Updated design of the ESS cryogenic moderator system

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Abstract. The European Spallation Source (ESS) has installed two hydrogen moderators, optimized to maximize neutron brightness while maintaining a parahydrogen fraction above 99.5%. The cryogenic moderator system (CMS) was developed to satisfy two key requirements: (1) a temperature rise of less than 3 K across each moderator and (2) a parahydrogen fraction above 99.5%. The dynamic heat load from nuclear heating in the moderators, together with the static heat load, is removed by a 20 K helium refrigeration system with a cooling capacity of 30.3 kW at 15 K. In 2020, the CMS cold box was fabricated and subsequently underwent acceptance cryogenic tests with gaseous and liquid nitrogen through September 2021. Additional components were designed and manufactured, including hydrogen transfer lines from the cold box to the moderators, an in-situ ortho-to-parahydrogen measurement system, a fast-response heater for thermal compensation, and a hydrogen filling station. Installation of all components was completed in May 2024. Commissioning of the CMS is ongoing and will continue until proton beam delivery to the target in early 2026.

1. Introduction

European Spallation Source (ESS) will provide long-pulsed cold and thermal neutron fluxes at very high brightness [1]. A 5 MW beam of 2.0 GeV protons with a nominal current of 62.5 mA, driven by a linear accelerator, will strike a rotating tungsten target at a repetition rate of 14 Hz with a pulse duration of 2.86 ms [1]. Fast neutrons produced by spallation process are moderated to cold and thermal neutrons by passing through a water pre-moderator and liquid hydrogen moderators [2]. Initially, the ESS will operate with two hydrogen moderators located above the target, with plans to upgrade to four moderators positioned both above and below the target. The hydrogen moderator vessels have a flat, butterfly-shaped design, fabricated from high-strength aluminum alloy (AL6061-T6), and have been optimized to maximize neutron brightness while maintaining a parahydrogen fraction above 99.5% [2]. The nuclear heating in the two-moderator configuration is estimated to be 7 kW at 5 MW beam power, increasing to 17 kW for the four-moderator configuration [3].

The cryogenic moderator system (CMS) was designed to meet two critical requirements: (1) a temperature rise of less than 3 K across each moderator, and (2) a parahydrogen fraction above

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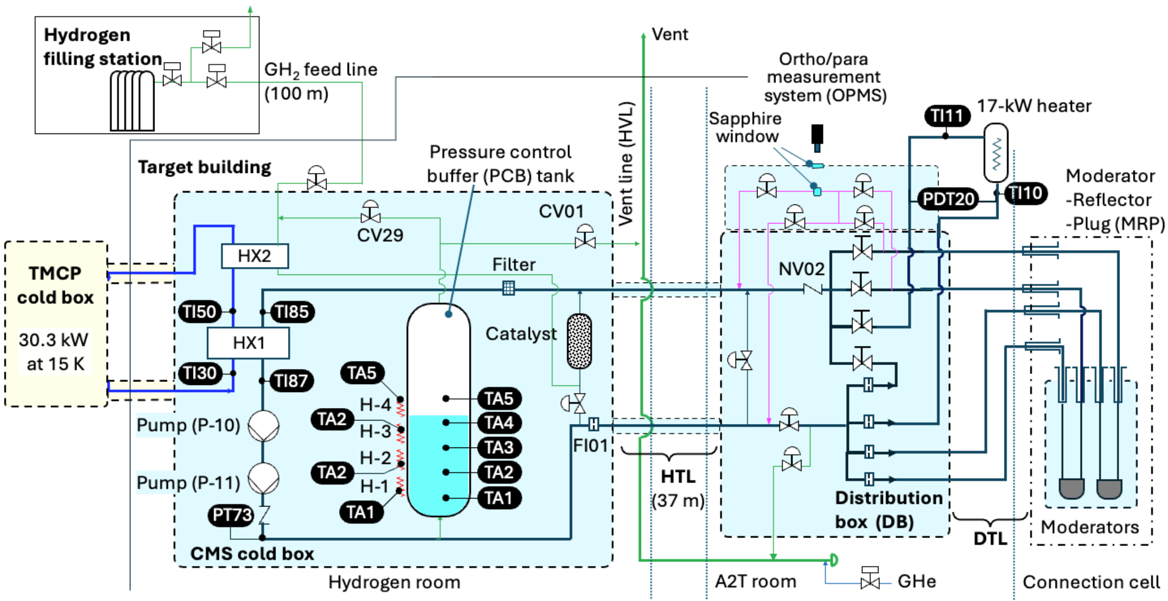

