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Performance test and optimization of the control system for the ESS cryogenic moderator system

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Abstract. The ESS Cryogenic Moderator System (CMS) was designed to supply a subcooled liquid hydrogen (17.5 K and 1.0 MPa) to two hydrogen moderators (to be increased to four in the future) where the nuclear heating is estimated to be 6.7 kW. The CMS is cooled by a helium refrigerator system with a cooling power of 30.3 kW at 15 K called the Target Moderator Cryoplant (TMCP). The CMS Process Control System (PCS) is responsible for controlling a wide array of equipment using different device types, generic software control blocks with a wide range of features and Operator Interface elements. In this paper it is presented the implemented functionalities, performance test and optimization of the TMCP Control Unit and the Proportional Integrative and Derivative (PID) Controllers implemented in the CMS PCS. These results enable us to start implementing sequential automated logic that shall cool-down and warm-up automatically the CMS in the future.

1. Introduction

The European Spallation Source (ESS) is one of the largest science and technology infrastructure project being built in Sweden [1]. Protons at 2 GeV are delivered by a superconducting linear proton accelerator and are injected onto a rotating tungsten target. Neutrons via spallation reaction are moderated to cold thermal energies by two dedicated moderators. The cryogenic moderator system (CMS) was designed to remove both static heat load (2 kW) and dynamic heat load induced by the nuclear heating at the moderators, which is estimated to be 6.7 kW for a 5-MW proton beam power, by circulating subcooled liquid hydrogen at 17 K and 1.0 MPa. The liquid hydrogen is transferred from the CMS cold box (CBX) to a distribution box (DB) via a transfer line (HTL) and is split into each moderator transfer line. The CMS is cooled via a plate-fin type heat exchanger by a large-scale 20 K helium refrigeration system, referred to as the Target Moderator Cryoplant (TMCP), with a cooling capacity of 30.3 kW at 15 K. Two compressors are operated at a discharge pressure from 1.0 MPa to 2.0 MPa (HP) and a compression ratio (CR) of 4.1 toward the low-pressure side (LP). A feed helium flow rate can be varied from 200 to 900 g/s when all the three expansion turbines are operated.

The CMS Process Control System (PCS) as seen on Figure 1 is comprised of three Programmable Logic Controllers (PLCs) that manage a variety of equipment [2]. Meanwhile, the TMCP PCS also includes three PLCs: one for process logic and one for each of the compressor skids. A direct data exchange between the two systems creates an interface that enables the integration and synchronization of their core functionalities. A goal of the CMS Process Control System (PCS) is to establish automated operational controls for processes such as cooldown, warm-up, steady-state, beam injection modes and safe shut-down when failure event happens. To achieve this various device types were developed to provide various functionalities, all accessible from the OPI block icons and faceplates, as well as the PLC logic. Most important ones are hydrogen pumps, vacuum pumps, valves, electric heaters etc. In this study we present the reusable

