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Conceptual Design of the Liquid Hydrogen Moderator Cooling Circuit for the European Spallation Source

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Abstract

The European Spallation Source in Lund, Sweden, will be a 5 MW beam power neutron spallation research center. As subsystem of the target station the moderators play a vital role by slowing down high energy neutrons set free during the spallation process. To provide maximum neutron flux intensities with high availability for scattering experiments a conceptual liquid hydrogen moderator cooling circulation design proposal was developed. Supercritical hydrogen at 17 K will be utilized to absorb energy of the incoming neutrons in two parallel moderator vessels. A helium refrigerator provides the necessary cooling capacity by implementing an additional helium expansion turbine downstream the refrigerator cold box. Strategies for the mitigation of pressure fluctuations due to beam trips are being presented. Solutions in form of electrical heaters and an accumulator or an expansion vessel are discussed. Different supercritical hydrogen circulator implementation scenarios are being matched to indicate the most reliable setup. For an efficient moderation process parahydrogen concentrations higher than 99 % have to be guaranteed at the moderator inlet. Due to potential conversion of parahydrogen to orthohydrogen via irradiation processes the implementation of an ortho-parahydrogen catalyst bed is being evaluated. Methods for a continuous measurement of the apparent parahydrogen concentration at the moderator in- and outlet will be introduced. The arrangement and interaction of the components will be detailed in the paper.

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Keywords: Spallation Neutron Source, Moderator Cooling, Cryogenic Hydrogen System, Ortho- / Parahydrogen, Irradiation

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1. Introduction

Cryogenic hydrogen serves as moderator fluid in a closed loop to decelerate high-energy neutrons in two parallel moderator vessels for scattering experiments in material science. An accelerated proton beam hits a tungsten target where those high-energy neutrons are being released. A design proposal for a 5 MW spallation neutron source has been worked out.

Nomenclature

c_p	Isobaric heat capacity
$\dot{m}_{He}$	Refrigerator helium mass flow
$\dot{Q}$	Heat load
ΔT	Temperature difference

2. Design basis

To comply with prospective European Spallation Source (ESS) moderator cooling system specifications the following preliminary requirements [1] serve as design requirements:

- Hydrogen at 17 K and 1.5 MPa at moderator inlet,
- Parahydrogen concentration ≥ 99 % at moderator inlet,
- At maximum beam power of 5 MW the neutron heating should not exceed 3 K,
- Constant density at the moderator inlet.

3. Circuit design

The general system setup shown in Fig. 1 is combining a helium refrigerator supplying cooling power at low temperatures to a separate liquid hydrogen circuit. The refrigerator will be connected over a rather long transfer line with a turbine box right beneath the hydrogen cold box. Latter will be connected to the moderator reflector plug via a transfer line, too. Due to radiation safety measures and civil engineering those locations and distances are necessary.

In the hydrogen circuit the dynamic heat load of two times 8.6 kW at full beam power of unprecedented 5 MW is going to be introduced into the two moderator vessels. Hence a constant mass flow of 0.8 kg/s has to be circulated to meet the requirement of less than 3 K temperature increase due to 17.2 kW neutron heating. To remain always above the critical hydrogen pressure of 1.28 MPa the maximum allowable pressure drop over the circuit has been set less than 0.2 MPa but should be further decreased if possible, which is emphasized in the turbo pump section later on. Due to the fact that the hydrogen will be circulated at around 18.5 K and 1.5 MPa a change in the dynamic heat load will change the average temperature and density. Supercritical hydrogen almost behaves as incompressible at the rated conditions. Hence a small change in temperature will result in a large change of pressure.

