IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012038 doi:10.1088/1757-899X/1344/1/012038

Results of fundamental operational function tests for the ESS cryogenic moderator system during preliminary commissioning with helium

H Tatsumoto*, A Horvath, T Vasilopoulos, and I Haag

European Spallation Source (ESS) ERIC, Lund, Sweden

*E-mail: hideki.tatsumoto@ess.eu

Abstract. At the European Spallation Source (ESS), a cryogenic moderator system (CMS) was designed to continually supply subcooled liquid hydrogen at 17 K with a parahydrogen fraction exceeding 99.5% to each moderator. The heat load is removed via a heat exchanger connected to a large-scale 20 K helium refrigeration plant, the Target Moderator Cryoplant (TMCP), with a cooling capacity of 30.3 kW at 15 K. The CMS installation was completed in May 2024. Preliminary commissioning of the CMS was carried out using helium, bypassing the moderators. The CMS was successfully cooled down to 17 K utilizing the developed controllers. This paper presents the results of the system function test and the activation of the CMS failure-action triggered by the accidental turbine trip during helium-base commissioning.

1. Introduction

At the European Spallation Source (ESS), two flat butterfly-shaped hydrogen moderator vessels have been designed and optimized to achieve a maximum neutron brightness under the condition of parahydrogen fraction exceeding 99.5% [1]. These moderators are currently installed above the target wheel, with future plan to replace them with four moderators positioned both above and below the target. The nuclear heating at the moderators is estimated to be 6.7 kW at a proton beam power of 5 MW, increasing to 17.2 kW for the four-moderators configuration [2]. To supply liquid hydrogen at 17 K with a parahydrogen fraction of 99.5% to each moderator, a cryogenic moderator system (CMS) was designed, as shown in Fig. 1. The hydrogen flow rate to each moderator is 0.25 kg/s, ensuring that the average temperature rise through the moderator remains within 3 K [3]. At 5 MW proton beam power, a total heat load of 21.9 kW, including a static heat load of 4.6 kW, is removed by the Target Moderator Cryoplant (TMCP), a 20 K-helium refrigeration plant with a maximum cooling capacity of 30.3 kW at 15 K [4].

The CMS will operate in combination with the TMCP through an automated operation control system currently under development [5]. This system comprises seven operational modes: cooldown, steady-state, energy-saving, beam injection, warm-up, quick warm-up and ortho-to-parahydrogen measurement. The cooldown operation mode requires two compressors operating at a discharge high-pressure of 1.5 MPa and two parallel cold turbines (T2 and T3) running in parallel, allowing the CMS to reach 17 K within 30 hours. Upon completing cooldown, the system automatically transitions to the steady-state mode. In this mode, liquid hydrogen is circulated at 17 K at a flow rate of 1 kg/s by two hydrogen pumps operating at 7,000 rpm, while the pressure is maintained at 1.1 MPa by the pressure control system [3]. The steady-state mode enables