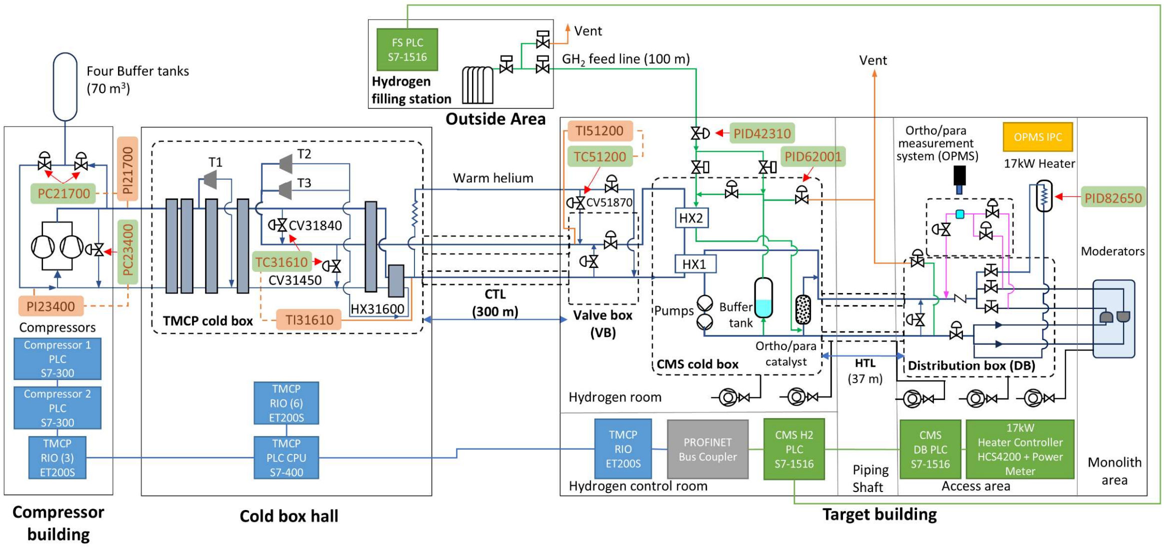

Figure 1. Overview of the CMS and TMCP control system

PID controller device type with setpoint ramping and holding functionality, various feedback devices, tuning profile selection, and a customizable auto-profile selector for fast controller tuning and a custom device type that was developed within the CMS PCS to manage the TMCP operation. This device offers several features, accessible via the Operator Interface (OPI), and PLC logic, which allow for control of the feed helium temperature using a split-range controller, a return helium temperature controller, and controlling the cooling capacity through a floating pressure process where the HP and CR controllers are directly manipulated by the CMS, alongside other functionalities.

2. TMCP Control

2.1 TMCP PCS and CMS PCS data exchange

A key objective during the development of the CMS PCS was to integrate the TMCP PCS in a way that enables both systems to function as seamlessly as possible, effectively operating as a unified unit. Given that the TMCP PCS is a commercially delivered system, including its own control system, achieving this integration required identifying essential functionalities through various commissioning activities that needed to be managed by the CMS PCS. These core functions were subsequently incorporated into the existing Controller–Agent architecture of the CMS PCS. To facilitate

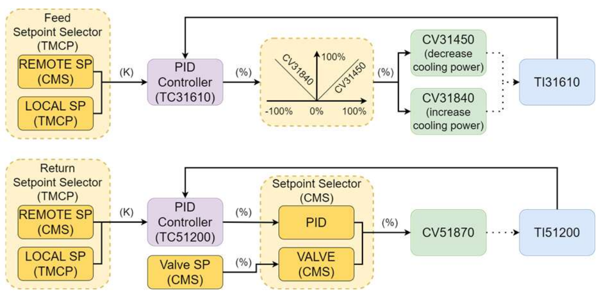

Figure 2. TMCP feed and return temperature control

this integration, a cyclic data exchange mechanism was established between the two control systems using a PROFINET–PROFINET bus coupler. This coupler connects to the internally isolated fieldbus networks of each control system, enabling the exchange of commands, setpoints, and status signals between the CMS PCS and TMCP PCS.

The most critical control blocks requiring integration into the CMS PCS were the TC31610 TMCP feed and TC51200 return temperature, as well as the PC21700 high- and PC23400 low-pressure lines. For this purpose, four controllers were implemented in the TMCP PCS, so the objective was to reuse those existing controllers and extending them with additional functionalities in the CMS PCS.