A double-acting temperature and pressure control system will be adopted to mitigate those fluctuations. A combination of two actively controlled electrical heaters and one accumulator downstream the moderator vessels is being utilized. The heaters compensate the nuclear heating and have to be able to introduce more than 8.6 kW each into the hydrogen at no beam operation. The accumulator is a device which offers a variable volume to the liquid hydrogen by implementing helium gas-backed metal bellows with a large room-temperature buffer vessel connected to the cold helium volume. If the neutron beam stops for example because of a loss of the proton beam, the dynamic heat load will decrease almost immediately too. The colder hydrogen will propagate towards the inlet of the heaters where an active PID control increases the electrical power to reach the same outlet temperature downstream of the heater thus the rest of the moderator cooling loop. The aim is to keep the thermal disturbance over the circuit, especially the He-H_2 heat exchangers, as small as possible. Still there will be a decrease in temperature in the transfer lines between moderators and the heaters which has to be compensated regarding pressure. The overall hydrogen density increases. Hence the helium volume of the accumulator gets larger establishing almost pressure equilibrium between hydrogen and helium in the device. The interaction of an actively controlled heater and the accumulator has proven to be an effective technology [2].

An alternative to the combination of electrical heater and accumulator might be the use of a supercritical hydrogen buffer vessel [3] which is not shown in Fig. 1. The principle is to have a rather long vertical buffer connected downstream of the moderator vessel inside the hydrogen box. The bottom is connected to the circuit. An electrical heater at the top of the buffer vessel establishes a vertical temperature gradient downwards to the connection to the circuit. If the dynamic heat load changes, cold dense hydrogen from the bottom of the vessel can flow inside or outside of the circuit. The warmer hydrogen at the top of the buffer vessel acts as a spring because it is more compressible due to the higher temperature.

The filter element in front of the electrical heaters serves as a barrier for irradiation-produced particles from inside of the moderator vessels. A rather small amount of ortho-parahydrogen catalyst can be used because of the good adsorption features and because it is needed for the > 99% parahydrogen concentration anyway. Thus those radiating particles cannot accumulate in sensitive equipment. The task of the He-H_2 heat exchangers is to release heat to the colder helium flow. More details will be given in section 4.

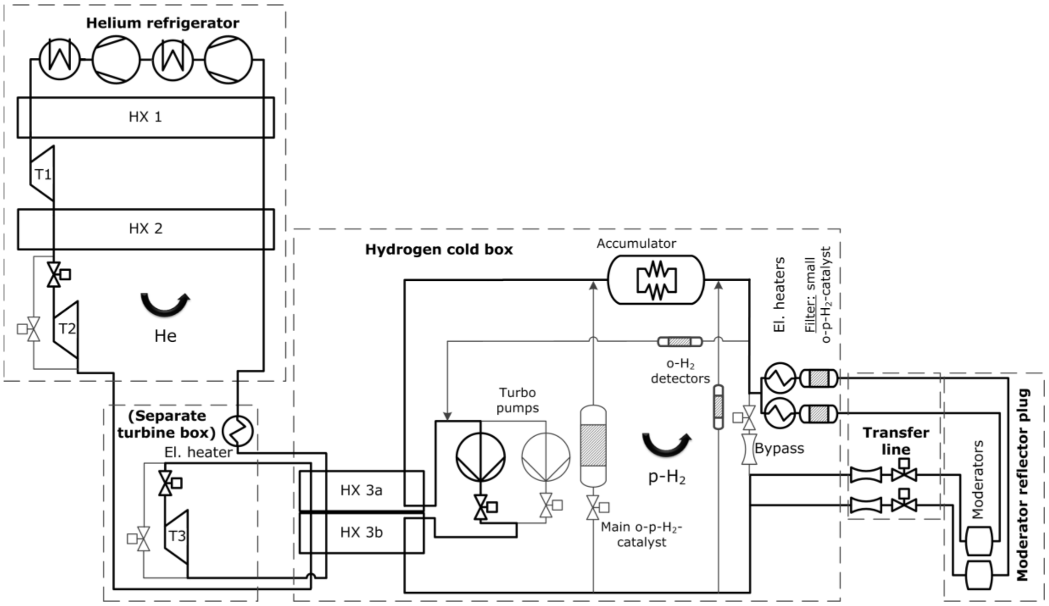

Fig. 1. Proposed flow-scheme for cryogenic hydrogen circulation and helium refrigerator.