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

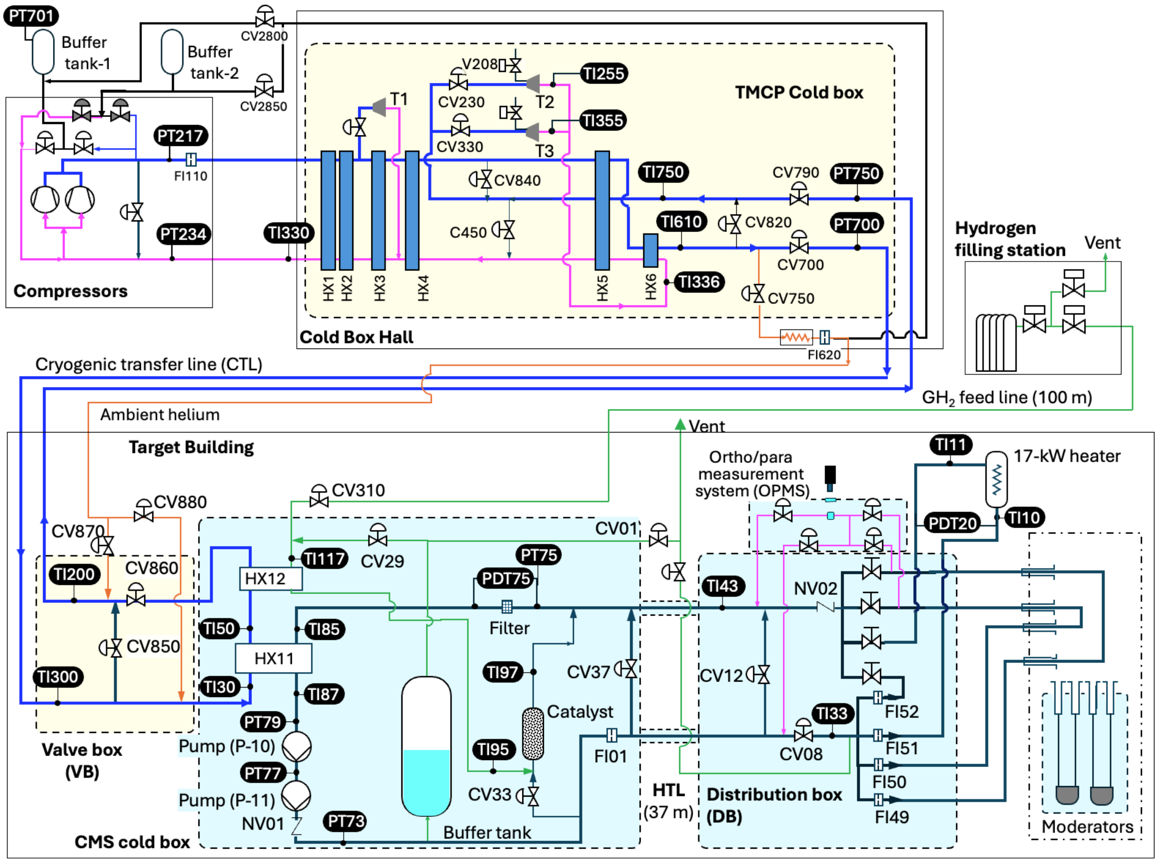


Figure 1. Overview of the ESS cryogenic moderator system (CMS).

transitions to both beam injection and energy saving modes. During a short maintenance period of approximately two weeks, the energy-saving mode is used to maintain the CMS at 17 K without a full warm-up. To reduce energy consumption, one cold turbine (T2 or T3) is shut down, followed by the shutdown of one compressor, and the TMCP discharge pressure is also reduced to 1.0 MPa.

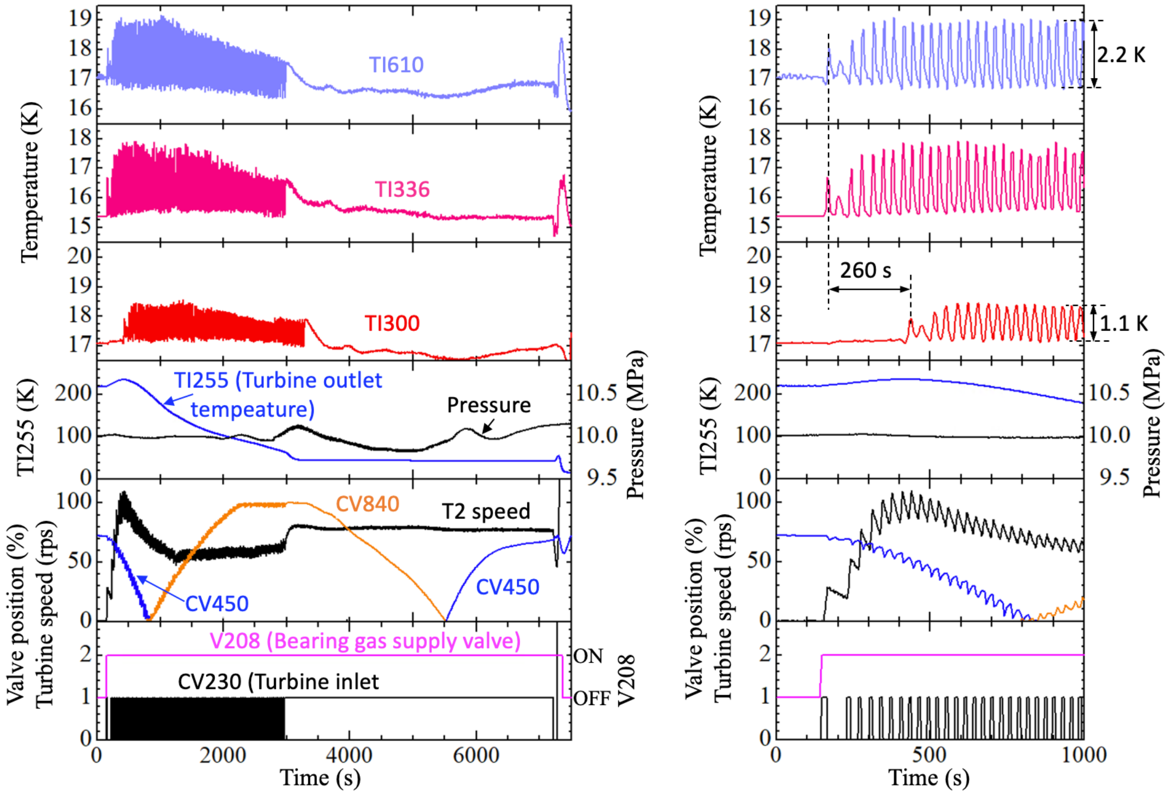
The initial CMS-TMCP commissioning was conducted without the moderators connected, using nitrogen and helium as preliminary steps before hydrogen operation [6]. During this commissioning period, fundamental operational function tests related to the operational mode transitions from steady-state to energy saving mode were conducted to establish the automated control logic. Additionally, a simultaneous trip of all turbines, triggered by the failure of the water-cooling pump due to an electrical glitch, led to the safe shutdown of the CMS via the operational failure-action system, as designed. This paper presents the results of the operational function tests and the activation of the CMS failure-action system in response to the accidental turbine trip.