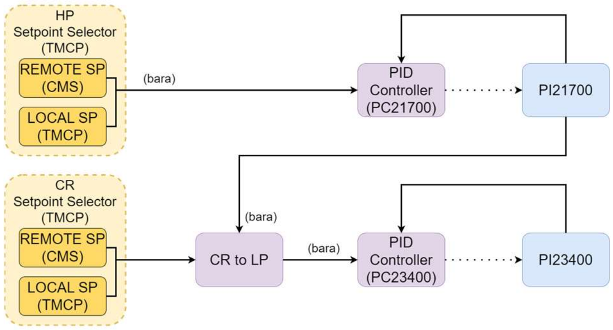

Figure 3. High Pressure (HP) and Compression Ratio (CR) control

In addition to these key controllers, the data exchange between the systems includes a wide range of instrumentation and actuator status signals. The CMS PCS can also send command signals to START or STOP the turbines. This comprehensive integration allows the CMS PCS to issue commands to the Cryoplant based on current operational demands, while simultaneously considering the real-time status of the TMCP cold box (CBX).

2.2 TMCP Control Unit in the CMS PCS

Within the CMS PCS, a dedicated control unit was developed to integrate all necessary functionalities for operating the TMCP, whether manually through the OPI or automatically as part of the CMS PCS cool-down or warm-up sequences. Given that the TMCP is designed to function in a steady-state mode with minimal disturbances, maintaining precise and stable control of the feed and return temperatures to the TMCP cold box (CBX) is critical.

In the TMCP PCS, feed temperature (TI31610) control is managed by the split-range PID controller TC31610, which operates over a range of -100% to 100%. Depending on cooling demand, it modulates CV31450 when less cooling is needed and CV31840 when more cooling is required. While this controller includes basic setpoint ramping, it lacks several critical features identified during commissioning as necessary for achieving a stable and well-controlled cool-down or warm-up process. To improve synchronization with the CMS, the initial PID controller was enhanced to accept setpoints from the CMS PCS, as shown in Figure 2. This implementation allows for the CMS to manipulate the setpoint if the TC31610 is configured to be in remote operating mode, either by jumping or ramping it to a target temperature setpoint. To cool down the CMS the ramping parameters must be changed between different target temperatures [3]. To facilitate this the target temperature in Kelvin, and the ramping time and ramping temperature combo allows to set the ramping speed in K/min. These values can be changed from the OPI and by the PLC implemented code.

Once ramping is started, it is crucial to monitor various system parameters to ensure stable and predictable operation. One key metric is the setpoint discrepancy that is the deviation between the setpoint and the measured value. If this difference exceeds a predefined threshold, the ramping process is paused, and the current value is held until the deviation falls below the threshold for a specified duration. During the commissioning activities a deviation of 2K with a pause duration of one minute provided the best results in most operating cases with helium but it is expected to be changed during hydrogen operation.

In the beginning of the cool-down it is important to monitor the temperature difference across HX31600 heat exchanger that cools the HP flow by the coldest LP flow downside the turbines since there is a possibility for the temperature difference across them exceeding the maximum allowed temperature difference of 40K. During the commissioning activities it was confirmed that the 35K as the pause threshold and 1 minute pause time provided enough safety margin to never reach the maximum allowed temperature difference.

Various tests were performed also to determine the limits within which the TC31610 can successfully control the process. One of these metrics is the CV31450 position, since when the valve position is too small the cooling power can't be controlled anymore. For this scenario, a holding function was implemented and fine-tuned that pauses the ramping if the valve position is lower than 20% until the controller starts to recover where the valve position is increased by 5% to 25%.