Figure 1. Overview of the updated cryogenic moderator system (CMS).

99.5% [4]. Subcooled liquid hydrogen at 17 K and 1.0 MPa is circulated at flow rates of 1.0 kg/s using two centrifugal pumps arranged in series, as shown in Fig.1. Each moderator is supplied through a dedicated distribution line arranged in parallel, ensuring that the moderator inlet temperature is maintained at 17.5 K. To achieve the required parahydrogen fraction, an ortho-to-parahydrogen catalyst is integrated into a bypass line. A buffer tank is included in the loop to stabilize pressure and mitigate pressure fluctuations caused by stepwise changes in heat load during proton beam injection or trip. The dynamic and static heat loads are removed through a heat exchanger (HX1) connected to the Target Moderator CryoPlant (TMCP), a 20 K large-scale helium refrigerator with a cooling capacity of 30.3 kW at 15 K [5].

In 2020, the fabrication of the CMS cold box was completed by the ESS in-kind partner, Forschungszentrum Jülich GmbH (FZJ). The cold box underwent acceptance cryogenic tests with gaseous and liquid nitrogen in September 2021 [6] and was subsequently installed at the ESS site in November 2021. The TMCP installation was completed in the summer of 2022, followed by standalone TMCP commissioning (without connecting the CMS), which concluded in December 2022 [7-9]. During this period, operational strategies for the TMCP were studied in various modes, such as a cooldown, warmup, and beam injection, to support the development of an automatic TMCP-CMS control system.

Meanwhile, additional CMS components were designed and manufactured, including hydrogen transfer lines from the cold box to the moderators, a valve box, an in-situ ortho-to-parahydrogen measurement system (OPMS) using Raman spectroscopy, a fast-response heater for nuclear heating compensation, and a hydrogen filling station. Furthermore, the heaters mounted on the buffer tank were redesigned after acceptance testing revealed that the original design did not meet the required specifications. Installation of all components was completed in May 2024. CMS commissioning is ongoing and will continue until the first proton beams are delivered to the target in early 2026. This paper presents the current design status of the ESS CMS.

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012043
doi:10.1088/1757-899X/1344/1/012043

2. Updated design of the cryogenic moderator system

Liquid hydrogen is delivered to the distribution box (DB) through a 37.6 m-long transfer line (HTL) with vacuum insulation [10]. In the DB, the flow is split into four distribution transfer lines (DTLs), which supply hydrogen to each moderator to maintain an inlet temperature of 17.5 K. The distribution lines for the future moderators are bypassed within the DB. A fast-response heater, designed to compensate for the nuclear heating generated in the moderators, has been installed in one of these bypass distribution lines [11]. Removable U-shaped bayonets connect the DTLs to the moderator pipes at the top of the moderator-reflector plug (MRP), enabling annual replacement as required. The feed flow rate to each moderator is adjusted by manual hand valves located in the return distribution lines. The return flows are combined and sent back to the CMS cold box through a return HTL. A dedicated sampling line with a sapphire window was integrated into the DB to allow in-situ measurement of the ortho-to-parahydrogen fraction, using Raman spectroscopy, for both the return hydrogen from each moderator and the feed hydrogen. From a safety perspective, all hydrogen is vented to the atmosphere through the hydrogen vent line during warm-up operations. Consequently, during cooldown, hydrogen must be resupplied to the CMS from 20 MPa hydrogen bundles at the filling station via a 100 m feed line.

