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Cryogenic cooling of the cold neutron source at ESS

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Abstract

The European Spallation Source (ESS) project currently being designed will be built outside of Lund, Sweden. The ESS design includes three He cryogenic plants, providing cryogenic cooling for the proton accelerator superconducting cavities, for the target cold neutron source, and for the ESS instrument suite. Supercritical H_2 circulates through and cools the target cold neutron source, and is in turn cooled from the target He cryogenic plant. This report describes the unique cooling requirements for the supercritical H_2 cooling system, defines the operating parameters for the target He cryogenic plant based on expected heat loads, and explores design options for the target cryogenic plant to optimize its performance.

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Keywords: cryogenic; spallation; cryoplant; hydrogen; helium

1. Introduction

The European Spallation Source is a neutron science facility funded by a collaboration of seventeen European countries, and currently under design and construction in Lund, Sweden (Peggs [1]). 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.

A key feature of ESS is a tungsten target wheel, which transforms high-energy protons via the spallation process to fast neutrons. 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 are the H_2 moderators, which use supercritical H_2 at 17 K and 1.5 MPa to reduce the neutrons energy before they reach the instrument lines. The neutrons deposit significant energy into the H_2 that must be removed to maintain the H_2 at its

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nominal operating temperature. The target moderator cryoplant (TMCP) will provide the cooling for these H_2 moderators. The heat deposited into the H_2 is removed via a heat exchanger in a H_2 circulator cold box that will transfer the heat from the H_2 circuit to a gaseous He circuit operating at 16.5 K. The helium circuit is connected to the target cryoplant cold box.

We anticipate that the TMCP will be procured from commercial sources, and the H_2 cold box will be designed and built by either ESS or as an in-kind contribution from one of the ESS partner countries.

2. System configuration

The TMCP is one of three He cryoplants planned for ESS (Arnold [2]). The target cryogenic system consists of He gas storage, the TMCP, target cryogenic distribution system, H_2 circulation cold box, and H_2 moderator. A concern with this cryoplant is the possibility of tritium migrating from the H_2 loop and contaminating the He flow. Consequently, we anticipate that the TMCP will have a He gas supply completely separated from the other cryoplants and will be designed to prevent automatic venting of the He to the atmosphere.

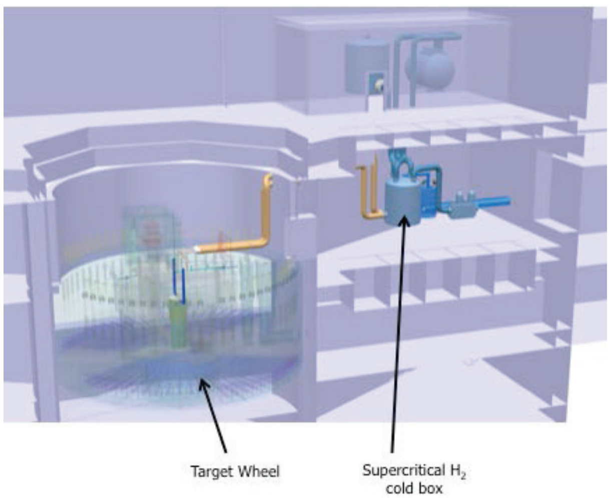
The H_2 cold box will be located close to the target wheel as shown in Fig. 1. The TMCP cold box will be located in the ESS cryoplant cold box room, approximately 240 meters from the H_2 cold box.

2.1. Supercritical cryogenic H_2 system

The ESS tungsten target wheel transforms high-energy protons via the spallation process to fast neutrons (Gallimore [3]). A H_2 moderator-reflector use supercritical H_2 at 17 K and 1.5 MPa to reduce the neutrons energy before they reach the instrument lines. A simplified schematic of the H_2 circuit is shown in Fig. 2. The circuit consists of pumps, a heat exchanger, an accumulator, a heater and an ortho-to-para converter. The main components of the circuit are housed in a double-walled vacuum vessel. The components in this vacuum vessel are connected via transfer lines and an appropriate coupling system to the cryogenic moderator vessels.

The main source of heat into the cryogenic H_2 system will come from neutronic heating inside the moderator vessel. This heat load scales directly with the proton beam power. In order to continue operation during beam trips and short shut downs, a heater provides heat to substitute for the neutronic heat load to the circuit. Additionally, an accumulator will dampen the remaining volumetric changes.