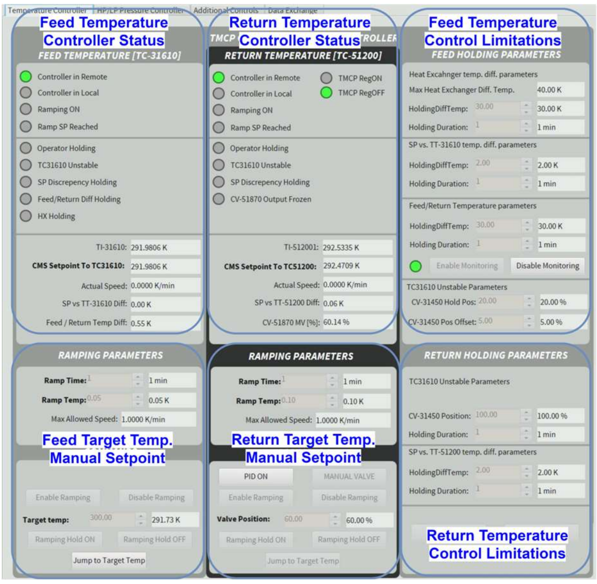

Figure 4. TMCP feed and return temperature control

Synchronizing the feed to the return temperature is vital to ensure a stable operation of the TMCP CBX. For this the temperature difference between the feed and return temperature needs to be monitored and if that exceed a certain threshold the feed ramping must be paused until the return temperature recovers. This threshold value was determined to be 30K. Early during the cooldown due to the long transfer lines (CTL) to the valve box located in the Hydrogen Room as seen on Figure 1 this temperature difference can be higher, so this holding functionality can be disabled. This can be achieved by the pushbuttons on the OPI or the by the implemented PLC logic.

The return temperature (TI51200) in the TMCP PCS is controlled by the TC51200 PID controller with an output between 0-100% actuating CV51870 that mixes warm gas to the return HP flow thus it can only increase the helium temperature and never lower it, due to this the operating point must be selected carefully. This controller similarly to the TC31610 has a basic setpoint ramping functionality implemented, but that deemed to be insufficient to ensure a stable control of the return temperature so it was extended so the CMS PCS can set the controller setpoint, furthermore it can disable and enable the controller allowing to apply a direct valve position as seen Figure 3. Parameters such as target temperature, ramping rate, and ramping time are similarly configurable via the OPI or PLC. During ramping it is important to monitor for setpoint discrepancy that was adjusted to be 2K with 1minute holding. Ensuring stable operation of TC51200 also requires verifying that TC31610 remains within its control region. For instance, if CV31450 is too much open and cannot further reduce cooling, instability in the return temperature may occur. This is particularly likely during initial cool-down, where TC51200 effectively acts as a brake to the cooldown speed. This controller is tuned for smooth and predictable conditions; however, under certain scenarios, such as starting up the TMCP T2 or T3 turbines when the system is cold instability may arise due to warm gas being trapped in the piping. This can cause the TC51200 to lose control and the valve to enter undamped oscillatory movements. To mitigate this behaviour, a pre-purging sequence was implemented in the turbine startup sequences that will be executed prior to turbine startup if necessary. Additionally, the CMS PCS has the capability to enable or disable the TC51200 regulation, allowing for direct valve control. And by temporarily freezing the valve position the undamped oscillations can be suppressed. The OPI for the feed and return controller can be seen on Figure 4.

Another important functionality of the control unit is the implemented HP and CR controller. The TMCP has a PID controller implemented that controls the pressure (PI21700) of the HP line called PC21700 and another one that controls the pressure of the low pressure (LP) (PI23400) line called PC23400. Both are important to change the cooling power of the cryoplant [3]. It is important to note that the compression ratio (CR) is used instead of directly adjusting the expansion ratio of the turbines, as both approaches achieve the same operational effect. However, the implemented turbine controller in the TMCP PCS does not support modification of the expansion ratio, and its code cannot be altered. Therefore, controlling the CR provides a practical and effective workaround within the existing system constraints. Also due to practicality towards the turbine operation instead of applying the pressure as a setpoint to the PC21700 it is changed to the compression ratio leading to the setpoint to be calculated as:

$$LP_{Setpoint} = \frac{HP}{CR_{Setpoint}} \tag{1}$$

This approach not only provides a more intuitive setpoint handling for the operator but also ensures that changes of pressure on the HP line will be automatically mitigated ensuring stable running conditions for the turbines where the optimal CR is 4.1.

