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First operational experience with the HIE-Isolde helium cryogenic system including several RF cryo-modules

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Abstract. The High Intensity and Energy ISOLDE (HIE-ISOLDE) upgrade project at CERN includes the deployment of new superconducting accelerating structures operated at 4.5 K (ultimately of six cryo-modules) installed in series, and the refurbishing of the helium cryo-plant previously used to cool the ALEPH magnet during the operation of the LEP accelerator from 1989 to 2000. The helium refrigerator is connected to a new cryogenic distribution line, supplying a 2000-liter storage dewar and six interconnecting valve boxes (i.e jumper boxes), one for each cryo-module. After a first operation period with one cryo-module during six months in 2015, a second cryo-module has been installed and operated during 2016. The operation of the cryo-plant with these two cryo-modules has required significant technical enhancements and tunings for the compressor station, the cold-box and the cryogenic distribution system in order to reach nominal and stable operational conditions. The present paper describes the commissioning results and the lessons learnt during the operation campaign of 2016 together with the preliminary experience acquired during the 2017 operation phase with a third cryo-module.

1. Introduction

The High Intensity and Energy ISOLDE (HIE-ISOLDE) project is a major upgrade of the existing ISOLDE (Isotope mass Separator On-Line facility) at CERN. The project consists in a staged upgrade including the deployment of a new superconducting linear accelerator (LINAC) that will be composed ultimately of six cryo-modules (CM) installed in series, each of them containing superconducting RF cavities and solenoids operated at 4.5 K. In order to meet the substantial cost savings required for the project, instead of purchasing a new dedicated cryogenic plant, one has re-used an existing refrigerator that was connected to the ALEPH (Apparatus for LEp PHysics) magnet during LEP (Large Electron-Positron collider) operation from 1989 to 2000. The cold-box was able to provide simultaneously an isothermal refrigeration power of 630 W at 4.5 K, a shield load of 2700 W between 55 K and 75 K and a helium liquefaction rate of 1.5 g/s [1]. The total heat load of the system required for the complete HIE-ISOLDE upgrade is very close to this refrigerator capacity [2]. The cryogenic system is completed with a new cryogenic distribution system (CDS) consisting of a 30m-long transfer line (TL) that connects the cold-box to a 2,000-liter liquid helium storage dewar and six distribution valve boxes (i.e jumper boxes - JB), one for each CM, and ultimately of a return box (RB) containing bypass valves at the end of the TL (figure 1) [4].

Since its first cool down in 2015 [4], the cryogenic system went through several phases including operation periods for physics runs followed by maintenance and commissioning campaigns linked to the addition of one CM each year.

