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To cite this article: Y Beßler *et al* 2018 *J. Phys.: Conf. Ser.* **1021** 012080

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The Cryogenic Moderator System Cryostat Design for the European Spallation Source

Y Bessler¹, M Klaus², C Henkes¹, G Natour¹ and J Ringnér³

¹ Forschungszentrum Juelich GmbH, Juelich, Germany

² Institute of Power Engineering, Technische Universitaet Dresden, Germany

³ European Spallation Source ERIC, Lund, Sweden

E-mail: y.bessler@fz-juelich.de

Abstract. The European Spallation Source in Lund, Sweden, is going to be a neutron scattering research center that aims to provide around 30 times brighter neutron beams than any other existing facility. As one subsystem of the Target Station, the Moderator & Reflector System slows down high energy neutrons from the spallation process. To gain maximum neutron flux intensities along with high system availability for condensed and soft matter research, an optimized liquid hydrogen Cryogenic Moderator System (CMS) has been developed. Hydrogen with a pressure below critical, an inlet temperature of around 17 K, and a parahydrogen fraction of at least 0.995 will be utilized to interact with neutrons in a unique Moderator vessel arrangement. Two turbo pumps are arranged in series and circulate the cryogen. The pressure stabilization is achieved by an active pressure control buffer in a bypass stream between high pressure and low pressure side. Hydrogen conversion from ortho- to parahydrogen will be controlled and monitored using a catalyst bed in a second bypass line between the high and the low pressure branch of the circuit. A helium refrigerator, the Target Moderator Cryoplant (TMCP), continuously re-cools the hydrogen mass flow.

1. Introduction to the ESS Cryogenic Moderator System

ESS is going to provide a long-pulsed cold and thermal neutron beam with highest brightness for a broad range of experiments. The main task of the Cryogenic Moderator System CMS is to supply the moderating media hydrogen to the cold Moderator vessels (cM) with a circuits average temperature of about 18.5 K (cM inlet controlled to 17.4 K) and an average pressure of 10 bar.abs (min. value at cM outlet). The cM's facilitate neutrons passing through the hydrogen, where they interact, get slowed down and leave the cM at useful energies. Two different moderator types with different geometry (30 and 60 mm LH₂ height, Butterfly 2 design), neutronic features and cooling demands are used at ESS. Subcooled liquid hydrogen, specifically parahydrogen (antiparallel proton spin), needs to be supplied continuously to the four cM's within tight operating boundaries and a high system availability.

The general CMS mission is to reduce the speed of higher energy neutrons set free during the spallation process by supplying a moderation media and producing cold (slow) neutrons, complying with the following key requirements [1, 2]:

- Cryogenic hydrogen at average 18.5 K and elevated pressure of 10 bar.abs (subcritical, subcooled LH₂) with a parahydrogen content of > 99.5 % shall be fed to the cM's,
- The hydrogen shall be kept within operational boundaries at all times to ensure availability,
- The hydrogen shall be provided in a safe and reliable way,



- The average temperature increase over the cM's due to a 5 MW proton beam and spallation neutrons shall be kept ≤ 3 K.

The overall target cryogenics at ESS [3 to 6] can be separated into the Target Moderator Cryoplant TMCP (helium refrigeration plant with about 30.2 kW cooling power at 15 K) which interfaces to the Cryogenic Moderator System (closed liquid hydrogen loop) via two heat exchangers inside the CMS cryostat. Figure 1 shows the overall system setup of the CMS and its peripherals.

