Spallation target cryogenic cooling design challenges at the European Spallation Source

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Abstract. The European Spallation Source (ESS) project is a neutron spallation source research facility currently being designed and built outside of Lund, Sweden. A linear accelerator delivers a 5 MW, 2.0 GeV, 62.5 mA proton beam to a spallation target to generate fast neutrons. Supercritical hydrogen circulates through two moderators surrounding the target, and transforms the fast neutrons emitted into slow neutrons, which are the final form of useful radiation. The supercritical hydrogen is in turn cooled from a helium cryogenic plant operating at 15-20 K. The supercritical cryogenic hydrogen circuit is a dynamic system, subject to significant changes in heat load. Proper pressure control of this system is critical to assure safe operation. The interaction between the hydrogen system and helium cryoplant poses unique challenges. This paper investigates the impact of the hydrogen system constraints on operation and control of the helium cryoplant, and suggests design options for the helium circuit.

1. Introduction

The European Spallation Source is a neutron science facility funded by a collaboration of 17 European countries currently under design and construction in Lund, Sweden. The ESS accelerator will deliver protons with 5 MW of power to a rotating metal target at 2.0 GeV with a nominal current of 62.5 mA [1]. A key feature of ESS is a tungsten target wheel, which will create fast neutrons via the spallation process from an impinging high-energy proton beam. A moderator-reflector system then transforms these fast neutrons into slow neutrons, which are the final form of useful radiation provided by the neutron source. A key feature of the target system will be the hydrogen moderators, which use supercritical hydrogen at 17 K and 1.5 MPa to reduce the energy of the neutrons before they reach the instrument lines. The neutrons will deposit significant amounts of energy into the hydrogen that must be removed to maintain the hydrogen at its nominal operating temperature of 17 K. The target moderator cryoplant (TMCP) [2] will provide the cooling for this hydrogen cryogenic moderator system (CMS). The heat deposited into the hydrogen will be removed via a heat exchanger in a hydrogen circulation coldbox that will transfer the heat from the hydrogen circuit to a gaseous He circuit operating between 15 K and 20 K which is connected to the target cryoplant coldbox.

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2. Hydrogen Cryogenic Moderator System (CMS)

2.1. Purpose
The spallation process creates neutrons with high velocity. To reduce speed, a moderating media have to be present to produce cold (slow), neutrons. The main tasks for the cryogenic moderator system are:

- To provide the moderating LH$_2$ at a supercritical pressure for the spallation process
- To keep the H$_2$ within the boundaries set at all times to ensure availability
- To provide the H$_2$ in a safe and reliable way

2.2. Parameters/constraints
The CMS uses cryogenic hydrogen to moderate the high-energy neutrons created by the spallation process [3]. Heat from the spallation process is absorbed by hydrogen circulating through the target moderator. In addition to the neutronic heat, there is a static heat load on the CMS from ambient heat, and energy added from hydrogen circulation pumps in the CMS hydrogen circuit. The top-level fluid parameters for the CMS are as follows:

**Heat load** - The maximum neutronic heat load to the CMS is 26.9 kW. There is an additional estimated static heat load of 4.0 kW, totaling an estimated overall heat load in the CMS of 30.9 kW. The static heat load is relatively constant for all operating scenarios. However, the neutronic heat load can change significantly depending on the proton beam power, which can vary from approximately 500 kW during initial facility commissioning to a maximum of 5 MW at full operation. Additionally, beam trips will result in very large changes in the heat load over short (on the order of seconds) durations.

**Pressure** – The maximum design pressure of the CMS is 17 bar(a), and is based on the maximum allowable design pressure of the moderator. The minimum operating pressure is set at 13 bar(a). The minimum pressure is determined by the requirement to operate at supercritical pressures to avoid the risk of two-phase flow in the hydrogen circuit.