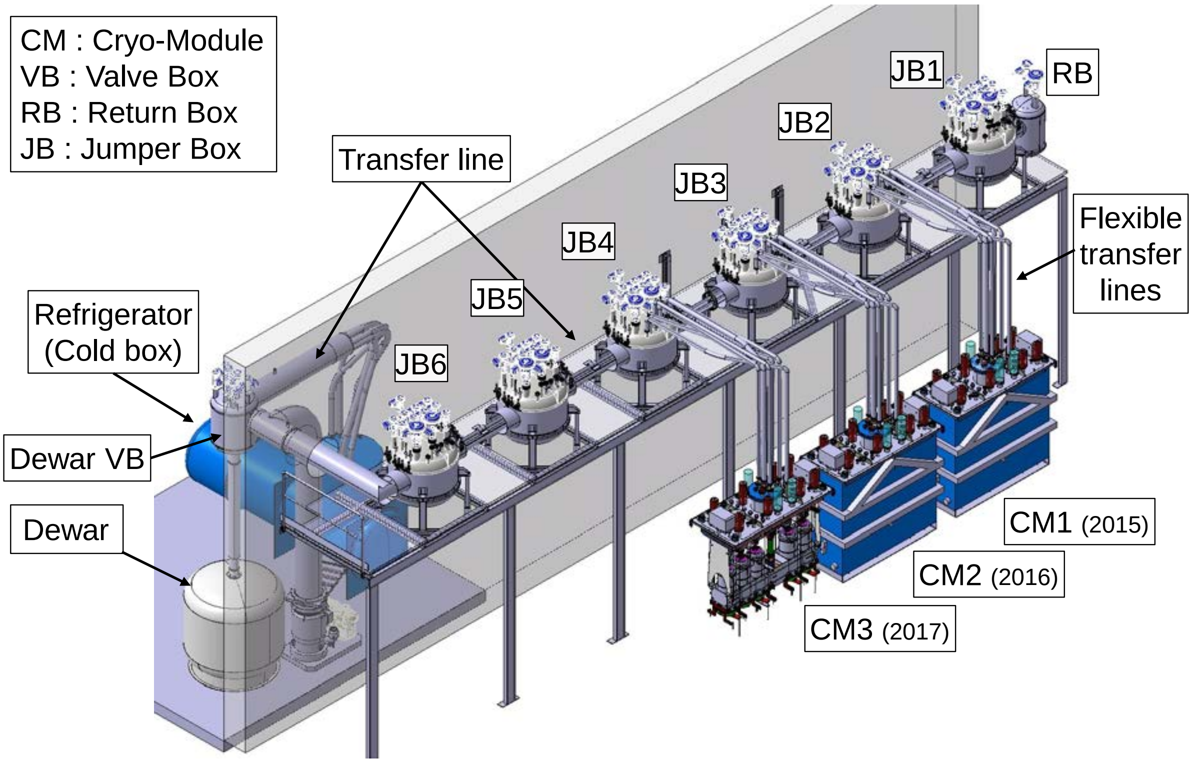

Figure 1. HIE-Isolde Cryogenic Distribution System (CDS).

2. Cryogenics operation in 2015 with a single cryo-module

The cryogenic system with a connection to a single cryo-module (CM1) was completed early 2015. The first cool down took place in June 2015 [4]. The system was then operated continuously for six months to allow the commissioning of CM1 without and with beam, followed by several weeks of operation for physics runs.

2.1. Cool down and first cryogenic operation period

In order to take into account the specificities of the cryo-module structure [2], to cope with the thermal stresses [3], and to cryo-pump and trap the residual gases onto the shield, a first cool down procedure had been established. Twelve days including special commissioning operations, were necessary for the cool-down from room temperature down to the cryogenic steady-state at 4.5 K [4].

In order to fulfill the above requirements, the cool-down procedure included five steps. The first three successive ones are performed with the gaseous helium of the shield circuit (GHe) of the refrigerator, while the two last ones are performed successively with the liquid helium circuit (LHe) :

- Thermal shield cool-down to 80 K with GHe;
- Vessel and frame cool-down to ~100 K with GHe;
- Cavities and solenoid cool-down to 100 K with GHe;

↓ Successive steps with GHe

- Vessel and frame cool-down to 4.5 K with LHe;
- Cavities and solenoid filling with LHe at 4.5 K.

↓ Successive steps with LHe

In terms of control logic for the cryogenic operation, the whole cool-down phase was managed manually. Basic software interlocks were implemented to respect the limits for the temperature gradients within the thermal shield (50 K maximum) and the supporting frame (40 K maximum) of the cavities.

During the CM1 cool-down, an overheating occurred with the 10 kW heater inserted in a by-pass line dedicated to the recovering of gas above 10 K and located inside the refrigerator. As a consequence the temperature sensor located at the outlet of the heater to control its power went out of order. Another sensor located further downstream was used to regulate, but the control was not easy since at the location of the sensor the flow from the heater is mixed with other gas returns.

During the commissioning of CM1, an overall static heat load at 4.5 K of 9.5W was measured, well below the expected design value [5].

