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Conceptual design of a high intensity liquid ortho-deuterium moderator for the European Spallation Source

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Abstract. The European Spallation Source (ESS) in Lund, Sweden, is designed to become the most powerful accelerator driven spallation neutron source in the world. ESS is currently under construction. The first beam on target is planned for 2025, with first user operation expected to start in 2026. As a key component of the neutron production, the cryogenic moderator slows down high-energy neutrons released from the spallation target. In the framework of a European funded research project (HighNESS), the next generation of ESS cold moderators were investigated [1]. The first, already built, cryogenic moderator for ESS was designed for high brightness, using para-hydrogen as a moderator material. For future developments of ESS, an additional cryogenic moderator is foreseen. In contrast to the first moderator, the new moderator is optimized for high neutron intensity, which is why liquid ortho-deuterium was chosen as a moderator material. The intensity of the presented liquid ortho-deuterium moderator is about 3-4 times higher than the existing so-called low-dimension para-hydrogen moderator. This opens up the possibility of providing significantly more neutrons to the users within the existing infrastructure, resulting into better research results. This paper describes the conceptual design of such a liquid ortho-deuterium moderator system for ESS including mechanical design, manufacturability verification, definition of fluid parameters, cooling process conceptual design and integrability verification.

1. Introduction

The first generation of ESS moderators consists of only a liquid para-hydrogen low-dimensional moderator, located above the tungsten target wheel [2]. However, the moderator support structure, which must be twisted in and out when it needs to be replaced and is therefore also called Twister, allows to use also the space below the target wheel for future moderator upgrades. **Figure 1** shows an isometric view of the ESS Target Monolith. The component highlighted in red is subject of the planned upgrades.

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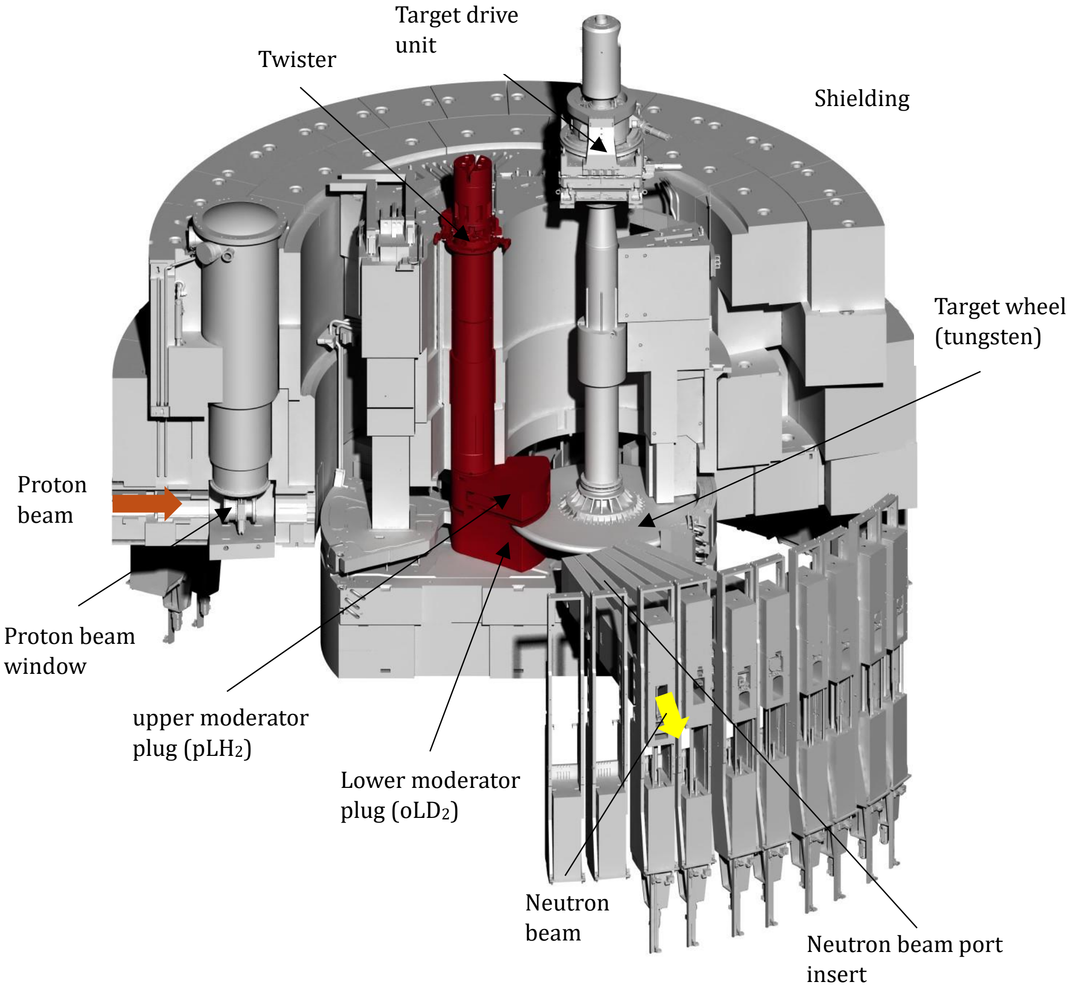