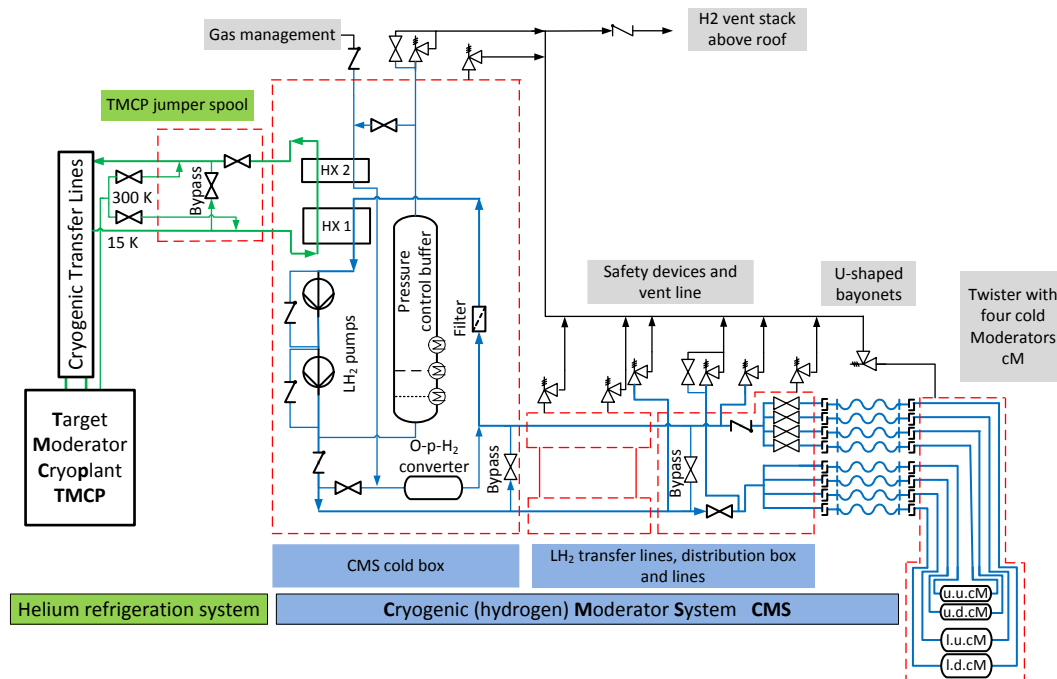


Figure 1: Schematic flow diagram of Cryogenic Moderator System (blue), Target Moderator Cryoplant (green) and vacuum sections (dotted red lines).

The flow diagram shows the two process media: The TMCP and its helium refrigeration cycle in green whereas the closed hydrogen circulation of the CMS is in blue color. The neutron moderation process results in average 17.3 kW as a dynamic heat for a 5 MW proton beam. The absorbed heat caused by neutron interaction with aluminum and hydrogen inside the cM's needs to be extracted by a steady hydrogen circulation. The static heat load as a sum of heat transfer from higher to cryogenic temperatures as well as the power input from the circulation pumps add 5.9 kW to the hydrogen. The total heat load adds up to 23.1 kW.

2. General description of the hydrogen circulation: Cryogenic Moderator System

The task of the CMS is cooling four cold Moderators, take up the neutron heat during the moderation process as well as static heat loads from the CMS loop in a safe and reliable manner. Subcooled liquid hydrogen at average 18.5 K and 10 bar.abs is used as the moderating and cooling media. Thus, the parahydrogen critical pressure of 12.85 bar.abs is not reached and temperatures above the boiling point (ca. 30.2 K at 10 bar.abs) result in vapor formation and phase separation. The design pressure of the system is 17 bar.g constrained by the structural limits of the complicated cM vessel geometry as the CMS most fragile components. The overall heat load gets transferred to the TMCP helium flow in the main H₂-He heat exchanger. Additionally, the system consists of two turbo pumps in series, a pressure control buffer in a bypass and an ortho-parahydrogen converter in a bypass. The CMS cryostat is placed in the upper level of the target building in a separate, ATEX classified room. Transfer lines get routed to the target ground level and close to the Connection Cell. A distribution box, splitting up the single hydrogen supply flow into four streams, sits close the Connection Cell wall. From here four

supply distribution lines get routed into the Connection Cell and further into the Monolith vessel. Inside the Twister four cM, two of 30 mm LH₂ height above and two of 60 mm LH₂ height below the Target wheel, get cooled by liquid hydrogen and moderate neutrons.