During the same period, two major faults that lead to stops of the refrigerator were experienced : the loss of a temperature sensor involved in the control of the turbines and an unwanted shut-off of a valve due to a bad electrical contact. Regarding the cryo-module, a process dysfunction combined with a non-optimum hardware security of the cryo-plant were at the origin of an over-pressure in CM1 that has activated the over-pressure protection system including the ultimate bursting of the rupture disc. The rupture disc was promptly replaced, avoiding a detrimental warm-up of the cryo-module [6, 7]. The process and the fail-safe position of the valves in the system were revised, and additional safety logic has been included to prevent an over-pressure of the cryo-module. Further investigations showed also that the setting pressures of the safety valve (2.1 barg ± 10%) and the rupture disc (2.5 barg ± 5%) which are acting in parallel were too close. The safety valve was consequently recalibrated at 1.8 barg,

From September 2015 and during the whole physics run till end of November, no more faults were experienced.

2.2. Cryo-module warm up

The machine commissioning of 2015 revealed an issue with the main RF coupler lines, which has limited the scope of the first physics run [7]. Consequently CM1 needed to be warmed up after the physics run in order to be improved together with the refrigerator where instrumentation issues had to be fixed. Similar to the cool down phase, most of the active warm-up operation had to be made manually.

After having emptied the vessel and the cavities, an active warm-up of the global structure up to 100 K was performed by diverting part of the GHe flow of the shield circuit to the LHe 4.5 K circuit. When the temperatures were above 100 K, part of the helium gas at room temperature from the high pressure (HP) of the compressor was mixed with the cold GHe flow of the shield circuit (figure 2). During the warm-up process, the thermal gradients were again limited as in the cool-down.

The warm-up phase lasted about eight days and was completed beginning of December.

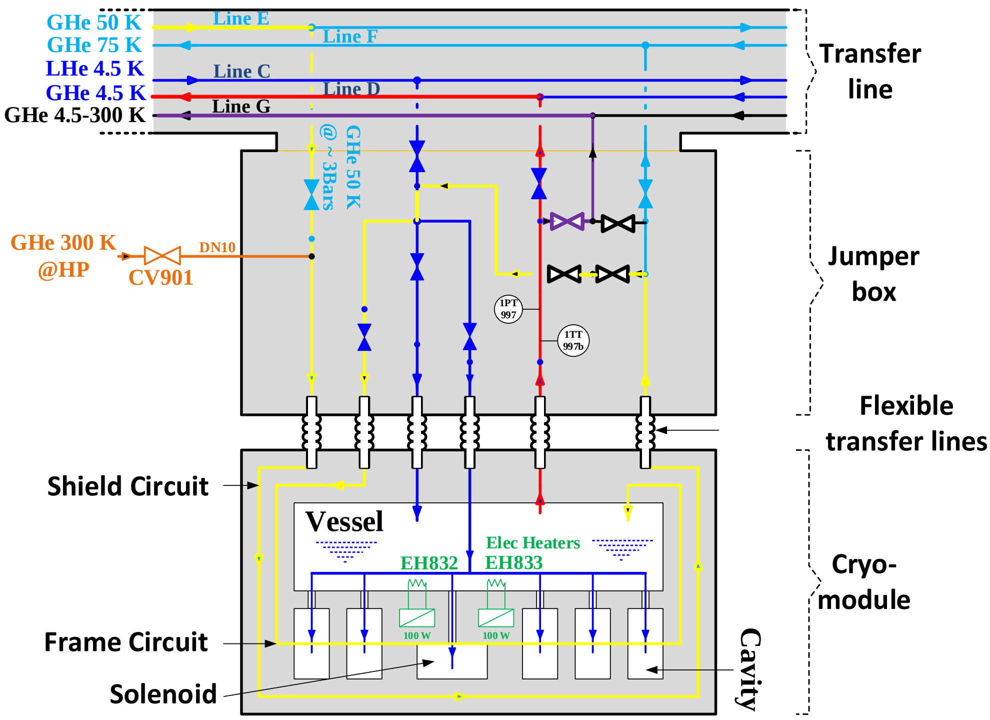

Figure 2. GHe circulation during the warm-up phase (2015).

3. Cryogenics operation in 2016 with two cryo-modules

3.1. 2016 shutdown works

Early 2016, the refrigerator was opened in order to evaluate the damage provoked by the overheating of the 10 kW heater. In addition to the burnt temperature sensors, multilayer insulation and some instrumentation or power cables in contact with the pipework were found damaged.