2.1 Liquid hydrogen pump

Two ball-bearing centrifugal pumps were installed to circulate liquid hydrogen at a flow rate of 1 kg/s, requiring a pump head of 160 kPa under nominal conditions. The pumps are arranged in series to meet the high head requirement. Pump speeds are adjustable from 1,000 to 14,000 rpm. The pump motors are cooled by circulating a glycol-water mixture at a flow rate of 5.7 L/min. Preliminary CMS commissioning, conducted with helium at 17 K prior to hydrogen operation, revealed that to maintain the flange temperature above 10°C, the discharge coefficients must be kept within the range of 0.027 to 0.034, which corresponds closely to the maximum efficiency point [12]. However, deviations from this range resulted in flange temperatures dropping to as low as 4°C, with circumferential variations in temperature distribution across the flange. During liquid hydrogen operation, the flange temperature is expected to decrease further, particularly at the O-ring seal location, which could lead to hydrogen leakage through a stiffened O-ring. To mitigate this risk, a water-radiator jacket was designed and integrated onto the pump flange, as shown in Fig. 2 [12]. This modification is expected to stabilize the flange temperature and ensure reliable sealing performance.

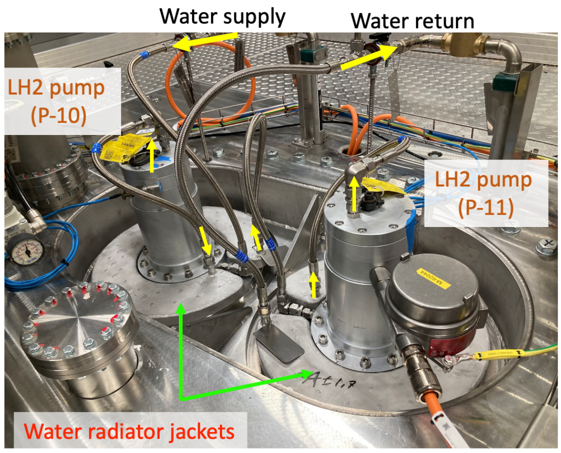

Figure 2. Water-radiator jacket to stabilize the flange temperature

2.2 Pressure control buffer (PCB) tank

The pressure control buffer (PCB) tank has an outer diameter of 300 mm and a volume of 71 liters. The liquid level is monitored using a differential pressure transmitter and six silicon diode temperature sensors located at 2.3, 7.8, 14.9, 20.4, 25.9, and 30.7 liters. Under nominal conditions, the liquid level is maintained between 20 and 25 liters. Four heaters are wrapped around the side of the PCB tank, positioned between the temperature sensors, to regulate

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pressure by adjusting the evaporation of liquid hydrogen. Excess pressure is mitigated by recondensing the gas phase in the tank via the second heat exchanger (HX2) through a control valve (CV29). At the beginning of the project, thin coated heater wires were wound around the side of the PCB tank and impregnated with epoxy resin (Stycast). During the first cryogenic test for the CMS cold box using liquid nitrogen at the FZJ in 2020, the epoxy cracked due to rapid cooling of the PCB tank, resulting in damage to the impregnated wires after the heater was turned off. To address this issue, four robust band heaters, each rated at 550 W (corresponding to a heat flux of 1.0×10^4 W/m^2), were selected and wrapped around the PCB tank to regulate the vapor and liquid hydrogen temperatures. To improve uneven and insufficient thermal contact, particularly in the vacuum environment, copper wool was introduced. A preliminary test was conducted to evaluate the effectiveness of copper wool in improving thermal contact, as shown in Fig. 3. A test band heater with an inner diameter of 101 mm, a width of 25.4 mm, and a capacity of 700 W was wrapped around a liquid nitrogen vessel with an outer diameter of 101 mm and a height of 250 mm. Copper wool or a thin copper plate (0.25 mm thick) was placed between the band heater and the vessel. The assembly was housed in a vacuum chamber and filled with saturated liquid nitrogen. Figure 4 presents the experimental results showing the temperature rise of the band heater, measured using a K-type thermocouple attached to its surface, as heater power increased. When the copper wool was wrapped four times, the temperature rise exhibited a nearly proportional relationship with the heat load, with slight deviation from the linearity above 92 W (1.1×10^4 W/m^2), attributed to the formation of a gap caused by thermal expansion of the band heater. In contrast, deviations occurred at much lower heat loads for copper wool wrapped twice (28 W, 3.5×10^3 W/m^2) and for the copper plate (8 W, 0.99×10^3 W/m^2). These results demonstrated that wrapping copper wool four times effectively improve thermal contact between the heater and the vessel within the operational heat flux limit of 1.0×10^4 W/m^2 for the PCB band heater. Based on these experimental results,

