.unit_{8A}$ / Run3	**CC1**	**CC2**	**CC3**	**CC4**
2021	2	1	1	1
2022	-	1	-	-
2023	-	-	-	-
2024	-	3	-	2
Total	2	5	1	3

Focusing on 2024, the two AMBC4 trips directly led to a hard-landing of CC4. Moreover, on three separate occasions — following the first AMBC4 trip, the initial pressure sensor error, and the SVC-induced VFD trip — CC2 experienced reverse flow, leading to an overspeed condition. The reason for CC2 to reach such condition was an issue with the separation valve, which took longer than requested to close itself and isolate the impellers. Because of that, once the VFDs of the cold compressors stopped and the impellers went into free-spinning, the higher pressure at their outlet reversed the flow towards the low pressure side, i.e., the client side. Such situation led most of the compressor impellers to turn



(a) Slow EV (1’24”) configuration at -1.5%/s. CC2 reached an overspeed condition (> 500 Hz), stopping its AMBC and hard-landing.

(b) Faster EV (40”) configuration at -4%/s. In this case, the overspeed condition of CC2 was narrowly avoided thanks to the faster closing of the separation valve.

Figure 4: Example of Cold Compressors (CCs) speed behaviour after two AMB4 trips with different separation valve closing speeds. In both cases, the release of air, and hence the closing speed of the valve, was controlled by the safety electric valve (EV).

backwards as the separation valve was closing (Fig. 4), and CC2 to reach an overspeed condition due to which it hard-landed (Fig. 4a). After three such events occurred on CC2, the calibration check was not passed anymore and the unit had to be replaced with a spare one and sent for repair. Due to the criticality of $1.8Kref.unit_{8A}$ and the importance of a prompt recovery, such intervention was done for the first time by warming-up only the train of compressors and keeping the rest of the unit cold.

An AMB failure during normal operation inevitably leads to a hard-landing. However, the reverse-flow induced hard-landing following any other failure cause can be avoided. A non-return valve at the outlet of a compressor is a standard approach to resolve the reverse flow phenomena following a trip. However, it adds additional pressure drop to the system, which has direct negative consequences on the total pumping capacity of the unit [10]. Another solution is to ensure that the separation valve closes faster than the speed decrease of the impellers in freewheel mode. If this is not possible, the valve should close faster than the shortest time it takes for any impeller to reach an overspeed condition.

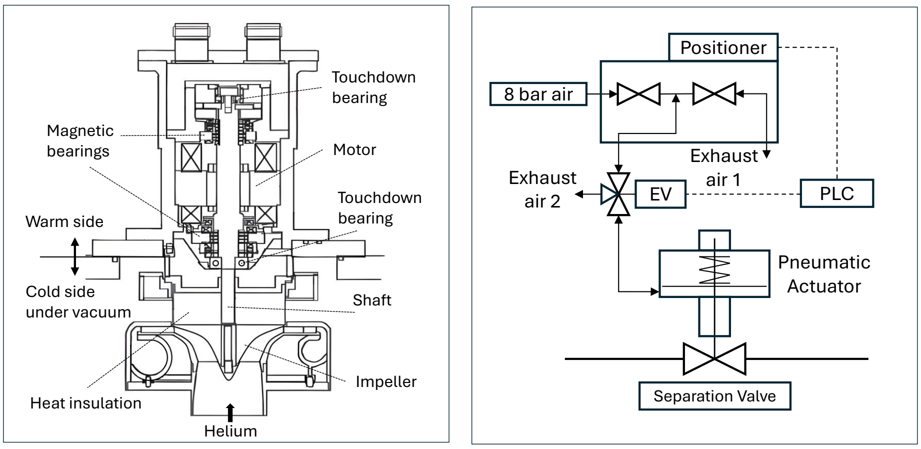
4.1 Separation valve closing speed

To reduce the added pressure drop, a DN250 butterfly valve is used as a separation valve shown in Fig. 1b. Its safety interlocks strategy defines different closing methods depending on the type of failure. Following the events of 2024, this strategy was fully revised with the goal of reducing a hard-landing probability, and hence, the repair time.

Depicted in Fig. 5b, the separation valve is controlled by a pneumatic actuator. For safety considerations, it is a normally closed valve. The normal control chain consists in routing pressurized air to the pneumatic actuator through the positioner. The latter receives the set point from a PLC, measures the actual position on the actuator, and sends or releases air from it in order to adjust the position. An electric valve (EV) is installed in series, taking over the closing of the valve in case of an emergency. Whenever an AMB is lost, it releases the air from the pneumatic actuator directly through “Exhaust air 2” indicated in Fig.5b. Over the year, it became clear that the existing exhaust restriction on the EV was improperly sized, preventing the valve from closing quickly enough. This can be seen when comparing Fig. 4a and Fig. 4b, with and without the added restriction. CC2 enters in an overspeed condition with the restriction, and misses it closely without. During the YETS, the existing EV was replaced with a larger orifice and a larger exhaust restriction one. In addition, the positioner was adjusted such that it does not fill the actuator with the maximum available compressed air pressure, but rather with just enough pressure to keep the spring compressed and the valve open, reducing the amount of air to be released. The combined measures allowed reducing the closing time of the valve from 45 s to 10 s. Such speed proved to be enough to prevent a future overspeed induced hard-landing.