During the first quarter of 2016 the damages in the refrigerator were fixed. The instrumentation for the heater was consolidated and the associated logic was revised. In parallel the instrumentation of the dewar that could not been fully installed in 2015 due to lack of time was completed, and a second cryo-module (CM2) was connected to the jumper box JB3.

3.2. 2016 commissioning and operation

The conditioning of the compressor station was perturbated by the presence in the helium circuit of high and persistent rates of moisture and of nitrogen, respectively >150 ppm and >>200 ppm. Purges allowed an efficient reduction of the moisture pollution, but not of nitrogen. Despite careful leak detection checks, it has not been possible to improve the situation. It was then decided to trap the pollutants in the the adsorbers of the cold-box during a partial cool down. The operation was successful : after the regeneration of the adsorbers, the levels of moisture and nitrogen decreased below 20 ppm.

The cool-down of the two cryo-modules CM1 and CM2 started at the end of May. Early on in the cool-down, limitations were observed due to a reduced helium flow provided by the compressor station with respect to its nominal performance. A maximum flow of 140 g/s could be achieved although the nominal performance was 160 g/s [1]. The limitation came mainly from a hardware interlock set too conservatively for the mid-pressure (MP), and from a non-adapted process regulating the low pressure (LP) slide valve. The LP slide valve was very sensitive : slight modifications of its opening led to overshoot the critical MP. Additionally, the large measurement range (0–20 bar) of the pressure transmitters used for the LP regulation did not allow a good tuning of the by-pass valves that was exacerbating the problematics related to the slide valve and MP overshoots (figure 3).

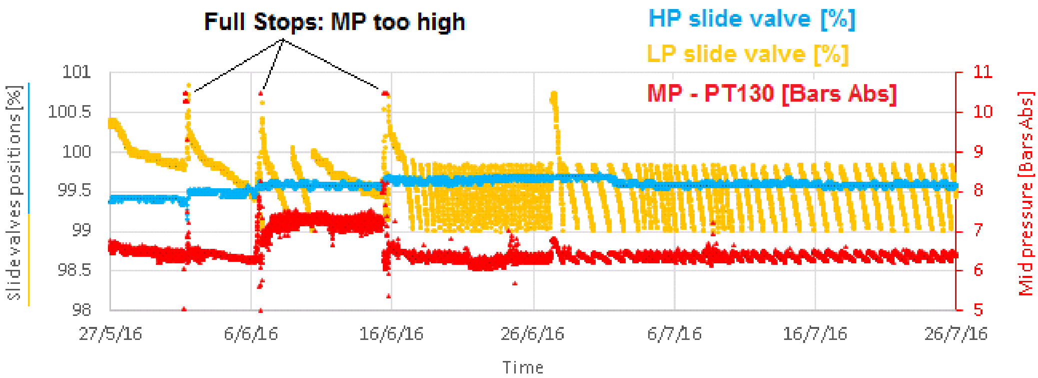

Figure 3. LP slide valve regulation and full stops caused by too high mid pressures

Due to several unwanted stops of the compressor, 14 days were necessary to complete the thermal shield cool-down, underlining the necessity to revise part of the cryo-plant interlocks together with the process control logic before pursuing the cool-down with LHe. Two weeks were dedicated to find mitigation measures while the shield circuit was used to circulate through the shield, the frame and the vessel of both cryo-modules. During this phase the temperature of the cavities went down from 200 K to 100 K and allowed to carry out the conditioning of the multipacting levels at low field [7]. When restarting the active cool-down of the cavities in-line leaks on process valves and wrong positioner settings were observed on the jumper boxes (JB2 & JB3).