As the moderators are optimized for pure para-H_2, an ortho-to-para converter will be installed in the circuit. At 300 K, para-H_2 concentration is 25%, and at 20 K, the equilibrium of para-H_2 is very close to 100%. As the H_2 temperature is reduced, a natural conversion takes place, albeit very slowly. An ortho-to-para catalytic converter will reduce the conversion time. It is proposed to operate the converter in a bypass line as the heat load and irradiation could potentially reconvert para to ortho H_2. There is no published data on the effect of irradiation on the rate of p-o conversion, and this configuration allows for flexibility in terms of the amount of fluid processed during operation.



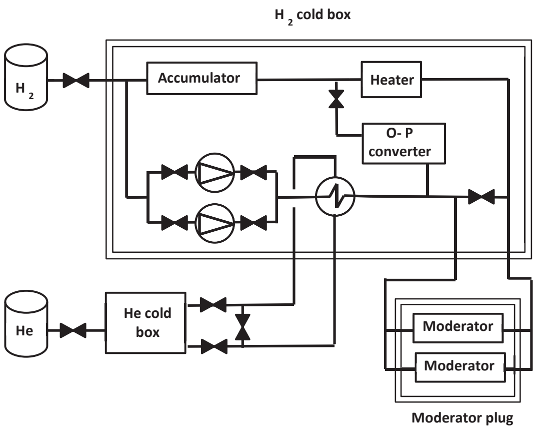


Fig. 1. Proposed layout of H_2 and He cold boxes.

Fig. 2. Target supercritical H_2 circulation system.

2.2. Cryogenic He system

The target moderator is cooled with supercritical H_2 at 17 K and 1.5 MPa. The heat deposited in the H_2 from the neutrons generated at the target will be transferred to a cryogenic He circuit operating at 16.5 K via a heat exchanger in the H_2 cold box The 16.5 K He is supplied from the TMCP. The He circuit between the H_2 cold box and He cold box consists of vacuum insulated piping approximately 240 meter long. The final TMCP configuration has not yet been determined. Based on the anticipated heat load and small temperature difference between the He supply and return, there will be a high He mass flow. To enable a more compact and efficient plant design, the proposed He refrigeration configuration is shown in Fig. 3 (Klaus [4]). This configuration will significantly reduce He mass flow. However, it requires that an expansion turbine be situated either in the H_2 cold box or in a He satellite box next to the H_2 cold box in the target building.

3. Design parameters

3.1. Supercritical cryogenic H_2 system

H_2 moderators use supercritical H_2 at 17 K and 1.5 MPa to reduce the energy of the neutrons produced at the target wheel. The moderator H_2 circuit current configuration includes two moderators for the target wheel – one above and one below the wheel. Recently, an innovative moderator design has been developed that is both smaller and results in higher neutron brightness. The impact of this change on the TMCP requirements is still being finalized. Table 1 summarizes design parameters for the supercritical cryogenic H_2 system as it currently stands.

3.2. Cryogenic He system

The heat deposited in the H_2 from the moderators is transferred to a cryogenic He circuit operating at 16.5 K via a heat exchanger in the H_2 cold box. The TMCP overall refrigeration parameters are shown in Table 2. Note that the He working pressure is not specifically set, and will be determined by the TMCP vendor when the final system is procured. Additionally, the He mass flow rate is based on the configuration shown in Fig. 3, and will not be determined until the final TMCP design is complete.

Table 1. Supercritical H_2 design parameters.

Parameter	Value
Heat load	
Moderators	10.8 kW
H_2 circulation pumps	4 kW
H_2	
Moderator inlet temperature	17 K
ΔT @ 5 MW beam power	3 K
Working pressure	1.5 MPa
Mass flow rate	0.8 kg/s

Table 2. TMCP design parameters.

Parameter	Value
Heat load (estimated)	
H_2 system dynamic heat load	20 kW
Static heat load (no beam)	5 kW
He	
Heat exchanger inlet temperature	16.5 K
ΔT	3 K
Maximum pressure	2.0 MPa
Mass flow rate	~0.6 kg/s

4. Operational scenarios

4.1. Target operating modes

Operating cycles will permute among four modes corresponding to specific needs such as machine development and qualification, power ramp-up, neutron production, cooling time and maintenance. The four modes are:

1. Production mode, which prevails when the facility is delivering stable beam to its scientific users;
2. Maintenance mode, during which access to most systems is permitted for preventive and curative maintenance;
3. Studies mode, during which tests, studies, and activities to develop or qualify the accelerator are performed;
4. Restart mode, which prevails during the transition from very low power to nominal power.