The controller allows for ramping of the HP in both directions while keeping the CR constant but also ramping the HP together with the CR. For example, early in the cool-down to reduce the cooling power the CR is temporarily changed from the optimal value to 3.6, later when this needs to be changed back it can be achieved by applying a final HP and CR setpoint and a ramping speed for the HP, so the controller will keep the LP at a constant while increasing the HP thus increasing the CR, when the CR reaches the final setpoint only the HP is ramped towards its final setpoint keeping the CR constant. If both controllers are ramping and setpoint discrepancy is detected on either of them the ramping will be paused on both, while if only the HP is ramping only the HP ramping is paused until the setpoint discrepancy recovers plus an additional period that can be parameterized from the OPI.

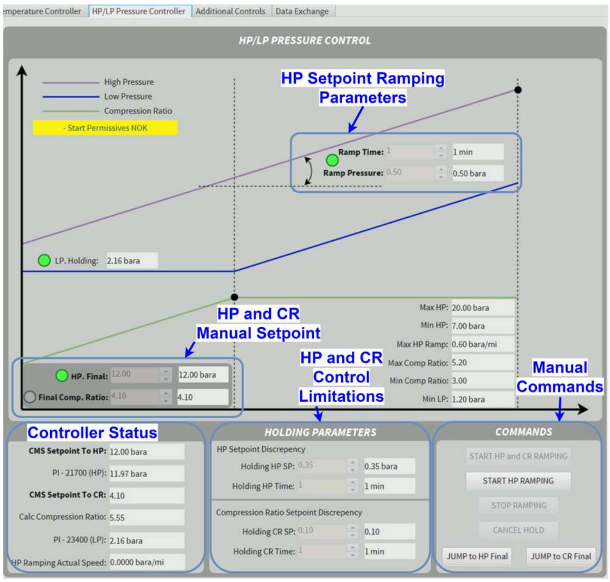

Figure 5. HP and CR Control

It is important to note that for all controllers described in this section, operators can manually pause and resume ramping or cancel pausing directly from the OPI. When a ramping resumption is requested, the system first verifies the current operational conditions. If the condition that initially triggered the ramping pause is no longer present and the system is simply waiting for the time delay to expire, ramping will resume as requested. However, if the triggering condition persists, the request is ignored to ensure safe and stable system behaviour. The OPI for the HP and CR controller can be seen on Figure 5.

Additional functionalities of this control unit include the ability to start and stop the turbines, as well as to select the currently active gas buffer. It is important to emphasize that any turbine start or stop request initiated by the CMS PCS is subject to validation by the TMCP PCS, which checks against its internally implemented start and stop permissive conditions to ensure safe operation.

3. CMS PID Controller

A custom, reusable PID controller has been implemented in the CMS PCS, enabling control of various system actuators. The underlying PID algorithm offers position-based control for any connected actuator (e.g., valve, pump, heater) and includes additional basic functionalities

