Cryogenic liquid H_2 heat pipe - possible application for ESS cold moderator

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Abstract. The European Spallation Source will have bi-spectral moderators using water at 300K and liquid H_2 at 20K. Heat pipes made of aluminium as structural materials and using liquid hydrogen at 15K were successfully tested for synchrotron at very low power. Based on this experiment, this paper presents a neutronic simulation and a thermal calculation to compare such heat pipes with the performances required for ESS cold moderator. Intrinsic limits of liquid H_2 heat pipes are also discussed.

1. Introduction

The ESS target station shown conceptually in Figure 1 performs 3 key functions in a spallation neutron source. It:

- transforms the proton beam radiation impinging on the heavy metal target into fast neutrons,
- transforms the fast neutrons emitted by the target into slow neutrons via moderators and reflectors,
- provides intense slow neutron beams to the neutron scattering instruments around the target.

ESS target station monolith contains mainly:

- the target itself, that performs the first function, is a rotating tungsten wheel, encapsulated in a stainless steel shroud and cooled by Helium flow,
- 2 neutron moderator, pre-moderator and reflector (PMR) systems that performs the second function,
- a beam extraction system for the third function,
- a thick cast iron shielding and safety containment barrier, protecting operators and neutron users from high level of radiation generated by the spallation process and its sub-products, the residual radioactive isotopes.

The main requirement for a target station is to perform these key functions safely and reliably. Therefore, to minimize the potential impact on the environment in all types of situations (normal to very unlikely off normal situations) must be considered from the very first step of the design process, in parallel with the goal to reach the best achievable scientific performance.

This paper presents the current PMR concept, after a neutronic optimization of the thermalized and cold neutrons output, and before any detailed engineering design, summarizes the main thermal parameters which will govern this design and explore an alternative solution (heat pipes) to remove the heat form this critical system.

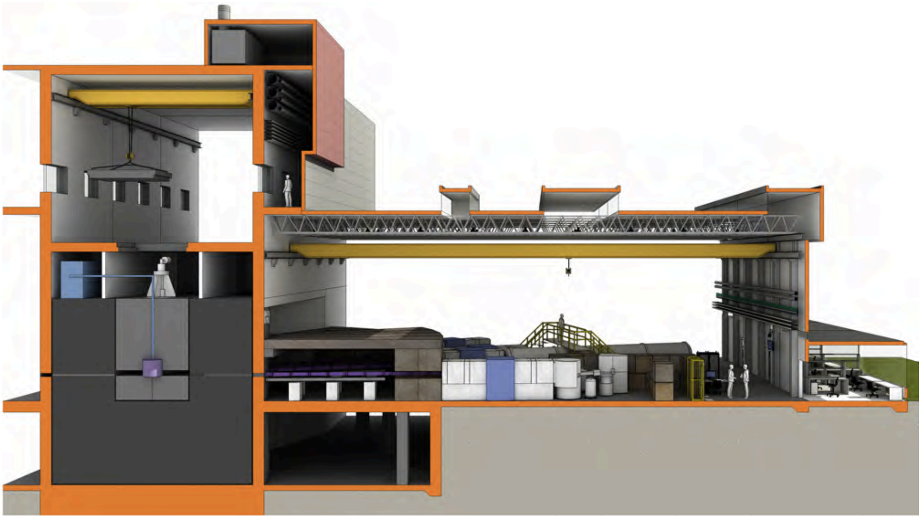

Figure 1: General conceptual layout of the target station. The target monolith is shown at the left, the moderator, premoderator and reflector unit is located in the centre of it. A representative neutron beam line serving a scientific instrument is on the right.

2. Moderator, pre-moderator, and reflector (PMR) description

The target station contains two premoderators, moderators and reflectors (PMR), located above and under the target hot spot where the fast neutrons are generated, as illustrated in figure 2 and figure 3.