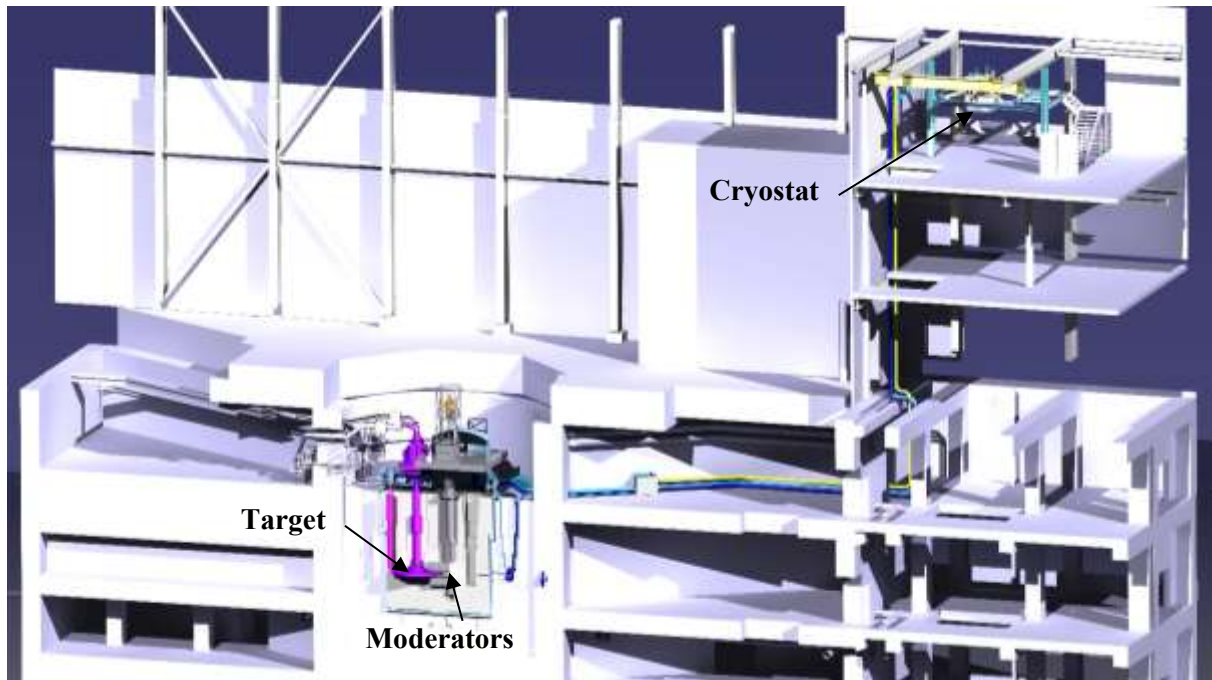


Figure 2: Isometric view of the ESS Target Station

Two identical hydrogen pumps are designed to circulate 1000 g/s hydrogen at 17 K and 9.1 bar.abs inlet conditions to the serial arrangement. A variable frequency drive VFD for each pump allows for speed control. The pump head is 0.94 bar per pump, which adds up to overall 1.87 bar to overcome the circuits pressure drop. Due to required redundancy, the pump design allows to operate the CMS with only one pump by increasing its speed and thereby operating at the same total pump head and mass flow. A bypass with a non-returning check valve over each turbo pump ensures sufficient and directed flow. Continuous circulation is vital for a safe, reliable and stable CMS operation.

The pressure control buffer PCB is a vertical vessel of 45 l volume in a bypass of the high to the low pressure side of the hydrogen circulation. Since the main circuit's subcooled liquid hydrogen behaves like an incompressible fluid, changes in the neutron heat load and fluid temperature would cause severe pressure fluctuations for a closed circuit at constant average density. A pressure control mechanism is required to stabilize the average CMS pressure level. Hence, the PCB is connected to the piping downstream of the second turbo pump and holds a liquid volume in its lower part. Above the liquid level a pressurized vapor fraction acts as gas spring or accumulator for the CMS pressure control system [7]. Liquid hydrogen can be stored or set partially as liquid storage volume to the loop by the lower bottom connecting pipe in case of a pressure increase or decrease because of changing neutron heat loads. A control valve on top of the PCB top enables vapor release to the low pressure side of the CMS. The gas gets liquefied in a coiled fin-tube heat exchanger and passes the ortho-parahydrogen converter before entering the bulk liquid hydrogen flow. Pressure overshoots after neutron heat ramp up can be effectively mitigated by doing so. For the other case of a loss of beam heating, electrical heaters on the PCB at the lower part boil liquid and restore extracted vapor avoiding too low pressures. Thus, the pressure control buffer provides volume compensation to the CMS.

The ortho-parahydrogen converter is a vessel of ca. 35 l volume and filled with a commercial o-p-H₂ catalyst (30 l bed volume), preferably chromium oxide on silica gel or ferrous oxide. It is arranged in a bypass of the high to the low pressure side of the hydrogen circulation and flow control is done by

a cryogenic control valve. At the moderator inlet, a parahydrogen concentration of $\geq 99.5\%$ is required, because the moderator vessel geometry is optimized for max. neutron brightness and pure parahydrogen as moderating media. Orthohydrogen could decrease the moderation performance significantly, absorb neutrons instead of slow them down and let them pass. This reduces the number of useful cold neutrons and increases the dynamic heat load.