**Temperature** – The maximum hydrogen operating temperature is 20.5 K, and is determined based on FEA analysis of the moderator temperatures. The minimum temperature is 17.0 K. This temperature is also limited by the moderator design, which imposes the restriction of a maximum temperature difference of 3 K across the moderator. The total CMS allowable temperature difference is 3.5 K, which includes an additional 0.5 K estimated temperature rise through the rest of the CMS.

**Mass flow** – The total estimated hydrogen mass flow through the CMS is approximately 1000 g/s. The total mass flow is not expected to vary significantly. With reduced or no neutronic heating, a constant hydrogen mass flow rate will result in a lower temperature rise across the entire CMS. However, it is preferable to keep the hydrogen circulating to maintain the temperature of the circuit constant, and operate the hydrogen circulation pumps at their most efficient point.

2.3. Design
The CMS is comprised of a vacuum insulated cryostat that contains hydrogen circulation pumps, a helium/hydrogen heat exchanger, an ortho-to-para hydrogen conversion catalyst bed, a pressure control accumulator, interconnecting piping, valves, and instruments. Supercritical cryogenic hydrogen circulates through vacuum insulated piping connecting the CMS cryostat with the cold moderators, which are located at the target wheel. Figure 1 shows a schematic of the CMS. A detailed description of the CMS is provided in reference [3].
3. Target Moderator Cryoplant (TMCP) cryogenic helium system

3.1. Purpose
The TMCP will provide the cooling for the hydrogen cryogenic moderator system (CMS). The heat deposited into the hydrogen will be removed via a heat exchanger in the CMS cryostat to a gaseous He circuit operating between 15 K and 20 K, which is connected to the TMCP coldbox.

3.2. Parameters/constraints

**Heat load** – The total heat load the TMCP will handle is the sum of the CMS heat load plus the additional static ambient heat load into the helium from the cryogenic transfer line (CTL). As mentioned in 2.2, there will be a large variation in the required cooling requirements. The ESS accelerator will be built and commissioned in several phases. As each phase is completed with additional cryomodules, the available proton beam power increases. Table 1 outlines the required cooling capacity of the TMCP with no beam, initial beam commissioning, and at each phase of the accelerator commissioning. Heat loads include safety and operational factors [4].

| Safety Factor | Beam off | Beam commissioning | Phase 1 | Phase 2 | Phase 3 |
|---------------|----------|---------------------|---------|---------|---------|
| Beam power MW (maximum) | 0 | 0.5 | 1.43 | 3.23 | 5.01 |
| Neutronic heating | 1.15 | 0 | 2.45 | 6.98 | 15.81 | 24.50 |
| Static heat load moderators | 1.5 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Static heat leak CMS cryostat | 1.0 | 1.20 | 1.20 | 1.60 | 2.40 |
| Static heat leak CTL | 1.5 | 0.54 | 0.54 | 0.54 | 0.54 | 0.54 |
| Subtotal TMCP heat load | 3.49 | 5.94 | 10.47 | 19.70 | 29.19 |
| Operational margin | 1.1 |

**Total TMCP heat load with operational margin**

| | 3.84 | 6.53 | 11.52 | 21.67 | 32.10 |

![Figure 1. CMS schematic diagram.](image-url)
Pressure – The maximum operating pressure of the TMCP and CTL is 20 bar(a). The only significant constraint on the TMCP system pressure is limitation of maximum operating pressure of standard helium compressors, and the desire to operate near this limit to optimize TMCP efficiency.

Temperature – The minimum allowable helium temperature is set considering the H₂ freezing point of 13.8 K. A margin of 1.2 K is added, setting the minimum TMCP supply temperature at 15 K. The maximum temperature is determined considering the maximum CMS hydrogen temperature of 20.5 K. Figure 2 shows the interface between the helium and hydrogen at the He/H₂ heat exchanger.

**Operational constraints** – The TMCP must operate efficiently at steady state heat loads between the minimum and maximum shown in Table 1. Additionally, the CMS requires system cool down to operating temperature or warm up to ambient temperature within 24 hours. Finally, the TMCP must respond to both short term and long term transients in heat load efficiently.