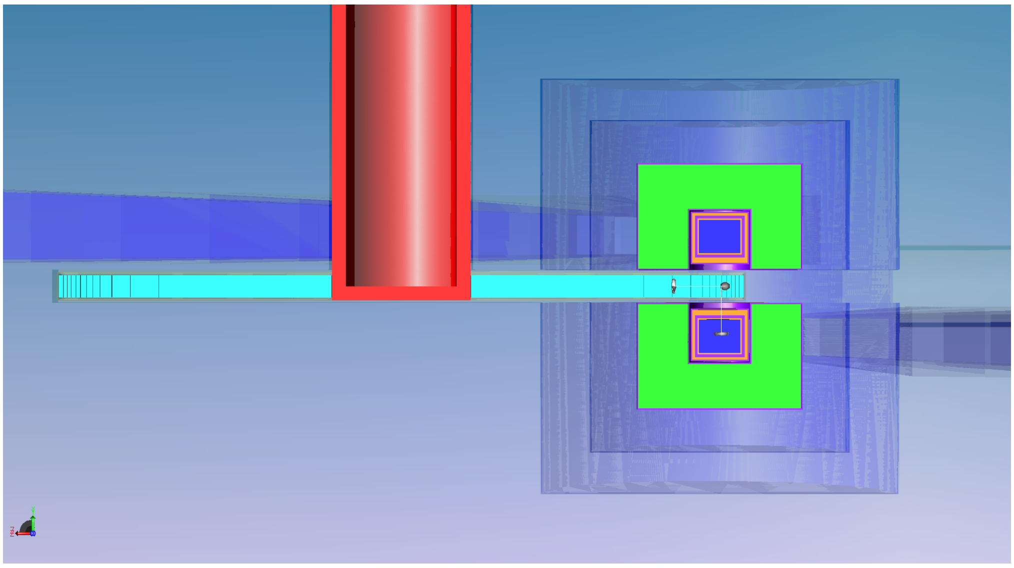

Figure 2: Vertical cut across the W Target wheel (light blue), liquid H_2 moderators (dark blue) and beryllium reflector (green). Openings for p+ beam and for neutron beam extraction can be seen on the right.

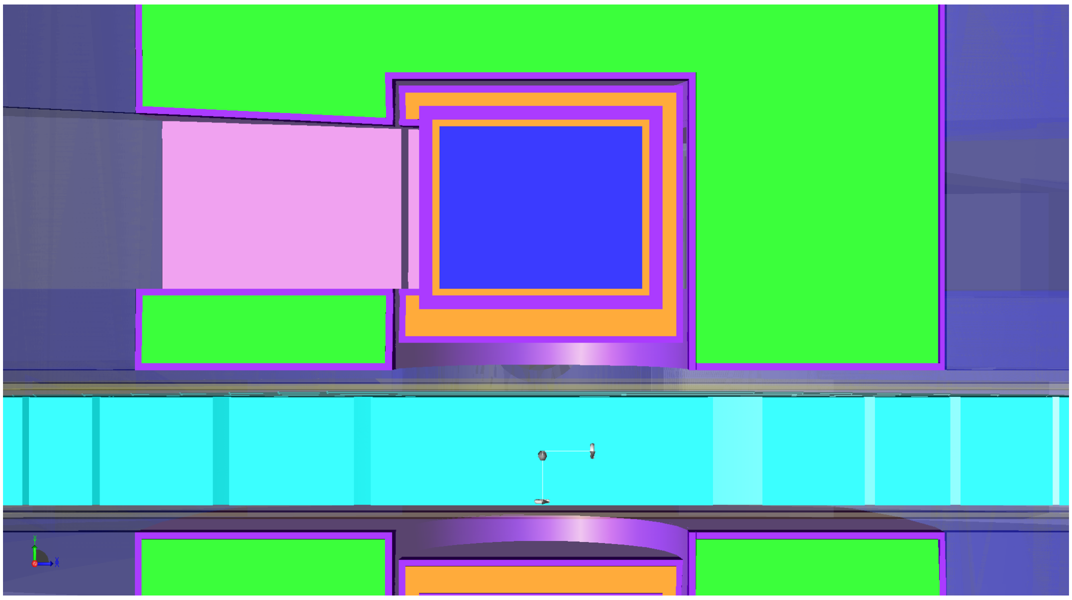

Figure 3: Zoom on the top moderator (blue), aluminium moderator container (orange), the vacuum gap (violet), the second aluminium premoderator container (orange) – Nota: the water layer in the premoderator is not shown on this figure.

Based on the ESS Target Station baseline [1], which is the collection of the main technical choices from which the more technical design to be performed all along 2012 by the ESS Target Station Design Update collaboration [2], the following neutronic optimization was performed [3]:

- The moderator is a cylinder of aluminium 6061-T6 (internal height 10 cm, internal diameter of 16 cm) filled with liquid para-H_2 at 20K,
- A premoderator is composed of liquid H_2O at 300K + few % of He, contained in an Aluminium 6061-T6 envelope (both thicknesses are 5 mm), separated form the moderator by a vacuum gap,
- The reflector is a cylinder of 80 cm of diameter, 80 cm of height, made of beryllium, with 2 opposite openings of 60° each, as shown is figure 4.

Additional details are available in [3].