2. CMS-TMCP commissioning

2.1 Restart and stop tests of the TMCP cold turbine

During the TMCP commissioning conducted in 2022 before the installation of the transfer lines between the CMS and the TMCP valve box, it was observed that the temperatures surrounding the cold turbine increased to approximately 200 K one day after the turbine was shutdown. This led to the conclusion that a precooling operation was essential before restarting the cold turbine, especially when the other cold turbine continues operating at 16 K. To address this, an automatic precooling mode was developed by intermittently opening the turbine's inlet valve (CV230 or

CV330) for short durations. The operational parameters for this mode were optimized accordingly. Figures 2 and 3 show the test results for the T2 turbine precooling process within the TMCP and CMS, respectively. During the test, the compressor discharge pressure was set to 1.0 MPa, and the TMCP circulation flow rate was 0.3 g/s. During the precooling process, CV230 was initially opened to 1% until the feed helium temperature (TI610) in the TMCP cold box increased by 0.2 K; however, it briefly peaked with an increase of 2 K. Once the feed temperature dropped below the initial temperature of 17 K, the valve was reopened. The initial turbine outlet



(a) Behaviors of the TMCP (b) At the initiation of the precooling

Figure 2. Operational behavior of the TMCP during the precooling process

temperature (TI255) was 220 K. It first increased to 235 K due to the supply of room-temperature bearing gas via V208, and then gradually decreased. This cycle was repeated until TI255 reached the target value of 65 K, as determined through preliminary testing. The temperature fluctuation at TI610 took 260 seconds to propagate through the 300-meter-long transfer line (CTL) to the valve box, where it was measured by sensor TI300. The temperature amplitude at TI300 was attenuated to approximately 1 K. Meanwhile, the CMS temperature (TI87) was maintained at 18.3 K, which was intentionally set higher than the nominal setpoint of 17.0 K, by activating the CV880 PID controller, to mitigate the propagation of temperature fluctuations into the

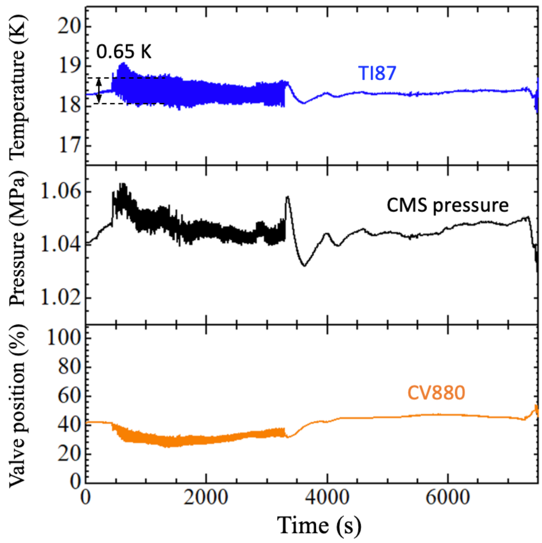


Figure 3. Operational behavior of the CMS during the precooling process.