The turbopumps have to circulate a constant hydrogen mass flow of 0.8 kg/s. Due to redundancy two pumps shall be installed. There are two preferred operation modes at this point. One can use one pump at 0.8 kg/s and leave the second pump in a cold standby recirculating a small fraction of the flow over the control valve to keep the machine ready. In the case of a failure of the main pump the second could be ramped up to full operation within ca. 45 s. The advantage would be a high efficiency and easy pump control. Disadvantageous might be the rather long time to recover full flow because the temperature over the electrical heaters might increase and over the heat exchanger decrease in an uncontrolled manner.

Furthermore an alternatively considered option would be to operate two turbo pumps at 0.4 kg/s in parallel. If one pump fails, the second will be ramped up to 0.6 kg/s. The advantage of this version is the uninterrupted flow of at least 0.4 kg/s and presumably smaller thermal disturbance over the hydrogen circuit in case of a malfunction. Disadvantages might be the more complex operation of two machines in parallel because of interdependencies. In

Addition the moderator loop could not be run at full beam power because only 0.6 kg/s can be guaranteed. Designing a pump which can operate both 0.4 kg/s and 0.8 kg/s for the same pressure drop comes with a reasonable decreased efficiency and flat characteristic curve. Hence this option is not considered for now.

To guarantee the parahydrogen concentration > 99% a catalyst has to be implemented into the circuit. At around 20 K the thermodynamic equilibrium between orthohydrogen with parallel and parahydrogen with antiparallel proton spin orientation is 0.2 % to 99.8 %. The natural conversion mechanism where orthohydrogen acts as a promoting agent is too slow. In Fig. 2 left three integration scenarios are presented. The catalyst can be put in the main stream with flow in the longitudinal or cross direction of the catalyst bed. The latter has the advantage of a much lower pressure drop. If the catalyst is placed in the bypass a certain amount has to be recirculated depending on the presumed [4] but not yet experimentally proven conversion of parahydrogen to orthohydrogen due to neutron irradiation. That will lead to a lower pressure drop but a higher mass flow of the circulators. Anyway one is interested in a continuous monitoring of the orthohydrogen concentration. The most convenient method would be to measure the temperature increase over a small amount of catalyst in a thin long tube. The observed temperature difference over this adiabatic catalyst cell can be attributed to a distinct amount of converted orthohydrogen [5].

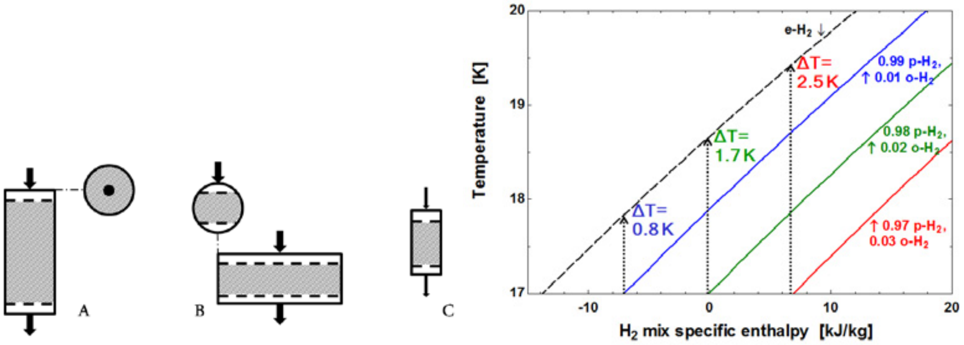

Fig. 2. Left: o-p-H_2 catalyst configuration in main LH_2 stream (A) vertical, (B) horizontal or (C) in a bypass, right: adiabatic temperature increase over catalyst in o-H_2 detector.