The two cryo-modules were next cooled, in parallel, with LHe from 100 K down to 5 K in about four days. A complex and long (four days) manual tuning of the cold-box and of the supply valves in the jumper boxes was necessary to complete the filling of the two cryo-modules. Indeed, when trying to fill the cryo-modules with LHe, the cryo-plant showed clear limitations related to the flow capacity of the compressor station. It was then mandatory to modify the cooling strategy by closing the LHe supply to CM1. This allowed to fill CM2 with LHe in about one day. Next the supply of LHe was restored to CM1. However, the temperatures of jumper box JB2 and flexible transfer lines connected to CM1 rose up to 60 K before the LHe flow could be restored. It was thus necessary to manage the return gas between the line G by-passing the cold box and the cold return line D to the cold box.

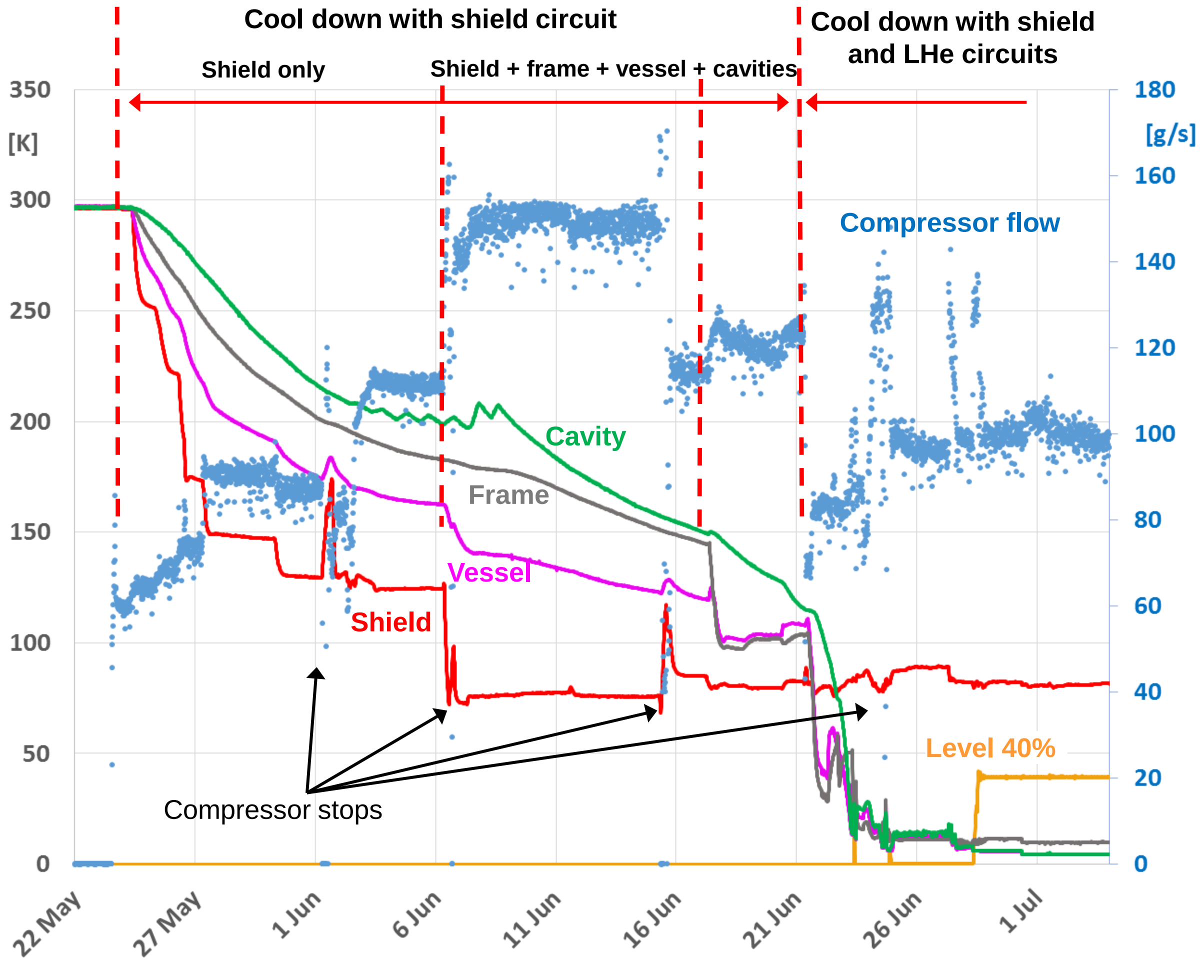

Figure 4. CM1 temperatures evolution during the cool down in 2016

The commissioning and the tuning of the cavities to their target frequency, revealed that cryo-plant perturbations were affecting the cavity frequency tuning, preventing their operation at the nominal field [8]. The origin of the perturbations was correlated with the tuning of the valve connecting the cold-box phase separator to the LP line and with strong oscillations of the return gas temperatures between the cryo-modules and the LP inlet of the cold-box (6 to 15 K) (figure 5). These oscillations were reduced by increasing the by-pass flow in the return box, and by activating the electrical heaters in each cryo-module vessel in order to increase the vapor return flow in the line D.