CMS. As anticipated, the fluctuations were suppressed to approximately 40% of those at TI300, as shown in Fig. 4. The feed helium temperature (TI610) was controlled by adjusting the flow to the cold turbine through two bypass valves (CV450 and CV840) using a split range. Although CV450 is typically used for control, CV850 was opened during the precooling process because TI610 exceeded the setpoint of 17 K. Once TI255 reached 65 K, CV230 was held at 1% until both of the following conditions were satisfied: the feed temperature (TI610) returned to the setpoint of 17 K, and CV450 opened to more than 55%. During this time, the turbine rotation speed was maintained at 77 rps. Without this adjustment, a direct turbine start could have resulted in an excessively low outlet temperature, potentially triggering a turbine trip due to a low-temperature alarm. After precooling was completed, CV230 was closed, and the turbine speed was allowed to decrease to the start-up condition of 50 rps. During the period, TI255 increased to 50 K due to bearing gas flow.

Figures 4 and 5 show the behaviors within the TMCP and CMS during the turbine restart. Upon turbine startup, TI255 dropped to 16.3 K. TI610 exhibited a temporary fluctuation, initially rising to a peak of 18.5 K before decreasing to a minimum of 15.9 K. The TI610 temperature controller gradually restored the temperature to its setpoint. At the valve box (TI300), a peak-to-peak temperature fluctuation of 2.1 K was observed. In contrast, the corresponding fluctuation in the CMS (TI85) was mitigated to within 1.0 K by the CV880 PID controller, which also resulted in pressure fluctuations of ±30 kPa. Following this initial fluctuation, both the TMCP and CMS stabilized within 30 minutes after the T2 turbine restart.

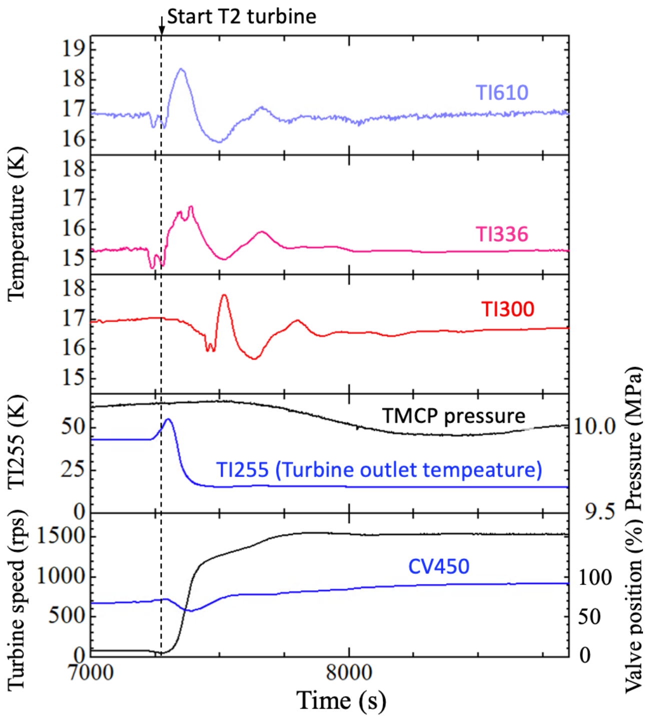


Figure 4. Operational behavior of the TMCP during restarting one of the cold turbines.

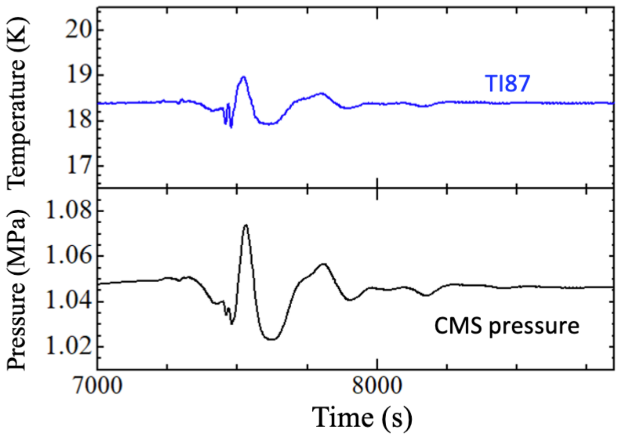


Figure 5. Operational behavior of the CMS during restarting one of the cold turbines.