Proton beam power to the target wheel will vary from 0 to 5 MW depending on which mode is being employed. This will result in significant variation in the supercritical H_2 heat load. Additionally, beam trips will result in low heat loads on the cryogenic H_2 circuit. In order to continue operation during periods with low heat loads, a heater is included in the H_2 circuit to substitute for neutronic heat loads.

4.2. TMCP operating modes

The TMCP operation must provide adequate cooling for the various target system operating modes. This will require that the TMCP have significant turn down capacity. Additionally, the TMCP will be subject to the following operating modes:

Purging and purification – Starting with a warm system, 300 K He gas from the high-pressure supply is circulated through all the He circuits and returned to the purifier via a purge return line. This process continues until the measured purity of the gas returning to the purifier meets He 4.6 purity (99.996% He).

Cool down and warm up – Cool down of the cold He circuit is relatively straightforward. Cold He from the cryoplant will circulate through the distribution system and target H_2 cold box and back to the cryoplant prior to initiating supercritical H_2 flow through the target moderator system. The heat load is in this case just the static load shown in Table 2. Once H_2 flow is initiated, the heat load will ramp up quickly to the nominal 20 kW value.

In the warm up phase (to 300 K), 300 K He gas will be brought into the distribution circuit warming up the H_2 cold box. The return flow is brought back to the plant via the vacuum jacketed He distribution line. Currently, there are no limits on the cool down or warm up rate defined.

Normal 16.5 K operations – Operations with the target supercritical H_2 cooling circuit operating is the nominal operating mode and should be the most common mode seen at ESS. This mode can occur with the beam power on and with the beam power off. In the case of beam off, the total heat deposited into the target H_2 cryogenic system is much less than with the beam on.

For the ESS target cryoplant, the heat load at 16.5 K may vary by a factor of 4 between stand-by (only static) and full-load (dynamic + static) operations. The 16.5 K refrigeration cycle of the ESS target cryoplant shall handle this large dynamic range of mass flow under the most effective and economical operation. For short duration interruptions of the beam, electric heaters in the cryogenic circuits may turn on to allow the heat load to the cryogenic plant to remain constant. For longer duration interruptions, the cryogenic plant capacity will be "turned down" via the control system to allow for this reduced heat load requirement.

Partial warm up mode – The target H_2 cooling system requires warm up, or partial warm up as a regularly scheduled event during a normal year operation. This warm up will likely bring the H_2 cooling system up to ~ 77K and last 3-4 days per event.

5. Optimization and design choices

The ESS 5 MW proton beam has a pulse length of ~3 ms, and pulses at 14 Hz. This combination of high power and long pulse lengths makes supercritical H_2 a logical choice for the cold moderator. Additionally, a pure para-H_2 moderator is almost transparent for low-energy neutrons, favoring neutron extraction (Batkov [5]).

The cryogenic cooling of the ESS target moderator poses a number of unique challenges including:

- Maintaining supercritical state of cryogenic H_2
- Highly variable heat load on cryogenic system
- Isolation of cryogenic He system from other ESS cryoplants due to risk of radioactive contamination

- Design of system and components in compliance with H_2 safety standards

As the supercritical H_2 circuit is a relatively small volume, quickly changing dynamic heat loads in the target can resulting in significant pressure swings if no controls are put in place. An immediate loss of neutronic heating from a beam trip could result in the H_2 changing from a supercritical to a two-phase liquid/gas mixture. As system response from the TMCP is too slow to respond to changes in the H_2 heating, the primary control of H_2 conditions will be within the H_2 cooling loop.

H_2 solidifies at temperatures below 13.8 K. As the operating temperature is between 17 and 20 K, there is not much temperature margin. Careful design in the H_2/He interface will be required to prevent freezing H_2.

Due to the possibility of tritium contamination and to allow operational stability of the quite distinct cryogenic processes, the TMCP will be completely separate from the other two cryoplants at ESS.

The H_2 used for the ESS moderators is a relatively small quantity, and is not used in any combustion process. There are several standards applicable to safe usage and storage of H_2 in this case. Along with appropriate radiation safety design, the moderator cryogenic cooling system must also take into account safe H_2 system design, and utilize standards addressing equipment location, quantity/distance (QD) requirements, and appropriate electrical classification of equipment, safe venting, and personnel protection.