However, the flow increase in the return box by-pass imposed to reduce the opening of the supply valves in JB. This, was a clear indication of the bad quality of LHe delivered by the line C at JB2 compared to JB3 and indicated an excessive heat load in the distribution system. Therefore, without any visible evidence of condensation or cold spots, it was concluded that the issue was internal to the cryogenic distribution system.

Settings were finally found for the bypass valve and the heaters which have allowed stable operation and 100% availability during the whole physics run in 2016.

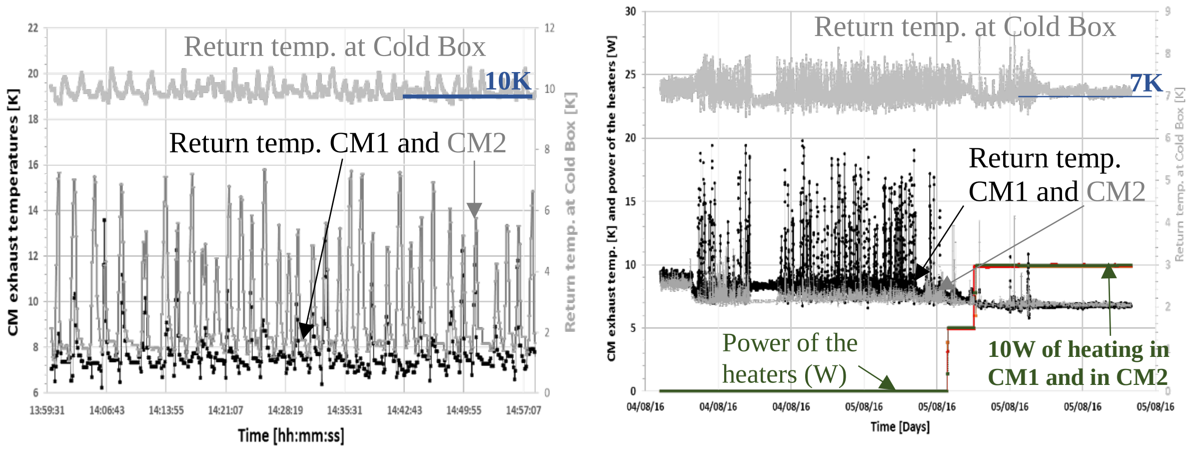

Figure 5. Tuning of the electrical heaters and the return valve to fight pressure and thermal instabilities

3.3. 2016 cryogenics tests

After the end of the physics run, static heat load measurements were performed on the two cryo-modules. Each cryo-module vessel was filled up to 80%. Next the filling valves were closed while the valve on the vapor return line D was left fully open towards the refrigerator LP stable at 1.06 bar. Cooling was continuously maintained for the shields. The level drops were measured in CM1 and CM2 (figure 7). Both were equivalent to a static heat load of ~11 W, in agreement with the expected values. This confirmed that the excessive heat load issue observed during the filling phase was related to the distribution system and not to the cryo-modules.

A capacity test was carried out using the electrical heaters of each CM as load. It was then possible to operate in stable conditions while applying 110W and 220W, respectively in CM1 and CM2 indicating that the cryo-plant has the necessary power margin to supply an additional cryo-module.