The diagram in Fig. 2 right indicates for example a maximum temperature increase starting at 17 K over the adiabatic cell of 0.8 K for 1 % respectively 2.5 K for 3 % orthohydrogen at the inlet converting to equilibrium hydrogen.

4. The helium refrigerator

The refrigeration load between 17 and 20 K for this case study can be assumed as follows:

• Permanent heat leak into the hydrogen loop:	1 kW
• Pump power at maximum flow rate:	3 kW
• Neutron heating depending on accelerator beam power:	0-20 kW
• Variation of load for refrigerator:	4-24 kW

In this whole range long term operation may be needed. This means that the refrigerator should have a very good efficiency in this large capacity range. The size of the refrigerator is more or less proportional to the mass flow rate. The needed helium flow rate can be calculated from the specific heat (5.2 kJ/kg-K) and the chosen temperature change.

$$\dot{m}_{He} = \frac{\dot{Q}}{c_p \cdot \Delta T} = \frac{24\left[kW\right]}{5.2\left[kJ/(kg \cdot K)\right] \cdot \Delta T[K]} = \frac{4.6\left[kg/s\right]}{[K^{-1}] \cdot \Delta T[K]} \tag{1}$$

The freezing temperature of hydrogen is about 13.8 K. It seems wise to keep also the minimum temperature of the helium above this temperature. So it seems that one has the choice between a very large flow rate or a dangerous low minimum temperature of the helium indicated in the table below.

Table 1. Mass flow rate of helium and lowest helium temperature.

ΔT [K]	3	4	5	6	7	8
m_{He} [kg/s]	1.53	1.15	0.92	0.77	0.66	0.58
$T_{He,min}$ [K]	16.5	15.5	14.5	13.5	12.5	11.5

The way out of this dilemma is to choose a flow diagram, where the helium flow is used twice for the cooling of the hydrogen. One has the choice between flow diagrams A and B shown in Fig. 3:

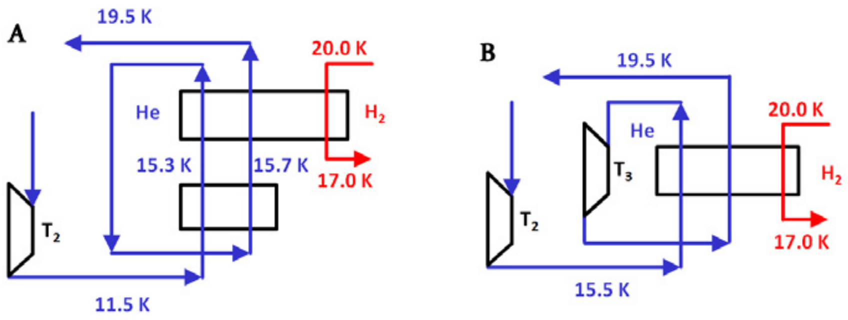

Fig. 3. Flow diagrams with double use of the helium stream in (A) two heat exchangers or (B) additional turbine.

In the left flow diagram A the helium comes from the refrigerator with a temperature of 11.5 K. In a co-current exchanger it is warmed to about 15.3 K, before it enters the He-H_2 exchanger, where it is warmed to 19.5 K. Then it returns to the co-current exchanger, where it is cooled to about 15.7 K before passing the He-H_2 exchanger a second time. In the right flow B diagram the helium comes from the refrigerator with a temperature of 15.5 K. It is warmed in the He-H_2 exchanger to 19.5 K. Then it is expanded in a turbine to 15.5 K, before passing the He-H_2 exchanger a second time.

Table 2. Comparison between flow diagrams A and B.