Figure 1. ESS Target Monolith, the Twister highlighted in red is subject of the moderator upgrade. The space below the Target wheel is currently not used. The area above the Target wheel is used for the liquid para-hydrogen low-dimensional moderator [3]

The goal of this study is to develop a cold moderator system that provides a high brightness neutron beam using the existing liquid para-hydrogen low-dimensional moderator and at the same time, to provide a high intensity neutron beam using the foreseen ortho-deuterium volume moderator, which is the main subject of this upgrade. The users can then freely decide which moderator they would like to use for their individual experiment.

The existing cryogenic moderator infrastructure at ESS was designed for hydrogen moderators only [4]. The main engineering challenge is therefore to find a technical solution to integrate a completely new cryogenic infrastructure for the liquid deuterium moderator into the existing neutron source. In addition, the moderator support structure was also not designed for containing a large deuterium moderator. This is why the integrability into the given Twister needs to be verified. The reason is that the dimensions of the Twister cannot be changed in the future due to the surrounding permanent shielding of the target station monolith (see **Figure 1**). Ultimately, a large volume also means a large amount of heat caused by particle interactions, which makes the design of the moderator vessel itself challenging. A first concept that addresses the main challenges mentioned above is presented here.

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2. Design parameters

The main fluid parameters of deuterium are defined in the following chapter, as these are required for the conceptual design of the liquid deuterium (LD_2) moderator upgrade. A neutron moderator is usually made of aluminum because aluminum is almost transparent for cold and thermal neutrons and therefore the moderated neutrons are able to escape the moderator vessel without being absorbed. To guarantee the mechanical stability of thin-walled aluminium moderator vessel, an operation pressure of 5 bar was chosen. Deuterium solidifies at the chosen pressure at a temperature of approximately 19 K and vaporizes at approximately 30 K, which defines the temperature range in the liquid phase for the moderator system. In order to avoid freezing during operation, the minimum temperature at the outlet of the heat exchanger of the deuterium liquefaction cryostat (see **Figure 2**) is set to 20 K. Furthermore, it is assumed that additional heat load from the circulation pumps and insulation losses increase the deuterium temperature by about 1 K before it arrives at the moderator inlet. The average temperature increases in the moderator caused by particle heat of up to 60 kW [1] is required to be less than 3 K, which means that the average outlet temperature will be around 24 K. As a result, there is still a safety factor for local temperature peaks due to the pulsed proton beam of approximately 6 K before the deuterium evaporates.

The mass flow can be estimated by using the chosen operating pressure, the inlet- and outlet-temperature and the heat load. A mass flow of at least 3400 g/s of liquid deuterium is needed to remove the enormous heat load caused by particle interactions and to keep the average temperature increase below 3 K. Assuming a flow velocity of ≤ 5 m/s, an inner pipe diameter of 70 mm would be required, which must fit into the existing Twister structure. **Table 1** summarizes the main deuterium operation parameters.