The dewar was also partially commissioned and filled with 300 liters of LHe.

Following these tests, the two cryo-modules were actively warmed-up to 110K and then left floating. They were back at room temperature in 23 days.

4. Cryogenics operation in 2017 with three cryo-modules

4.1. 2017 shutdown works

In addition to the installation of the third cryo-module CM3, and to cope with the reported issues in 2016, an extensive actions plan was organized for the Extended Year-End Technical Stop (EYETS) beginning 2017 at CERN. Additionally to the planned standard preventive maintenance tasks and expected minor corrective interventions after 10’000 h of operation, major consolidations were implemented to improve the operation of the cryo-plant :

- Hardware and software interlocks were revised and simplified. In particular, the interlock related to the MP of the compressor has been removed and pressure transmitters on the LP were exchanged with sensors of 0 to 6 bar range. The slide valves were re-calibrated and their control revised.
- The whole instrumentation including the hundred cryogenic valves of the cryo-plant and the CDS was checked and re-calibrated.
- The architecture of the process control software of the cryo-plant and the cryo-modules has been completely revised : automatisms were implemented to allow the full performance together with a robust and reliable operation including quasi-automated restarts to cope with short stops of the cryo-plant and the requirement to maintain a continuous cooling of the shields..
- In order to prevent the opening of the pressure safety devices set at 1.8 barg on the cryo-modules (section 2.1), two additional safety valves were added. The first one calibrated at 1.1 barg was

installed on the LP of the compressor in parallel of the control valve releasing the helium when the pressure is above 1.25 bara. The second safety valve calibrated at 1.3 barg was installed on the cold vapor flow return line G that is used when the pressure is rising above 1.6 bara in a cryo-module. This allows a gradual release in any case of overpressure in the LP and the cryo-modules (figure 6).

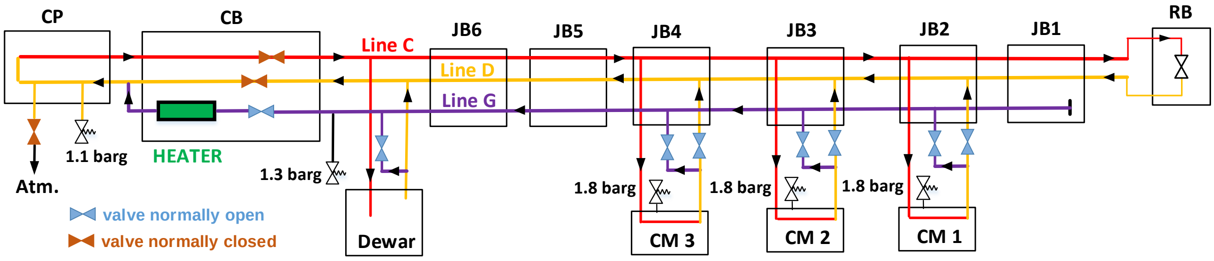

Figure 6. Revision of the safety system with respect to overpressure events

The excessive heat load detected during the 2016 operation in the CDS was evaluated to be three times higher than the expected figure of 120 W. Endoscopic examinations of the TL from the JB were performed revealing that the increased heat loads was related to the contact of the 4.5 K process pipes (lines C & D) with the shield. In addition, holes in the multilayer insulation system were discovered.

To mitigate these issues, all JB were opened and insulated spacers were inserted to remove direct contacts. The consolidation of the line C (LHe) was successful, but it was not possible to fully suppress the contact in all points of the line D, as there was a risk of breaking due to the high forces required. This issue being enabled by a bad shield design of the TL (the gap between the process pipes and the shield is too small), plans are made to redesign and repair the CDS during the next shutdown scheduled early 2018.