Cryogenic transfer lines supply liquid hydrogen from the CMS cold box towards the Twister that holds the four cM. For the first 40 m the bulk flow is carried in a single vacuum insulated pipe and gets split into four distribution lines in a distribution box. From here four lines are routed ca. 10 m inside the Connection Cell and Monolith vessel close to the upper part of the Twister. Removable u-shaped bayonets connect each distribution line with Twister piping to the cM and back. The parallel flow allows operating each moderator with the same temperature and results in less pressure loss. Drawbacks are an increased hydrogen inventory and flow distribution compared to a serial flow through the cM's. Four distribution return lines connect again to the distribution box. Four manual fine control valves adjust the flow so that 240 g/s are being supplied to each of the two upper and 260 g/s to each of the two lower cM's. The four individual flows get united again and take the bulk return line to the CMS cold box. A filter upstream of the plate-fin heat exchanger and turbo pumps prevents any debris or particles to block the heat exchanger, harm the pump impellers or block valves. Passive, spring-loaded safety relief valves protect the CMS process pipes. At least one pressure relief device protects each insulation vacuum space from overpressure. Two actively controlled valves allow H_2 release in case of pressure excursions before the spring-loaded safety relief valve lifts. Every source of hydrogen release is connected to a shared vent line to the outside of the building. The vent line features a small flow inert helium gas with an overpressure because of flap at the end above the building's roof. Explosive mixtures with hydrogen can be excluded at all times.

3. Cryostat design as result of CMS process design

The main components of the cryostat (Figure 3) are the vacuum vessel consisting of three parts (a valve plate, an upper section and a lower part), the pipes for the process gases (helium and hydrogen) and related cryogenic components, i.e. control and check valves, heat exchangers, pumps, a pressure control buffer and an ortho-parahydrogen converter. The weight of the cryostat adds up to 2.9 t with a height of about 3.1 m from the bottom to the upper control valves and its diameter is about 2.5 m.

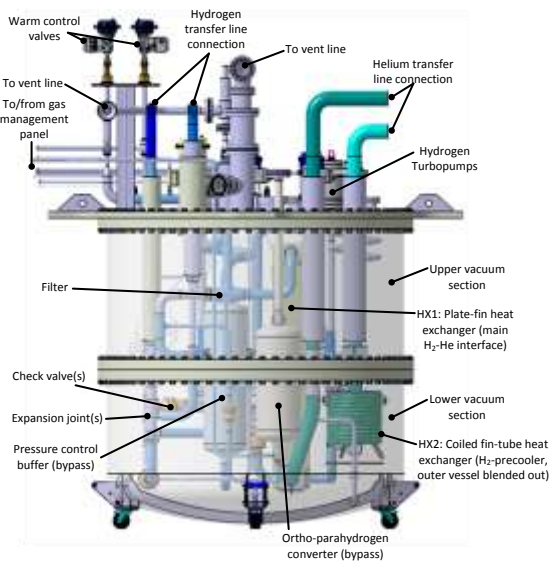


Figure 3: CMS cryostat vessel with most of the hydrogen systems functional components.

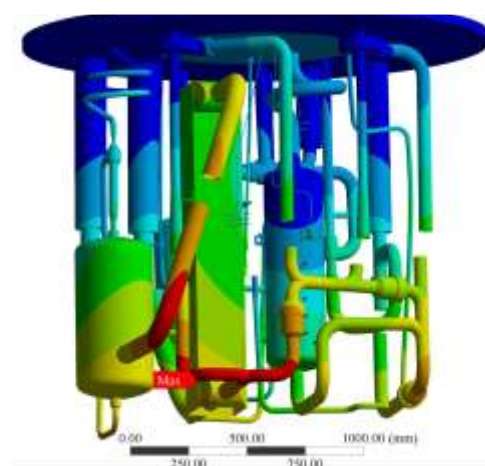


Figure 4: Thermal simulation result of total deformation during cold operation (linear color gradient: blue min. 0 mm to red max. 8.4 mm).

Figure 4 shows an exemplary result of the conducted thermal and mechanical analysis for the verification of the CMS cryostat structural integrity under cold operating conditions.

4. Conclusion and Outlook

Based on the ESS Preliminary Design and the requirements a final Cryogenic Moderator System has been developed and a cryostat containing most of the CMS functional components has been designed.

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Acknowledgments

This work was conducted within the In-Kind TIK 3.1/3.2 agreement between ESS and FZ Juelich GmbH (TU Dresden contributing the final CMS process design) supported by the German BMBF.