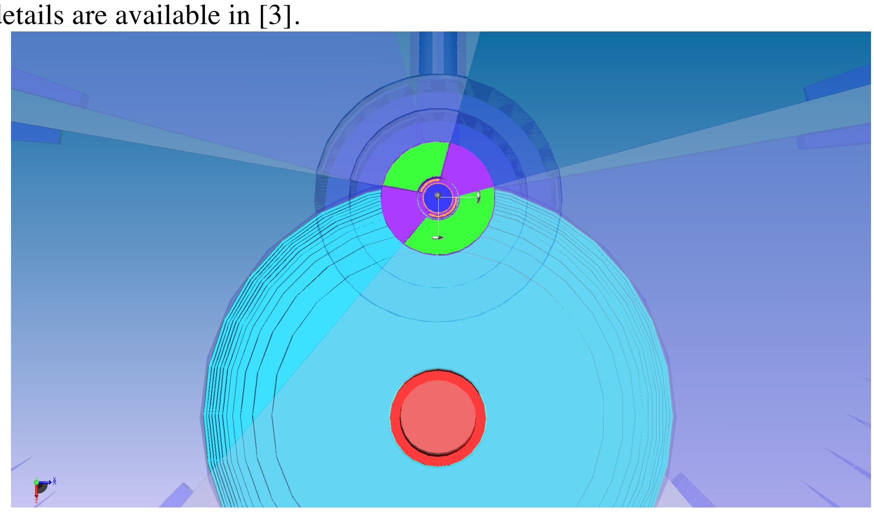

Figure 4: Top view on the top PMR and the target wheel, with openings for beam extraction, p+ injection opening is on the top.

3. PMR - energy deposition

Based on this preliminary neutronic design, an evaluation of energy deposition, summarized in table 1 below was performed [4].

Table 1. Engineering values for preliminary PMR design

Materials	Power density (W/cm^3)	Total Power (kW)
Liquid H_2	2.64	5.3
Aluminium	9.70	3.3

4. PMR – Basic fundamental design values

The cryogenic moderator mechanical design is a balance between primary stresses coming from the maximum pressure foreseen in the liquid H_2 (aiming at increasing the container thickness) and the thermal stresses (secondary) generated by the power deposition in it.
Prior to any detailed design (currently starting within the TSDU collaboration) and based on a geometry consistent with the neutronic optimization, the basic following PMR characteristics can be deducted from table 1, taking into account 6061-T6 properties given in [5].

Table 2. Preliminary PMR design - Cold moderator

Container	Al 6061-T6 at 20K	Comments
Nominal pressure	1.5 MPa	
Allowable primary stress	242 MPa	[5] Primary
Minimal thickness	0.5 mm	Cylindrical zone
Allowable stress (primary/total)	87 MPa/261 MPa	[5] - Incl. temperature transients
Al. thickness selected value	2.1 mm	
Estimated thermal stress (primary total)	57 MPa/138 MPa	In cylindrical zone
Maximum ratio between max stress and av. stress in cylinder	2	To adapt fabrication constraints and cylinder/plate connection

The minimum thickness required, to withstand pressure in the cylindrical part of the cold moderator is very low (0,5 mm), generating very low thermal stresses (4.5 MPa).

Choosing a thickness of 2.1 mm in this zone would allow to keep the total stress (due to pressure and thermic load) below 140 MPa. This total stress shall be limited to 3 times the maximal allowable primary stress (87 MPa), for all thermal transients between operating temperature and room temperature. In addition, this thickness gives a factor 2 between the stress in the normal cylindrical zone of the moderator and any local maximal stress in it (e.g. connection between cylinder and flat bottom plate), which is achievable by appropriate design.

5. Liquid H_2 circuit

According to [4], power deposition in liquid H_2 and its aluminium container is 8.6 kW per moderator. Limiting the temperature increase between inlet and outlet of the cold moderator would require a minimum H_2 mass flow of 0.2 kg/s (per moderator), given:

- a minimum margin of 3K to the saturation curve at 1.5 MPa,
- not taking into account the thermal losses in the cryogenic hydrogen circuit.

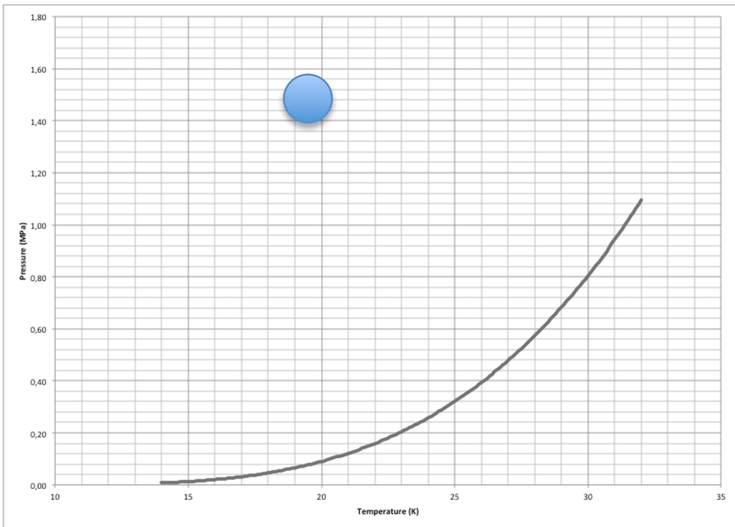

Figure 5: Saturation curve of H_2 around 20 K – ESS cryogenic moderator operating point