The heat load applied to the CMS was estimated to be approximately 1.0 kW, based on the observed temperature increase of TI85 from 18.4 K to 19.0 K and the circulation flow rate of 0.32 kg/s. For a liquid hydrogen operation at flow rates of 1 kg/s, 0.5 kg/s and 0.2 kg/s, this corresponds to temperature rises of 0.13 K, 0.27 K and 0.67 K, respectively, The CMS pressure control system [7] is capable of compensating for pressure fluctuations associated with 0.13 K temperature rise, which aligns with the expected design fluctuation level. These results indicate that the hydrogen pump speeds should be increased to achieve a flow rate of 1 kg/s prior to restarting the cold turbine. Overall, the results confirm that the establish precooling operation mode, in conjunction with the CV880 PID controller, effectively mitigated temperature fluctuations within the CMS during the cold turbine restart under 17 K conditions.

Figure 6 shows the system behaviors during the shutdown one of the operating cold turbines. Following the shutdown, the TMCP flow rate decreased from 0.51 kg/s to 0.28 kg/s. The temperature rise of TI87 in the CMS was 0.7 K, corresponding to pressure fluctuations of 22 kPa, which were lower than those observed during the turbine restart. The return helium temperatures (TI200) from the valve box were maintained within ±0.4 K through adjustment by the TI200 temperature controller. After the initial fluctuation, the TI610 temperature controller operated as intended, enabling both the TMCP and CMS to stabilize without further disturbances within 30 minutes of the turbine shutdown. These results demonstrated that the CV880 PID controller effectively mitigated the temperature and pressure fluctuations within the CMS, not only during the turbine restart but also during the shutdown process.

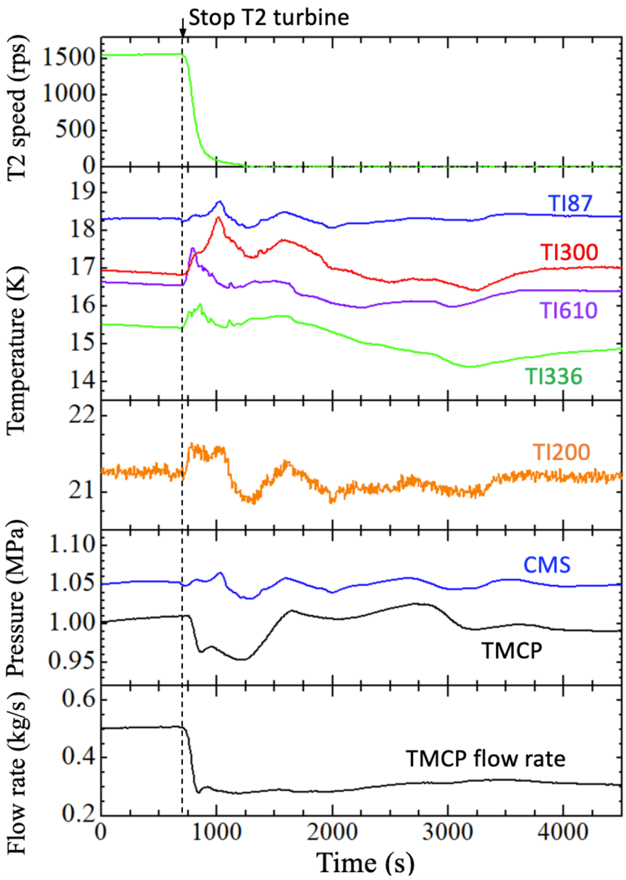


Figure 6. Behaviours observed during the shutdown one of the operating cold turbines.

2.2 Optimization of the TMCP discharge high-pressure control

Transitions from the cooldown or energy-saving mode to steady-state mode require adjustments to the discharge pressure (HP) while avoiding harmful temperature and pressure fluctuations within the CMS. Figure 7 shows the results of tests in which the TMCP discharge high-pressures (PT217) was increased to a target pressure at ramping speeds, S_R, of 0.8, 2.0 and 10 kPa/min to investigate the effects of S_R on CMS stability. The HP controller features a safeguard that holds the