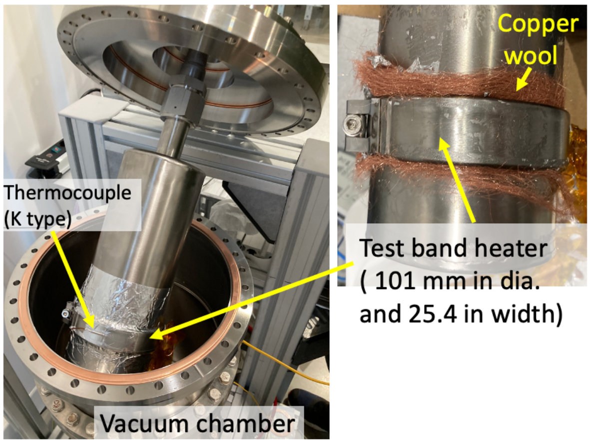


Figure 3. Test band heater for the PCB tank.

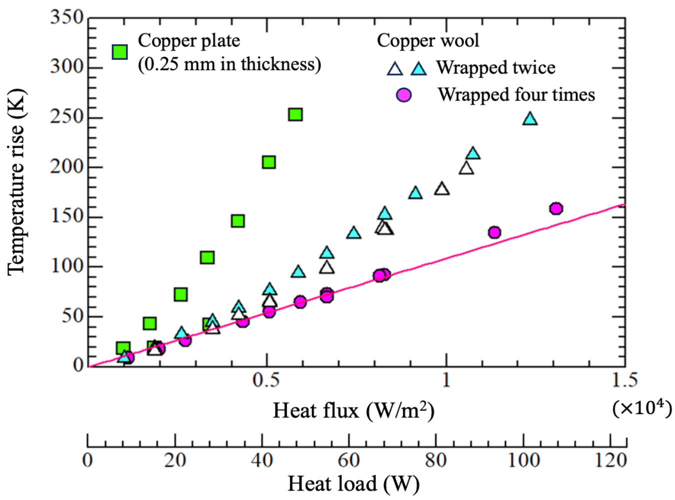


Figure 4. Test band heater for the PCB tank.

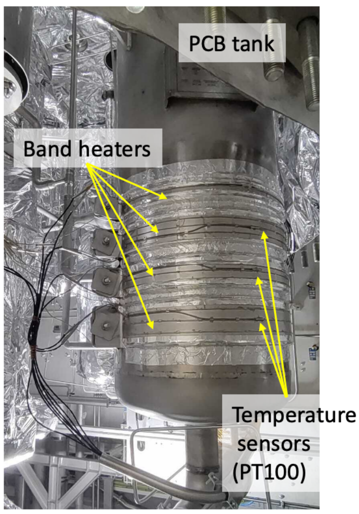


Figure 5. Band heater installation

copper wool was applied four times around the PCB tank prior to installation of the band heater, as illustrated in Fig. 5.