The global H_2 quantity estimated for such a circuit is estimated to more than 10 Nm^3.
Although several solutions are considered to reduce the volume of liquid H_2 (natural convection loop or reduction of operating pressure), such solutions will not reduce drastically the H_2 inventory.
The risk and system complexity related to such a system could fruitfully be reduced by using a passive heat dissipation system in the neutron production zone.

6. Heat pipes characteristics for the cryogenic H_2 moderator zone

It is proposed to replace the flowing H_2 by vertical H_2-aluminium heat pipes (HP), with a length of approx. 50 cm, packed in an equivalent cylinder. The evaporator part of the heat pipes would be the neutronic moderator while the condenser part would exchange the power with a liquid or gaseous intermediate circuit.
This paper only considers the thermal capacity of such heat pipes in the evaporation zone, considering the condenser would be located in a less constrained location in the PMR plug.
The required characteristics for ESS cold moderators are summarized in table 3 and compared with tested cryogenic H_2 - steel heat pipe for COSY [6].

Table 3. LH_2 –Aluminium heat pipe requested performances vs. tested

Materials	ESS cryo moderator	Tested for COSY [6]
Internal diameter	5 mm	5 mm
Fluid	H_2 at 20K 50% void	H_2 at 20K 50% void
Wick thickness	0.1 mm	0.1 mm
Wick material	Aluminium	Steel
Axial flux	4.2 W/pipe	1 W/pipe
Axial flux density	19.5 W/cm^2	100 W/cm^2
Radial flux in evaporator	0.26 W/cm^2	0.13 W/cm^2
Number of heat pipes	# 1000	-

According to [6], an operational limit for a classic 20K H_2 heat pipe is total axial power which could be transmitted (around 1 W/pipe). This is a strong limitation to use such classic heat pipes for ESS moderator which requests 4 times more.

7. Prospective

Classic heat pipes do not fulfil the ESS requirements for cryogenic moderators.
One possibility would be to replace heat pipes by Oscillating Heat Pipes (OHP - see figure 6) which have an efficiency of 1 or 2 order of magnitude higher than classic heat pipes [7].

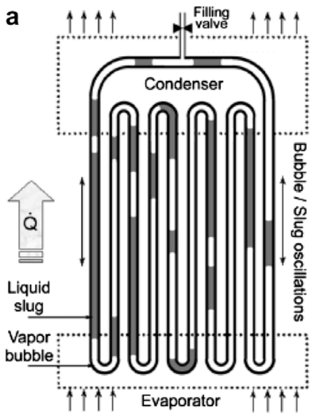

Figure 4: Top view on the top PMR and the target wheel, with openings for beam extraction, p+ injection opening is on the top.

Using heat pipes solution to evacuate power deposition from the cryogenic moderator could be used to:

- Suppress the liquid H_2 circuit connected to the moderators,
- Adapt, by design, the operating temperature profile inside a multi layer cryo moderator structure, using different distribution of reflecting materials.

8. Conclusions

Classic heat pipes do not fulfill the ESS requirements for cryogenic moderators.

For our geometry, a rough neutronic estimation shows the neutronic performances would scale the H_2 density, which is essentially governed by void fraction in the heat pipe. Typically, the optimum liquid fraction is around 50%, but some results show that HP with higher liquid fraction could be used and still fulfilling the moderators thermal performance requirements.
Further investigations should be conducted to evaluate and test such OHP for the ESS cryogenic moderators.

References

[1] ESS TSDU report 1166507 v2 - Target Station Baseline
[2] ESS TSDU document 1184366 v1 - Project Specification for ESS Target Station Design Update Project
[3] ESS TSDU report 1183355 v1 - Initial model of MCNPX for ESS bispectral moderators
[4] ESS TSDU report 1183827 v1 - Assessment of heat deposition and radiation damage in the monolith
[5] NASA NSS 1740.16 Safety standard for hydrogen and hydrogen systems
[6] 6th Conference on Nuclear and Particle Physics 17-21 Nov. 2007 Luxor, Egypt A thin gold coated hydriogen heat pipe – cryogenic target for external experiment at COSY
[7] IEEE Transaction on applied superconductivity, Vol. 20, N° 3, June 2010 - Development of Highly Effective Cooling Technology for a Superconducting Magnet Using Cryogenic OHP