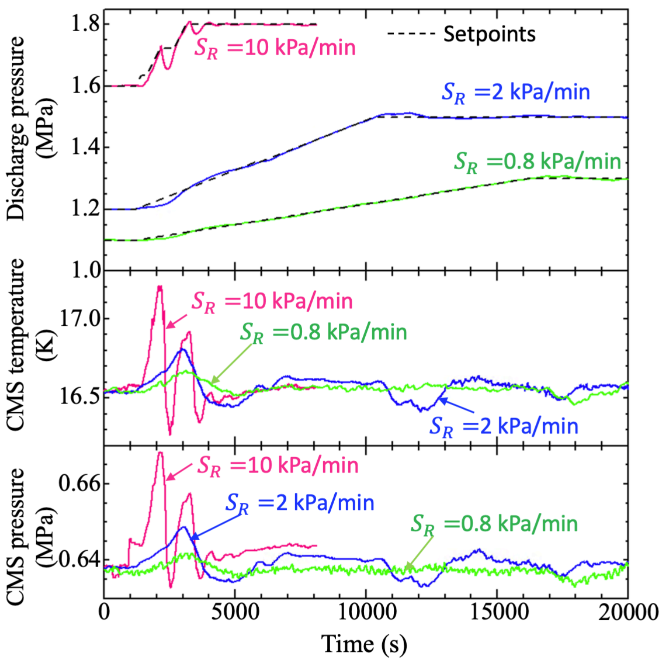


Figure 7. Fluctuations caused by increasing discharge pressure at various ramp-up speed.

setpoint for one minute if the discrepancy exceeded 35 kPa. At a ramping speed of 10 kPa/min, the discharge pressure failed to follow the ramping function setpoints, triggering the hold function. During the ramping process, a discharge pressure fluctuation of 70 kPa was observed. Once the target pressure was reached, a peak discrepancy of 30 kPa occurred, which gradually attenuated. These fluctuations affected the CMS temperature, represented by TI87, as well as internal CMS pressures. Both temperature and pressure fluctuation amplitudes decreased as the ramping speed was reduced. Fluctuations were found to occur primarily at the beginning and end of the ramp-up process, attributed to the initial positions of the unload and load valves controlled via split range. In contrast, during the mid-phase of the ramp-up, the discharge pressure followed the setpoints more closely. These findings suggests that a slower S_R should be applied at the beginning and end of the ramp-up process, while a faster S_R can be used in the middle. Figure 8 shows test results for a three-step discharge pressure ramp-up with varying S_R: 0.8 kPa/min at the beginning, 2.0 kPa/min in the middle, and 0.8 kPa/min at the end. Minor discrepancies between the discharge pressure and setpoint were observed only during the slow ramping segments (S_R= 0.8 kPa/min). The discharge pressure closely followed the setpoints, particularly at S_R= 2.0 kPa/min. Pressure and temperature fluctuations within the CMS remained below the allowable limits. These results confirm that this stepped ramping approach effectively adjusts the HP setpoint without causing harmful distributions in the CMS.

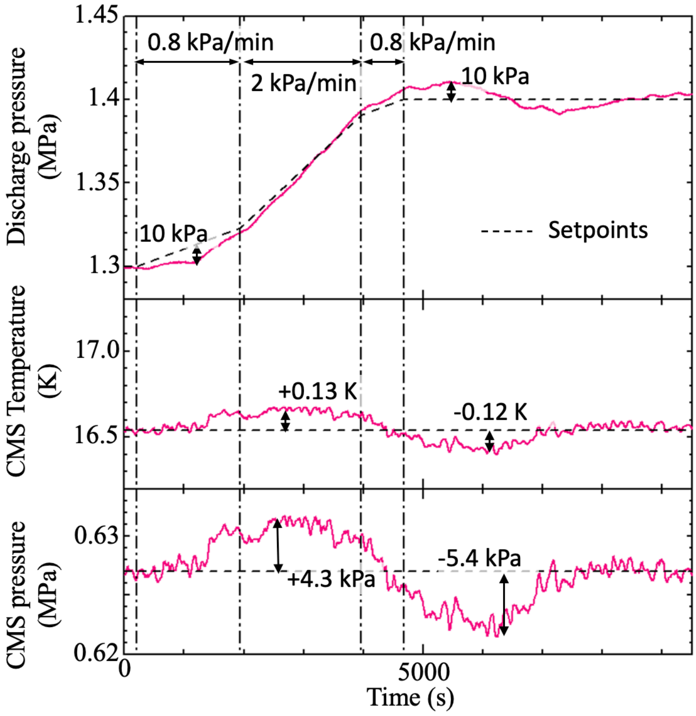


Figure 8. Fluctuations at the mixed ramp-up speed.