Flow diagram	A	B
Power consumption at maximum load	+ 14 %	
Main compressor	+ 33 %	
Investment	Additional co-current heat exchanger	One of the turbines near H_2 box
Transfer line	Both lines at 1.6 bar	One line at 5 bar, one at 2.3 bar

The comparison shows that flow diagram A needs a somewhat larger compressor, an additional heat exchanger, a somewhat larger transfer line and it has a 14 % higher power consumption. The flow diagram B has the disadvantage that the last turbine has to be placed close to the He-H_2 exchanger, which may be at a large distance away from the refrigerator cold box. To ease acceptance tests a separate turbine box could be arranged outside of the hydrogen cold box. Flow diagram B seems to be the better choice. The refrigerator must cope with the situation that the neutron heating falls from its maximum level to zero within a few seconds. Therefore the refrigerator has to reduce its cooling power from 24 kW to 4 kW very quickly. In the ideal case the helium refrigerator should be controlled in a way that the average temperature in the hydrogen loop does not change. If at full load the hydrogen loop has temperatures between 17 and 20 K, i.e. a mean temperature of 18.5 K, then at minimum load the temperature should vary between 18.25 and 18.75 K. The normal way to vary the refrigeration rate of a Brayton refrigerator is to reduce the helium inventory by directing a certain flow from the high pressure side to the medium pressure storage vessel. Thus all pressures in the cycle and the circulating flow rate and the turbine power are reduced. This is a relatively slow process. It is good enough for the scheduled increase or reduction of the accelerator power. But it is not fast enough in case of a sudden loss of neutron heating.

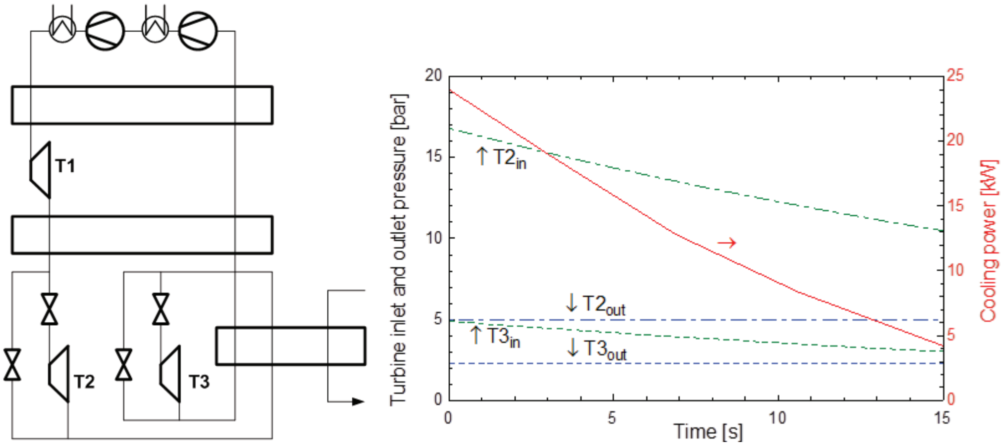

Fig. 4. Two turbines with throttle and bypass valves (left), reduction of the refrigeration rate by throttling in front of the turbines (right).

It is proposed to use a system (Fig. 3, B), where in such an event all cycle pressures and mass flow rates stay more or less constant and the turbine power is reduced by opening bypass valves around the lower two turbines and to reduce the flow rate and inlet pressures to both turbines by throttle valves in front of the turbines. Fig. 4 shows that the refrigeration rate can be reduced from 24 to 4 kW within about 15 s. The maximum rate of change of a turbine pressure is about 3 % of its actual value within 1 s. To guaranty a constant temperature at the inlet of the first He heat exchanger and therefore mitigate thermal disturbance a heater should be installed downstream of the He-H_2 heat exchanger.

5. Conclusion

A basic concept for a cryogenic hydrogen circulation system for neutron moderation of a 5 MW spallation source and preliminary boundary conditions has been developed. Future research has to be conducted by designing all components based on updated system parameters and validate their performance. In particular the transient characteristics during beam trips and loss of neutron heating is of interest to guaranty safe and specified operation combined with very high availability.

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