2.3 Hydrogen transfer line (HTL)

The hydrogen transfer lines (HTLs) each 37.6 m in length, connect the CMS cold box to the Distribution box (DB). The process line has an outer diameter of 60.3 mm and a thickness of 2.0 mm, is wrapped with 40 layers of multilayer insulation (MLI). The vacuum envelope of the HTL has an outer diameter of 139.7 mm and a thickness of 2.0 mm. The vacuum envelopes of the supply and return HTLs are connected at each end, forming a single continuous vacuum space with a volume of 0.823 m^3. This vacuum space is physically isolated from those of the CMS cold box and the DB. To ensure effective evacuation of the long transfer line, two vacuum pump units are installed at each end of the HTL. After installation, the vacuum envelope was continuously purged with dry nitrogen through the units. This process effectively removed moisture from the MLI and reduced helium background level for the helium leak test. Two vacuum safety relief devices are installed upstream of each vacuum unit. The size of each device was determined to be 100 mm, based on the analysis results of a potential liquid hydrogen leak from the process line into the vacuum envelope [10]. In such an event, the leaked hydrogen would be discharge to the atmosphere through the safety device via a dedicated hydrogen vent line.

2.4 Fast-response 17 kW heater

When 5 MW proton beams are injected, a stepwise heat load is applied to the hydrogen moderators, causing a sudden temperature rise of about 1.76 K. This temperature fluctuation propagates downstream with the circulation flow. To prevent this thermal disturbance from reaching the TMCP through the heat exchanger (HX1) and to maintain the hydrogen supply temperature (TI87) at 17.0 K within $\pm$0.1 K, it is necessary to compensate for the transient heat load within the CMS. A high-power heater with fast-response capability was therefore designed to enhance the stability of the CMS and TMCP operations, based on the J-PARC orifice heater developed by Tatsumoto et al. [13]. The total capacity was set to 17 kW, corresponding to the nuclear heating in the moderators under 5-MW proton beam operation. The 17-kW orifice-type heater [11] was installed in one of the distribution lines for the planned future moderators. located next to the Distribution box (DB), as shown in Fig. 6. Sheathed heater elements, directly immersed in liquid hydrogen, were selected to ensure rapid response. The elements are arranged

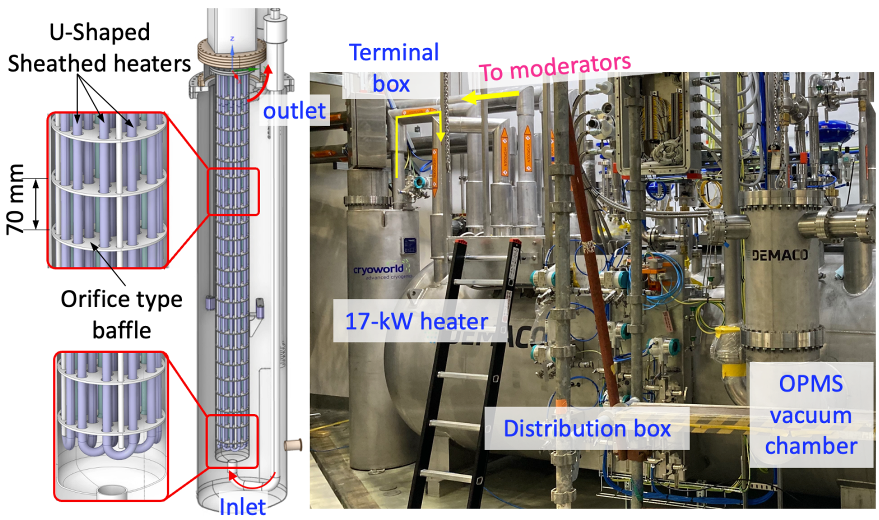


Figure 6. Developed 17-kW orifice-type heater.