2.3 CMS failure actions induced by TMCP turbine trip

Late in the evening on December 6, 2024, during the commissioning period, a power glitch caused a water-cooling pump to stop. The standby pump automatically started and reached its rated speed within 50 seconds, as shown in Fig.9. The two TMCP compressors remained unaffected due to a delay timer implemented as a safeguard against such power disturbances. However, the incident led to a temporary drop in cooling water flow

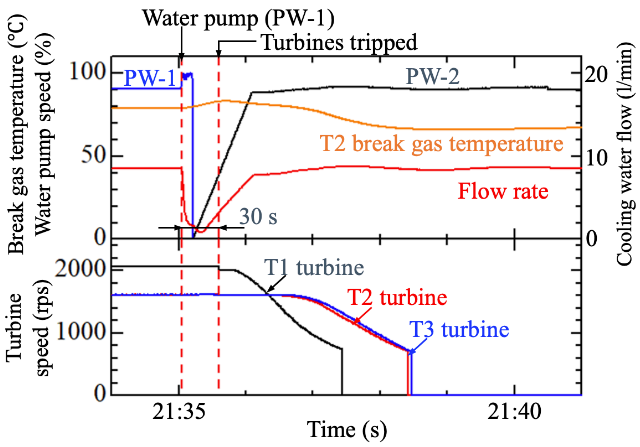


Figure 9. Turbines tripped during the commissioning.

rate, causing to all TMCP turbines to trip within 30 seconds, having exceeded their delay timer threshold. Although the turbine break gas temperature was increased from 352 K to 356 K, it remained below the alarm threshold of 363 K. Once the cold turbines had completely stopped, the CMS failure monitoring system detected the event as a "TMCP trip", as shown in Fig.10. To allow for the immediate restart of the turbines, the activation delay timer for activating the CMS failure action was temporarily extended from 30 seconds to 10 minutes during commissioning phase. Ten minutes after the turbine trip, the two hydrogen pumps were stopped, and the return valve (CV860) was closed to halt helium flow to HX11 in the CMS cold box. Simultaneously, the setpoint of the release valve (CV01) was changed to 1.1 MPa to release helium. This event demonstrated that the CMS failure-action functioned as intended. Furthermore, to prevent the recurrence of such failure events due to power glitches, the turbine protection logic was revised to rely solely on the break gas temperature threshold.

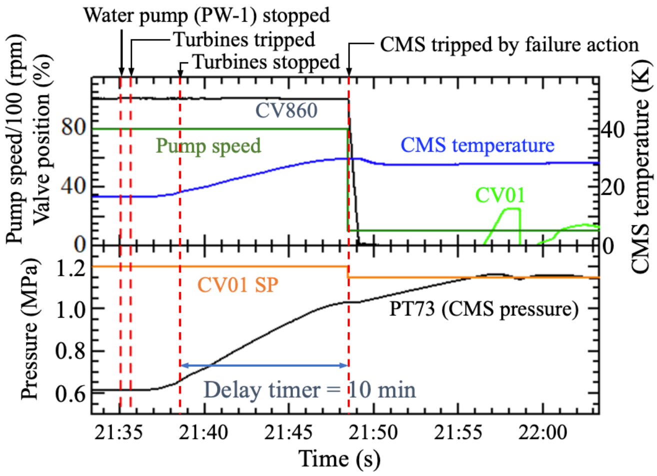


Figure 10. CMS tripped by its failure action.

2.4 TMCP cold box trip

As described in Section 2.5, the cold turbine trip triggered the closure of CV860 according to the CMS failure-action function, while the bypass valve (CV850) in the valve box remained closed. As a result, the pressure upstream of the valve box, including the supply long CTL, was maintained at the discharge pressure, whereas the pressure downstream, including the return CTL, was relieved to the LP side via CV450, which automatically opened to 24% in response to the turbine trip.

As shown in Fig.11, four hours after the turbine trip, the TMCP cold box trip signal was activated when the temperature (TI330) at the warm end of HX01 dropped below the alarm threshold of 248 K due to high-pressure backflow from the CTL return line. In response, the TMCP cold box was isolated from the compressors by closing the isolation valves at the warm ends, and CV450 was closed. Consequently, the pressures in the CTL supply and return lines began to