4.2 Redundancy

Each cryogenic island is attached to two sectors and has two 1.8 K refrigeration units (see Fig.1a). Only one of these units is active in stable operation, and maintains the conditions on both sectors, whilst



(a) (b)

Figure 5: (a) Typical CC cartridge cross-section indicating the magnetic and the touchdown ceramic bearings. (b) Separation valve interlock strategy, including a valve positioner, its actuator, an electric valve (EV) and a Programmable Logic Controller (PLC). The compressed air is routed to the actuator through the positioner and the EV. Different conditions can trigger the release of air to close the valve.

the other one stays in standby at 20 K. The standby unit effectively provides a redundancy if an issue occurs with the active unit. The fact of using a mixed cycle, with an independent oil removal system and volumetric compressor also allows the usage of the 1.8 K refrigeration unit in combination with any of the two 4.5 K refrigerators located at the same point. This has proved highly beneficial when one of the 4.5 K refrigerators undergoes an extended stop for maintenance. However, as the system was initially designed such that each sector is pumped by its 1.8 K refrigeration unit, this redundancy is not fully optimized for availability and could be further improved for a similar layout in a future project. Essentially, the standby 1.8 K refrigeration unit should have the interconnection lines always thermalised and ready for reconnection, as this would allow connecting the unit immediately after a stop of the active unit. Today, the time it takes to thermalise the lines is often higher than the repair and restart time of the stopped unit. It should also be possible to use both units during transient operations, that is, with each pumping on one sector, with a smooth transition to just one of them once stable conditions are achieved. This would halve the recovery time after an undesired stop. Finally, each 1.8 K refrigeration unit should be capable of connecting to any of the 4.5 K refrigerators, independently of their status. Today, it can only be done if the 4.5 K refrigerator associated with the 1.8 K refrigerator unit is fully isolated from the client, limiting the configuration possibilities when rebalancing the two 4.5 K refrigerators.

4.3 Process control logic

Mastering the process control logic has proved to be an essential part in both reducing the recovery time and on mitigating certain instrumentation failures. The complexity of such system and the dynamic nature of the requirements of a particle accelerator require a complete understanding of the logic. Initially, the control logic of the unit was a black box for the operations team, causing severe diagnosis and operation limitations, directly impacting the repair time and the pumping performance. During the LHC Long Shutdown 2, 13 years after the commissioning of the cold compressors, the dedicated proprietary PLC software was translated and adapted into the master PLC, following CERN standards (UNICOS) [11]. Additional developments were also included improving the overall operability as well as the diagnostic capabilities of the system.

During 2024, one of the pressure sensors that failed in the $1.8Kref.unit_{8A}$, did so by dropping by a fixed value, effectively introducing an offset to the measured pressure at the inlet of one of the intermediate cold compressors, impacting its speed. Thanks to the described upgrade, it was possible to perform a thorough diagnostic and get a quick understanding of the effects on the control of the cold compressors. It was then possible to prepare a mitigation measure consisting in compensating the failed sensor with additional calculations, finding the actual operating point of each compressor. Nevertheless, more refactoring of the control logic would be beneficial to simplify it and make it clearer. For example, the second of the 2024 stops was partly due to a misunderstanding of the implications of forcing a sensor value on the control logic - a clearer logic specification could have helped avoiding the full stop.

A control system following open standards and ideally, co-developed with the future operation team, is clearly advantageous for an increased operability and diagnosis capability, both impacting the repair and recovery time of the system following a stop. Such approach also allows for a gradual improvement of the control by taking into account the changing machine requirements and the gained operational experience, necessary for it to be able to evolve together with the life cycle of the machine.

5 Outlook and conclusions

For particle accelerators with a large He II inventory, the dedicated pumping system must be more robust than the rest of the systems due to a slower recovery, increased complexity and higher sensitivity to process variations. 80% of 2024 LHC cryogenic unavailability came from the $1.8 Kref.unit_{8A}$. Its architecture and the gains on recovery time thanks to the reconnection capability were discussed. The different failure causes were analysed together with the taken measures aiming at improving the availability of the system. The experienced issues showed that the higher radiation exposure of the unit, which is directly proportional to the accelerator luminosity, increased the failure probability through SEUs and, potentially, accelerated ageing of critical components. When considering the positioning of such system in future projects, a holistic trade-off assessment is necessary, addressing pumping capacity against higher radiation exposure with stricter maintenance and shielding requirements. The strategy to ensure good availability levels of the cryogenics system during the following increasing luminosity LHC years consists in reducing both, the failure occurrence by improving the preventive maintenance and the affected unit shielding, as well as the repair and restart time following a failure. Whilst the latter is a wide goal, this paper addressed the avoidance of a cold compressor hard-landing due to an abrupt AMB stop. The separation valve closing speed has proven fundamental in preventing reverse flow leading to such situation. Finally, in view of future projects, ideas on redundancy enhancements for similar architectures, as well as on the importance of a well-integrated, easily accessible and adaptable control logic were discussed.

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