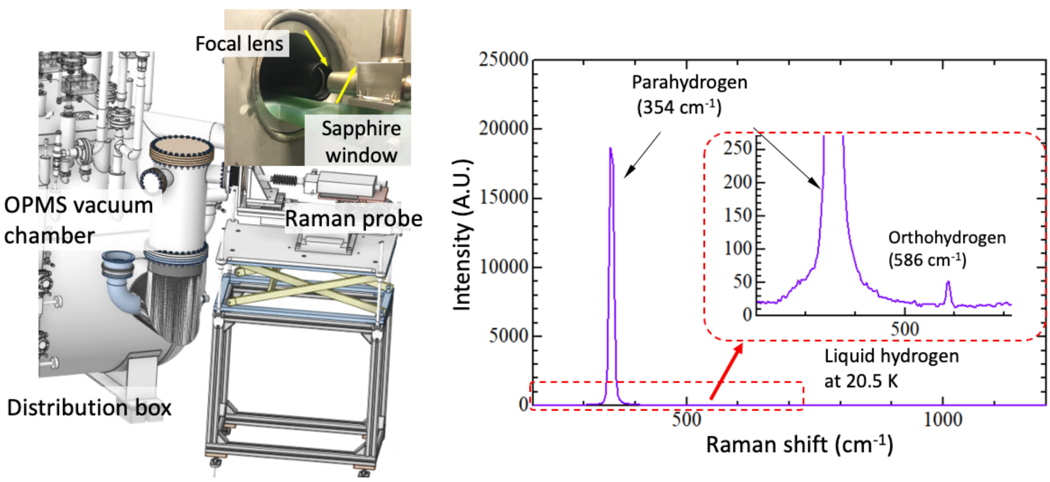
parallel to the liquid hydrogen flow direction. Enhanced heat transfer performance is expected due to the stirring effect, as the liquid hydrogen passes through a baffle plate with a hole slightly larger than the heater element diameter. The heater power is regulated by a PID controller to maintain the return hydrogen temperature at 20.0 K. When the proton beam is turned on, the heater power corresponding the nuclear heating is rapidly reduced, ensuring that the heat load transferred to TMCP through HX1 remains constant.

2.5 In-situ ortho-to-parahydrogen fraction measurement system (OPMS)

Raman spectroscopy was adopted to measure the ortho-to-parahydrogen fraction in-situ, with an accuracy requirement of 0.1%. A dedicated sampling line with a sapphire window, through which the laser beam and backscattered photons pass, was designed to continuously measure these fractions in liquid hydrogen flowing to and from the moderators [14], as shown in Fig. 1. The OPMS vacuum chamber, with a volume of 0.0895 m³, is physically isolated from the distribution box (DB). A 12-mm outer diameter pipe with a thickness of 1.0 mm is used to minimize hydrogen inventory. In the event of a sapphire window failure, detected by a pressure rise in the OPMS vacuum chamber, the CMS failure protection function is triggered. The sampling line is automatically and completely isolated from the main CMS process line by closing the supply and return control valves. The remaining liquid hydrogen in the sampling line is discharged through a release control valve, while leaked hydrogen in the vacuum space is directed to the HVL via a vacuum safety device.

A highly reliable sapphire window, with a diameter of 15 mm and a design pressure of 1.7 MPa, was developed for liquid hydrogen operation at approximately 17.5 K and 1.0 MPa, as shown in Fig. 7 (a). The 2.0 mm-thickness sapphire window was brazed to a Kovar pipe (Fe-Ni-Co alloy), leveraging the close match in thermal expansion coefficients. The absence of leaks was confirmed by helium leak tests after subjecting the sapphire window to 3,000 pressure cycles and 100 thermal cycles in liquid hydrogen [15].

The Raman optics system consists of a 532 nm single-mode laser with an output power of 100 mW, a Raman spectrometer with a resolution of 3.5 cm⁻¹, and a Raman optical probe [16]. The laser beam is delivered into the vacuum space through another sapphire window and then focused through a 25.4 mm diameter focal lens into the hydrogen environment. A performance test of the developed Raman system and sapphire window was conducted using subcooled liquid



(a)Overview of the OPMS. (b) Raman spectrum of liquid hydrogen.

Figure 7. In-situ ortho-to-parahydrogen fraction measurement. System (OPMS)

hydrogen at 20.5 K and a flow rate of 26.5 g/s at a dedicated test facility, prior to on-site installation. The test results demonstrated the system could measure the parahydrogen fraction within an error range of -0.006% to +0.004%, while effectively suppressing background noise, as shown in Fig. 7 (b) [16].