### 3.3. Physical Layout

The TMCP is one of three helium cryoplants at ESS. The other two cryoplants are the Accelerator cryoplant (ACCP), which provides cryogenic cooling for the linear accelerator, and the Test and Instruments cryoplant (TICP), which provides cryogenic cooling for ESS test stands, and LHe for the ESS instrument suite facility wide [5]. All three cryoplants are co-located to consolidate operations, provide common utilities, and facilitate maintenance. The warm compressor stations for all cryoplants are located in a common compressor building, warm gas storage tanks located outside the compressor building, and the cold boxes for all cryoplants are located in a cold box room adjacent to the linear accelerator klystron gallery as shown in figure 3.

![Figure 3. ESS cryoplants location.](image)

### 4. TMCP operating modes

ESS has defined 5 operating modes: Shutdown, Studies, Studies on Target, Start up, and Production [1]. From cryogenic services point of view, these modes translate into specific ranges of heat loads that the TMCP must accommodate.

Shutdown, Studies, Studies on Target, and Start up modes will have either no proton beam on target, or very low power proton beam to target. Consequently, the cooling requirement for the TMCP will be as low as 12-20% of nominal design.
Production mode will have higher proton beam power to the target, resulting in a cooling requirement of ~36-100% of nominal design.

Required TMCP capacity versus proton beam power is shown in figure 4. Accordingly, the TMCP will be designed and manufactured to fulfil the full nominal heat load requirement. However, in order to optimize the TMCP operation and efficiency during the first years of operation, and during turndown and transient modes, the TMCP shall be designed to allow efficient operation down to approximately 20% of its nominal capacity.

![Image](image_url)

**Figure 4.** TMCP cooling requirement vs proton beam power.

To accommodate the expected ESS overall operating modes and the CMS requirements, the TMCP has defined the following modes:

- Steady state modes – Nominal design, nominal low power, and nominal turndown
- Transient operating modes – Cool down and warm up
- Switching modes – Long term switch from nominal to turndown, long term switch from turndown to nominal, and beam trip

### 4.1. Steady state operating modes

The heat loads at various modes, the helium property and mass flow rates at the cooling loops interface are shown in Table 2. The heat loads consist of static heat loads from the CMS, the dynamic heat load from the proton beam, and the static heat load in the helium CTL. The values for mass flow rates and system pressures listed in Table 2 are calculated based on the heat loads and temperature rise between the supply and return helium streams.

| Operation modes          | Heat load, W | Mass flow, g/s | Pressure, bar(a) | Temperature, K |
|--------------------------|--------------|----------------|------------------|----------------|
| Nominal design (Max)     | 32100        | 1020           | 19.6             | ≥15 ≤20        |
| Nominal low power (Min)  | 15050        | 505            | -                | ≥15 ≤20        |
| Nominal turndown (Min)   | 4400         | 160            | -                | ≥15 ≤20        |
| Nominal turndown (Max)   | 3800         | 145            | -                | ≥15 ≤20        |
Nominal design mode – This mode will occur with the beam on and should be the most common mode seen at ESS. This mode features the highest cooling capacity needed.

Nominal low power mode – This mode will occur with the beam on, but operating at less than full power. During initial operations in particular, beam power could vary from ~ 2-10% of nominal design for extended periods of time.

Nominal turn down mode – The mode will occur with the beam off. For short duration interruptions of the beam, appropriate means will be used to allow the heat load to the cryogenic TMCP to remain constant. For longer duration interruptions, the cryogenic TMCP capacity will be “turned down” via the control system to allow for this reduced heat load requirement in the most energy efficient manner.

4.2. Transient operating modes
Cool down – The TMCP will be capable of being cooled down independent from the ESS CTL and CMS. Additionally, the TMCP will be capable of cooling down the entire CTL line and He/H₂ interface HEX from ambient temperature to 15 K. Note that the CTL consists of two vacuum jacketed pipes, nominally DN100, inner process pipe, and approximately 335 m long.