4.2. 2017 commissioning and operation

The strategy used in 2016 with regards to the conditioning of the helium circuit was adopted as the same pollution issue was experienced. The cryo-plant was tested alone and its nominal performance confirmed. The cool down with the shield circuit of the three cryo-modules from 300 K down to ~110 K was carried on within height days. One week later, after the multipacting conditioning phase of the cavities, the cool down was restarted with LHe. This time CM1 and CM2 were filled in parallel with LHe within 4 hours. CM3 was probably also filled but due to issues with the level transmitters (LT), it was only possible to confirm it few days later after their repair. The 2017 cool-down performances with respect to 2016 have validated the improvements of the hardware and software upgrades executed during the EYETS.

Static heat load measurements were also performed on each cryo-module. This time both cooling circuits (shield and LHe supply) were stopped. The static losses derived from level drop in each CM were, as expected, slightly higher (~13 W) with respect to 2016 measurements except for CM2 that presented an increase by a factor three (figure 8). Investigations are still going on to understand this discrepancy.

The system was then stably operated with an electrical power of 100 W in each of the three cryo-modules, which gives confidence that the system can accommodate with a fourth one.

The dewar was filled once at 60% this time, but there was no commissioning time left to complete the functional test.

During the commissioning of the superconducting cavities, a frequency perturbation was detected and correlated to the liquid helium temperature and pressure oscillations. It was nevertheless less severe than the one observed in 2016 and easily corrected by the cavity tuning system as the cavity frequency shift was slow (repeating 10–20 minutes) and limited to only about 10 Hz [9].

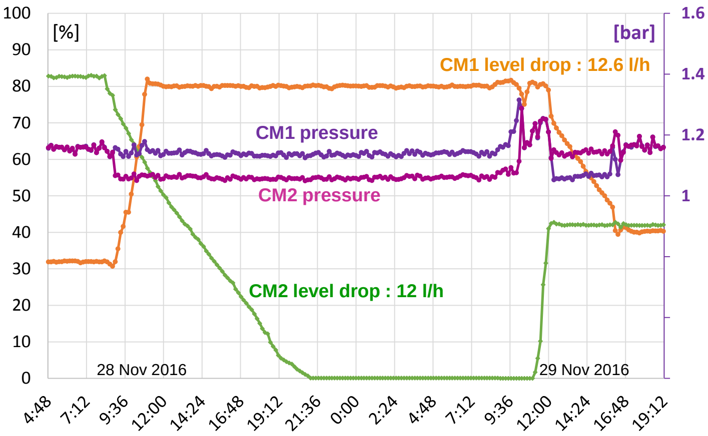

Figure 7. LHe level drop of CM1, CM2 during static heat load tests in 2016

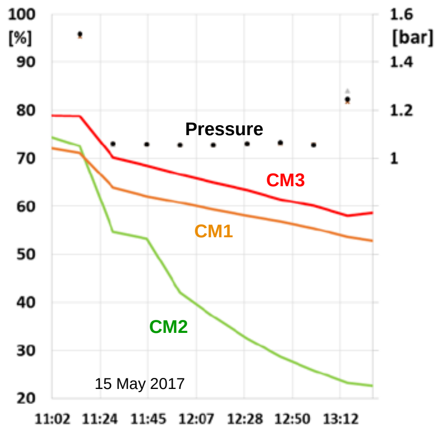

Figure 8. LHe level drop of CM1, CM2, CM3 during static heat load tests in 2017

5. Conclusion

The long series of issues observed during the three years of operation and the time taken to detect and correct them is the consequence of : first, the lack of time available to commission completely the cryo-plant and the CDS with the associated control logic and to test it at full capacity. Second, the absence of CM test in the CERN test facility as originally planned. Thus it was difficult to identify the origin of the lack of performance and to prepare the CM control logic.

However, the numerous hardware and software modifications brought to the cryo-plant during the rotation of shutdown and operation periods, and mainly during the last EYETS, have significantly improved the reliability of the facility and reduced the cool-down time of the cryo-modules. In addition, the optimisation of the process and efforts brought to the training of operators, have given the possibility to operate in better conditions. Nevertheless, at the end of the present run, the automated warm-up of the facility will have to be validated, and last but not least the hardware consolidation program will have to be completed to include, among other, the repair of the cryogenic distribution system in view of the operation with four cryo-modules.

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