2.6 Hydrogen filling station

Based on the latest updated CMS piping layout, the total liquid hydrogen inventory in the CMS is estimated to be 436.3 liters, including 25 liters in the PCB, while the gaseous hydrogen inventory is estimated at 46 liters. Five hydrogen bundles are required for a single cooldown operation. Each hydrogen bundle consists of 12 hydrogen cylinders, each with a volume of 50 liters at 20 MPa, corresponding to 8.7 kg of hydrogen.

During cooldown, gaseous hydrogen (GH_2) is supplied from the bundles in the hydrogen filling station to the hydrogen room through a 100-m long feed line with a design pressure of 2.6 MPa, as shown in Fig. 8. The high-pressure hydrogen from the bundles is reduced to 2.2 MPa by a pressure regulator on the gas management panel (GMP) located at the filling station. Cooldown simulation results indicated that a maximum feed hydrogen flow rate of 2.5 g/s [17], equivalent to 100 Nm^3/h, is required near the critical temperature of 33 K. A cryogenic purifier will be installed to ensure that impurity levels remain below a few ppm. All release pipes are connected to a dedicated vent line. This vent line is purged with dry nitrogen from a nitrogen bundle during gaseous hydrogen release. The same nitrogen bundle is also used to operate three pneumatic valves (V1, V2 and V3) in the filling station.

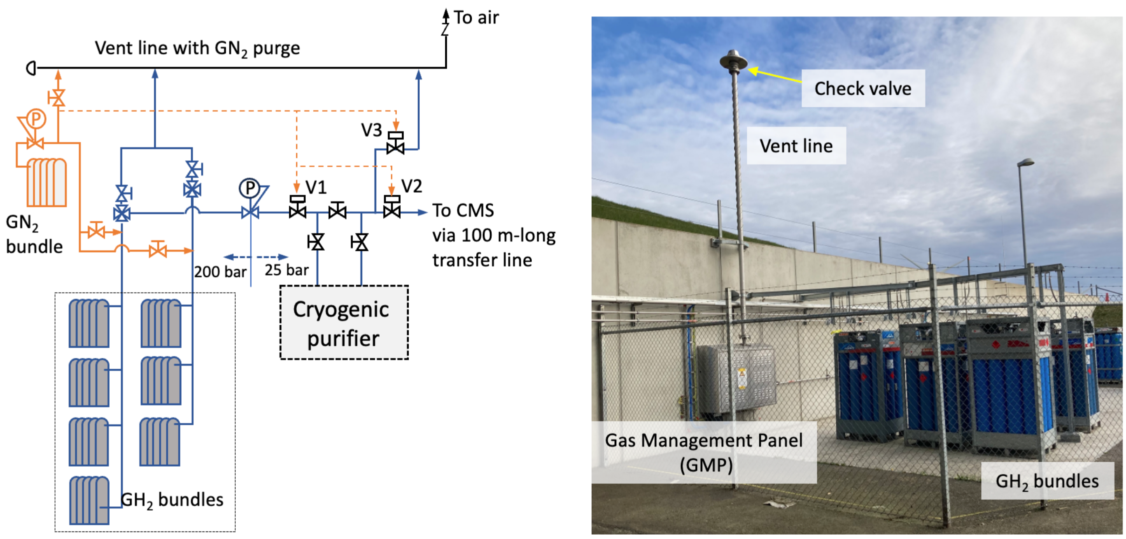


Figure 8. Hydrogen filling station.

3. Conclusions

The design of the ESS cryogenic moderator system (CMS) has been updated to include the hydrogen transfer line, fast-response heater, in-situ ortho-to-parahydrogen fraction measurement system, and hydrogen filling station. Modifications were also implemented to address issues identified during the previous commissioning, specifically related to the PCB heaters and the reduction of hydrogen pump flange temperatures. A cryogenic test of the developed Raman system using liquid hydrogen, conducted at a dedicated test facility, demonstrated that the system met the specified accuracy requirement. Installation of the CMS was completed in May 2024, and commissioning CMS is ongoing in preparation for first beam on target in early 2026.

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