Warm up – Complete warm up of the TMCP will rarely occur. In this mode, the TMCP is warmed up from operating temperature to room temperature. This warm up includes discharging approximately 300 kg of cold helium from the CTL to warm gas storage buffers, and warm up of the CTL line. In some cases it may be necessary to warm up the TMCP while maintaining the cold helium inventory in the CTL. In this case, the TMCP will be isolated from the CTL and warmed up from operating temperature to room temperature.

4.3. Switching modes
Long term switch from Nominal to Turndown – The TMCP will transition from nominal mode to turn down mode by unloading helium inventory from the CTL by means of specific bypasses in the TMCP through a heat exchanger to the ESS warm helium HP and LP buffer tanks.

Long term switch from Turndown to Nominal – The TMCP will transition from turn down mode to nominal mode by loading helium inventory to the CTL from the ESS warm helium HP and LP buffer tanks.

Beam trip – In the event that proton beam to the target trips off when the TMCP is operating in “nominal design mode”, the cooling required for the CMS drops significantly. The result is a significant change in the load seen by the TMCP. To deal with this situation, the cold helium supply to the CMS will be partially bypassed, and warm helium injected into the return stream back to the TMCP sufficient to produce the same load as that lost due to the beam trip. Thus the TMCP will see a constant load through the whole event. As the beam to target is re-established, the warm helium will simultaneously throttle back, thereby maintaining a constant load. In the event that the beam cannot be re-established in a reasonable period of time, the TMCP settings can be adjusted to “nominal turndown mode” by throttling warm helium flow, and permitting the TMCP control system to adjust the TMCP settings so that it can benignly follow the ramp down.

5. TMCP design
5.1. TMCP process design
The TMCP must operate between approximately 3.8 and 32.1 kW heat load as per Table 2. The large variation in heat load, and narrow operating temperature range of 15-20 K will require a sophisticated control scheme to operate efficiently. The proposed process design for the TMCP can utilize the so-called floating pressure cycle [6] for a significant portion of the operating range, and is described fully in reference [7].
5.2. CTL configuration

Early in the project, a decision was made to co-locate all ESS helium cryoplants. This resulted in a long helium transfer line between TMCP and CMS. This approach had the advantage of consolidating all ESS cryoplants to facilitate maintenance and consolidate utilities. However, the long transfer lines result in a large helium inventory and large pressure drop through the helium loop. Early in the project, the initial heat load estimate for the TMCP was only 20 kW, but changes in the moderator design resulted in a heat load increase to 32.1 kW as detailed in Table 1. This increase led to a greater helium mass flow rate in the CTL. Additionally, the CMS cryostat was relocated from its original location to comply with hydrogen safety requirements. This added length to the CTL, resulting in an overall length between CMS and TMCP of ~ 335 m, and a helium inventory in the CTL of 336 kg.

Table 3. CTL size and fluid parameters

| Parameter                        | Supply | Return |
|----------------------------------|--------|--------|
| Helium mass flow rate (kg/sec)   | 1.02   | 1.02   |
| Inlet pressure (bar(a))          | 19.6   | 19.2   |
| Temperature (K)                  | 15     | 20     |
| Density (kg/m³)                  | 63.81  | 45.22  |
| Pipe length (m)                  | 335    | 335    |
| Pipe I.D. (mm)                   | 108.2  | 108.2  |
| Pressure drop through CTL (bar(a))| 0.055 | 0.076  |
| CTL helium mass (kg)             | 197    | 139    |

To accommodate the increase to 32.1 kW refrigeration requirements, the CTL process pipe diameter increased to minimize pressure drop through the loop. The pressure drop through the CTL is directly dependent on the helium density, so the TMCP process is set with the expansion turbines on the return side of the helium loop. This allows higher pressure (and therefore higher density) helium in the entire CTL, thereby minimizing pressure drop through the circuit. Table 3 shows details on the expected CTL size and fluid parameters.