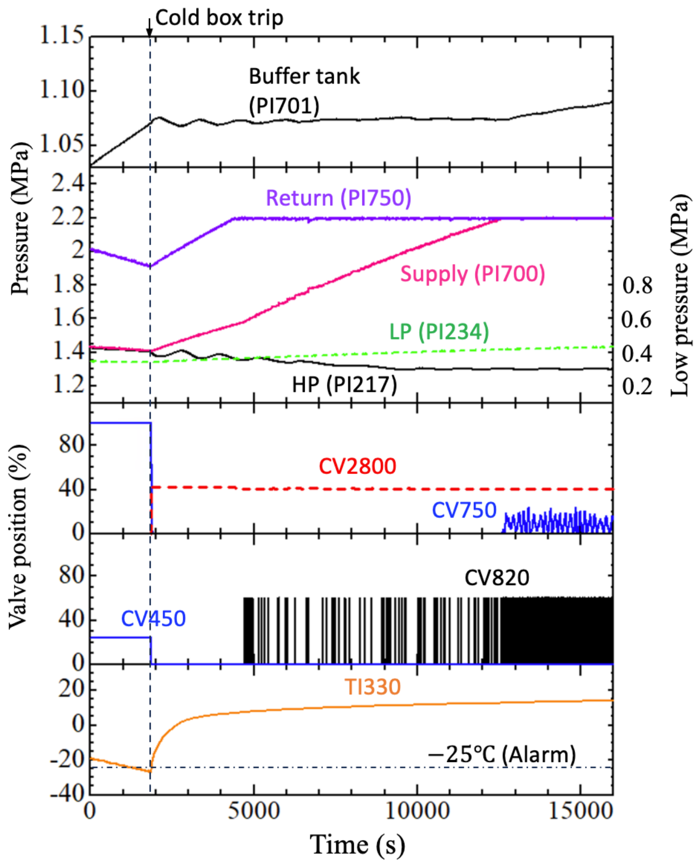


Figure 11. Behaviors during the cold box trip.

increase independently toward the setpoint of 2.2 MPa. The pressure in the CTL return line was relieved to the CTL supply line, which has a larger volume, through the bypass valve (CV820) at the cold end of the TMCP cold box. Upon reaching the setpoint, the collection valve (CV750) was activated to divert excess helium to the buffer tank-1 via an ambient heater, as designed, without activating the safety relief valves. Another collection valve (CV2800), which also led to the buffer tank-1, had already opened when the cold box trip was triggered.

When the TMCP cold box trip occurred, the discharge pressure was slowly ramping down from 1.5 MPa to 1.3 MPa according to the TMCP discharge high-pressure controller. Despite the cold box trip, both compressors continued to operate stably, and the discharge pressure (PI217) steadily decreased to 1.3 MPa. The effects of both the ramp-down operation and the turbine trip caused the buffer tank-1 pressure to rise to from 0.49 MPa to 1.07 MPa. If the buffer tank-1 pressure had exceeded the discharge pressure setpoint, the compressors would have tripped. To address this issue, the control logic was revised to redirect excess helium to the buffer tank-2, designated as the collection buffer in the event of a cold box trip, via another collection valve (CV2850). This change would ensure that the buffer tank-1 remains unaffected, allowing the stable compressor operation.

3. Conclusions

Fundamental operational function tests for the mode transition from steady-state to energy saving mode were conducted during preliminary commissioning to establish the automated control logic. The tests confirmed that the optimized operational parameters functioned effectively. Additionally, an unexpected turbine trip occurred due to the shutdown of a water-cooling pump caused by an electrical glitch. The failure-action system successfully executed a safe shutdown of the CMS, as designed.

References

[1] Bessler Y, Henkes C, Hanusch F, Schumacher P, Natour G, Butzek M, Klaus M, Lyngh D and Kickulies M 2017 *IOP Conf. Ser: Mater. Sci. Eng.* **171** 012131
[2] Tatsumoto H, Lyngh D, Bessler Y, M Klaus, Hanusch F, P Arnold and H Quack 2019 *IOP Conf. Ser: Mater. Sci. Eng* **755** 012101
[3] Arnold P, Hess W, Jurns J, Su X T, Wang X L and Weisend II J G 2015 *IOP Conf. Ser: Mater. Sci. Eng.* **101** 012011
[4] Tatsumoto H, Arnold P, Boros M and Horvath A 2024 *IOP Conf. Ser.: Mater. Sci. Eng.* ***1301*** *1131.*
[5] Tatsumoto H, Horvath A, Arnold P 2025 *IOP Conf. Ser.: Mater. Sci. Eng.* ***1327*** *012026*
[6] Tatsumoto H, Horvath A, Arnold P Segerup M Tereszkowski P Arriagada J 2025 *IOP Conf. Ser.: Mater. Sci. Eng.* ***1327*** *012032.*
[7] Tatsumoto H, Lyngh D, Arnold P, Segeup M, Tereszkowski P, and Beßler Y 2023 *Proc. 28th Int. Cryo. Eng. Conf. and Int. Cryo. Mater Conf.* Hangzhou, China pp.203-210.