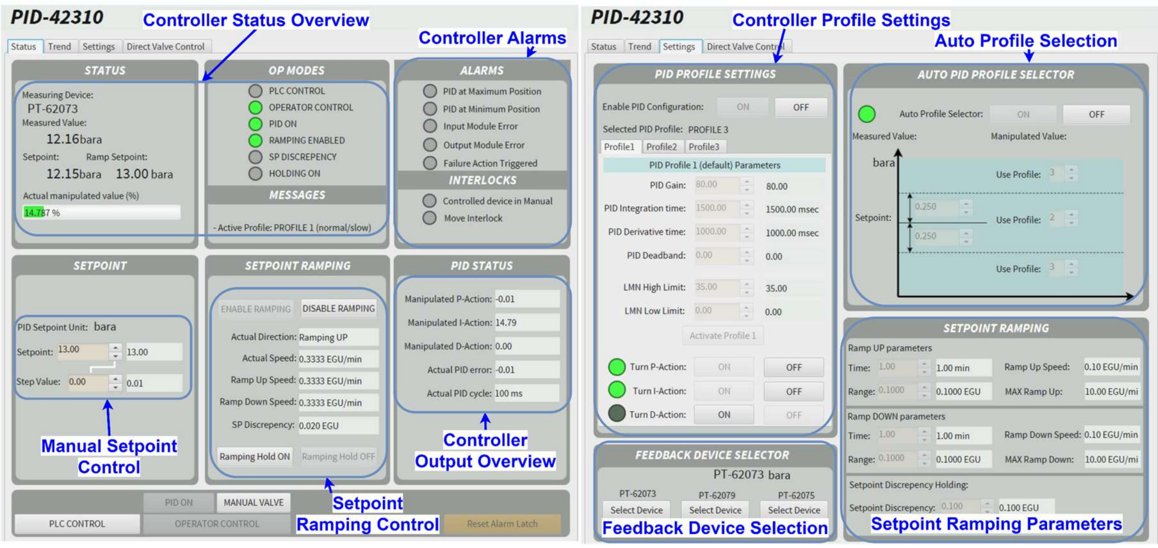

Figure 6. PID OPI faceplates with status and setting tab for PID42310

accessible both from the OPI and the implemented PLC code.

Since the CMS will liquify hydrogen, it is anticipated that a single set of tuning parameters will not ensure stable and predictable control across all scenarios. One such scenario is the system's pressure control: PID42310 increases system pressure by injecting warm hydrogen from the filling station, while PID62001 decreases it by venting gas through the release line as seen on Figure 1. Due to changes in hydrogen's density gradient during cool-down (affecting PID42310) and warm-up (affecting PID62001), each controller is expected to require different tuning parameters depending on the operating conditions. To address this, the controllers were designed to support the configuration of three distinct PID profiles. These profiles enable tuning for different operating conditions where the system behaves linearly. Each profile allows adjustment of PID Gain, Integration Time, Derivative Time, Deadband, and the actuator's maximum and

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minimum positions. Additionally, the proportional, integral, and derivative components can be enabled or disabled independently and run in parallel, allowing the controller to operate in P, I, PI, PD, or full PID mode. An added feature enables automatic switching between profiles based on the error between the setpoint and the process value, as shown in Figure 6. For example, in the case of PID62001, this allows the use of a slower tuning profile when the error remains within ±0.06 bara and a faster tuning profile when the error exceeds this threshold. This dynamic adjustment helps prevent pressure overshoots thus avoiding excessive pressure and undershoots thus minimizing hydrogen inventory losses from the process loop.

In certain scenarios, switching the feedback device used in the control loop can enhance operational flexibility for specific controllers within the system. A relevant example is PID82650, where in certain scenarios the temperature needs to be controlled right after the 17kW heater or the temperature of the total hydrogen flow. To accommodate this, each PID controller includes a feedback device selector feature, allowing the feedback signal to be switched between predefined devices either manually via the OPI or automatically through PLC logic.

To maintain smooth and predictable operation during transitions, setpoint ramping functionality has been implemented, along with discrepancy-based holding mechanisms that temporarily pauses the ramping when setpoint discrepancy is detected. This functionality with the feedback device selection proved to be useful during the cool-down of the OPMS sampling lines when the whole system was already cooled down while the sampling lines were not yet.

The PID algorithm can be turned ON or OFF as needed. To ensure smooth, bumpless transitions between modes, specific measures are taken depending on the direction of the switch. When transitioning from control ON to OFF, it is assumed that the system is stable at the most recent actuator output. Therefore, the actuator is held at its last manipulated value until a new setpoint is issued either by the operator or the automatic PLC logic. Additionally, although the PID algorithm is inactive, the internal integral action is updated to match the actuator’s current output, preparing the controller for a seamless reactivation. When the PID algorithm is turned back ON, to avoid any sudden jumps in the output due to a setpoint change, the setpoint is aligned with the most recent process value, ensuring a stable and controlled resumption of operation.

4. Results

The functionalities of the TMCP control unit, as described above, along with all device types integrated into the CMS control system, were thoroughly tested and fine-tuned throughout various commissioning activities with Helium.