5.3. TMCP proposed configuration

A simplified schematic diagram of the proposed TMCP is shown in figure 5. Two parallel warm compressors and two parallel expansion turbines provide efficient operation at reduced loads, and partial redundancy for maximum loads. Helium can be loaded or unloaded into the high-pressure buffer (HPB) or low-pressure buffer (LPB) as required. An ambient heater serves to provide a warm helium bypass supply as make up heat load during short term decrease in heat load as described in [7]. The heater serves the additional function as an acceptance test heater during commissioning. The placement of expansion turbines downstream of the return line from the CMS keeps maximum system pressures in the CTL, allowing higher fluid density and consequently smaller diameter vacuum insulated piping.

6. Project challenges

The design of the ESS target moderator-reflector system has evolved significantly from the original concept detailed in the ESS technical design report [1]. The original moderator-reflector cryogenic
system required approximately 20 kW of cooling at 17 K from the TMCP. In 2014, an engineering assessment was made of the cold moderator design. The result was a novel design moderator that provided a significant increase in neutron brightness, but at the cost of additional heat load to the CMS hydrogen and consequently the TMCP. Original TMCP designs considered expansion turbines on either the supply line from the cold box or the return line to the cold box. However, the increased helium mass flow rate drove the decision to abandon expansion turbines on the supply side, as a lower pressure supply to the CMS required significantly larger and more costly vacuum insulated piping.

Earlier TMCP design concepts also considered a slightly warmer helium supply temperature of 16.5 K (slightly below the required 17 K hydrogen temperature), and a return temperature of 19.5 K. However, the increased heat load and consequently increased helium flow rate required very large warm helium compressors. An engineering assessment was made for the cold moderators, and it was determined that they could tolerate a maximum outlet temperature of 20 K. This, and the decision to lower the helium supply temperature to 15 K provided some relief in the helium flow rate and compressor size, but with some small additional risk to the CMS, as the helium supply temperature was now much closer to the hydrogen freezing point.

The increase in TMCP size also required a re-evaluation of its location. An engineering analysis was performed to assess the feasibility of relocating the TMCP closer to the CMS to decrease the CTL length and helium inventory, and possibly improve control of the integrated system. Although there were some advantages to moving the TMCP, the final evaluation determined that the move would be too costly and have a significant negative effect on the overall project schedule.

7. Summary

ESS will be the highest power neutron spallation source of its kind in the world when complete. The cryogenic heat load to the CMS and subsequently to the TMCP are characterized by a wide range of heat load, narrow range of operating conditions, and expected fast changes in heat load that the systems must respond to safely and efficiently. The proposed configuration of the TMCP and CTL effectively address these challenges by providing a system that can operate efficiently over the entire range of operating conditions, can respond quickly to changes in heat loads, and is designed to minimize helium mass. It is expected that ESS will initiate a formal procurement process in 2015 to solicit proposals for the TMCP consistent with the design proposed herein.

References

[1] Peggs S 2013 ESS Technical Design Report (Lund: ISBN 978-91-980173-2-8)
[2] Jurns J et al 2014 Physics Procedia Proceedings of the 25th ICEC and ICMC 2014 67 101-6
[3] Ringner J, Jurns J, Kickulies M, Arnold P, Quack H and Klaus M 2015 Design challenges of a 20kW liquid hydrogen cooling system for The European Spallation Source cold moderators, CEC-ICMC 2015 (Tucson: to be published)
[4] Arnold P et al. 2014 Proceedings of LINAC2014 939-41
[5] Weisend II J G et al. 2014 Physics Procedia Proceedings of the 25th ICEC and ICMC 2014 67 27-34
[6] Ganni V and Knudsen P 2010 Advances in Cryogenic Engineering, AIP Conference Proceedings 1218 1057-71
[7] Arnold P et al. 2015 ESS Cryogenic system process design, CEC-ICMC 2015 (Tucson: to be published)