5.1. TMCP remote expander

As mentioned in section 2.1, preliminary analysis has indicated that a third turbo-expander can reduce by approximately half the required He mass flow from the TMCP, and to better manage the refrigeration power required for the moderator H_2 cooling loop. There are several options to consider for the location of this third turbo-expander:

- Inside the H_2 cold box;
- In a satellite cold box adjacent and connected to the H_2 cold box;
- At the TMCP.

As the turbo-expander will be within the scope of supply of the He refrigerator supplier, it would be unreasonable to attempt to integrate the turbo-expander in the H_2 cold box. The H_2 cold box will be provided either by ESS or an in-kind contributing partner. Depending on the schedule, the H_2 cold box may not be available when TMCP commissioning takes place.

If the turbo-expander is located in a satellite cold box, this cold box could be temporarily connected to the TMCP with jumpers for commissioning, and then relocated and connected to the H_2 cold box when that is available.

The third turbo-expander could also be placed in the TMCP cold box. However, this would require additional supply and return lines between the TMCP and H_2 cold box, with associated efficiency losses and cost.

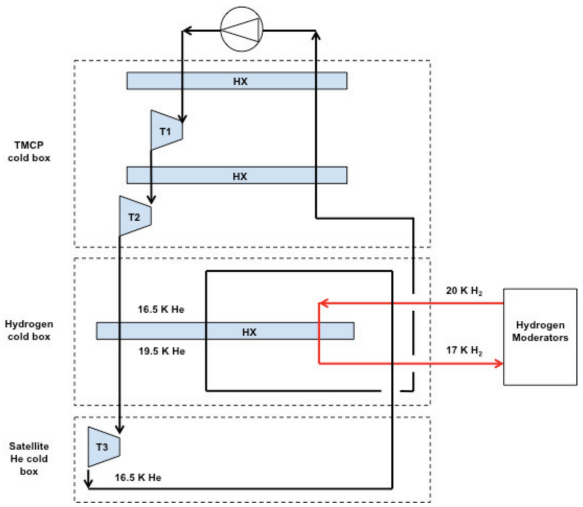


Fig. 3. Proposed He refrigeration cycle.

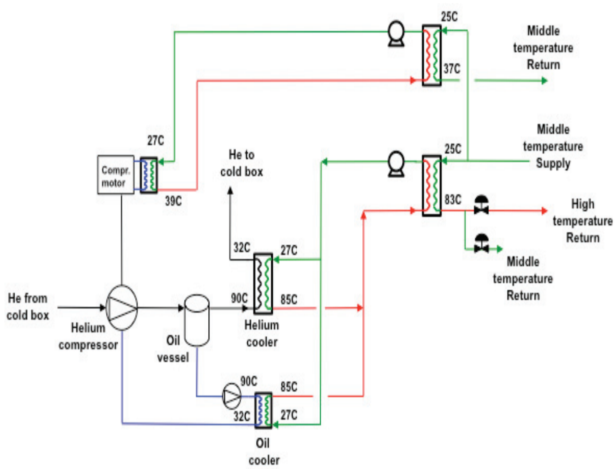


Fig. 4. TMCP energy recovery concept.

Based on these considerations, the current plan is to mount the turbo-expander in a satellite box that will connect to the H_2/He heat exchanger in the H_2 cold box via a short set of vacuum insulated pipes.

5.2. Optimizing energy recovery

ESS has committed to a facility-wide energy management plan, which includes maximizing efficiency to reduce consumed power, and recovering waste heat which will be recycled to the city of Lund district heating system or other warm water consumers (Jurns [6]). As the warm He compressors generate a significant portion of heat, ESS energy goals should be taken into consideration in the design.

In order to fulfil this top level requirement the He and oil coolers of the TMCP compressor system shall be designed to allow recovering waste heat as high a temperature as reasonably possible, i.e. control the cooling water flow in order to minimize the warm end temperature differences to <10 K (e.g. by using plate fin heat exchangers). An example of a energy recovery scheme for the TMCP is shown in Fig. 4.

6. Summary

The configuration of the supercritical H_2 moderator circuit for the ESS target wheel has not been finalized. However, we expect that the moderator designs options being considered will not have any first-order effect on the overall H_2 cooling system or TMCP design. The moderator design concept will be decided in 2014, and detailed design started following. We anticipate that a technical specification for the TMCP and other tender documents will be issued in the first quarter of 2015, and contract award third quarter of 2015. The current ESS schedule has acceptance testing of the TMCP complete mid-2018.

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