Figure 7 presents the results from one of these helium-based cool-down operations, showing the process values and setpoints for the TMCP feed and return temperatures, the CMS loop temperature, and the HP and CR. The cool-down process was divided into multiple segments, each with distinct ramping speeds and target temperatures [3].

Using the developed TMCP control unit and the optimized parameters outlined in this paper, the CMS loop was successfully cooled down and warmed up with helium on multiple occasions through sequential setpoint changes issued by the operator.

This commissioning result confirmed that all essential control system functionalities for hydrogen operation, including the automated cool-down and warm-up process, were functioning as intended.

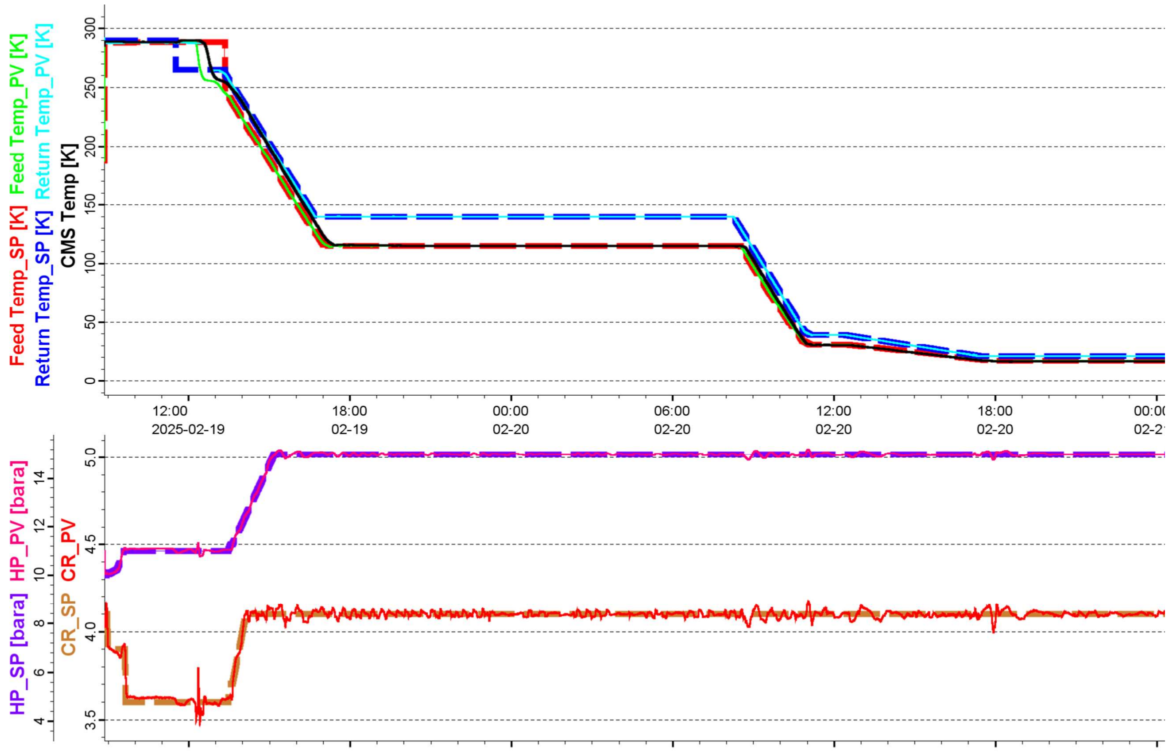

Figure 7. CMS and TMCP cool-down

5. Conclusions

We developed, tested, and optimized a control unit within the CMS PCS that can monitor and issue command to the TMCP PCS, allowing cooldown and warmup process to be executed through high-level sequential commands in the form of setpoints. During these operations key control blocks, such as the TMCP feed and return temperature control, HP and CR control, CMS pressure and temperature PID controllers were tested and fine tested. These functions besides other of the CMS PCS together with the TMCP PCS were demonstrated to work effectively during the preliminary CMS commissioning using helium at 17 K, prior to hydrogen operation.

References

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