Table 1. Summary of preliminary liquid deuterium operation parameters

Name	Value	Unit
Deuterium volume	≈30	l
Ortho content	≥99	%
Heat load moderator	≈60 (max)*	kW
Total heat load	≈70 (max)*	kW
Average pressure	5	bar
Average density	173.8	kg/m^3
Flow velocity	≈5	m/s
Average mass flow	≥3400	g/s
Average temperature	22.5	K
Average temperature increase	≤3	K
Pipe inner diameter	70	mm

*See summary & outlook

3. Cooling process concept design

With the defined fluid parameters, a simplified P&ID was created as shown in **Figure 2**. The process and instrumentation diagram of the cryogenic deuterium moderator system (CDMS), is a graphic view of the system consisting of the helium refrigeration system (TMCP II) with 75 kW cryo-power at 20 K, the deuterium liquefaction cryostat (CDMS Cold Box), which is comparable to the existing hydrogen liquefaction cryostat [5] at ESS, and the Twister with the lower moderator plug used for the deuterium moderator upgrade. The Twister is the only component of the CDMS that is located inside the radiation area of the neutron source. Furthermore, the helium transfer lines (HTL), which interface the TMCP II with the Cold Box and the deuterium transfer lines (DTL), which interface the Cold Box with the Twister complete the CDMS.

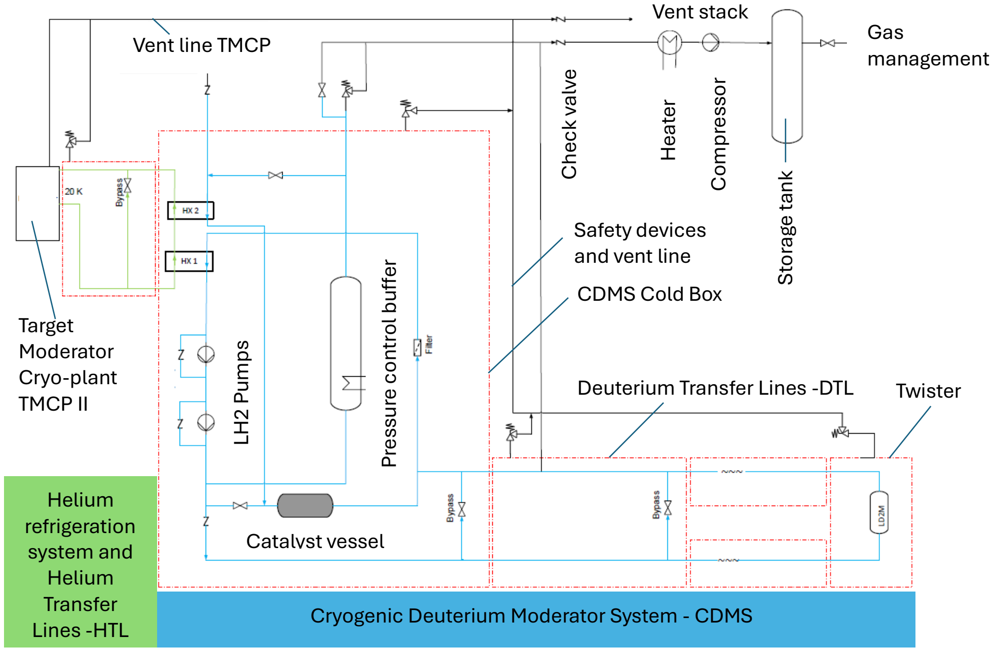

Figure 2. Simplified P&ID of Cryogenic Deuterium Moderator System CDMS

The TMCP II provides the required cooling to the CDMS Cold Box to liquify the gaseous deuterium and to remove the static and dynamic heat loads during operation. For this, gaseous helium is pumped in a closed loop at a temperature of 20 K via the helium transfer lines to the CDMS Cold Box heat exchanger and back to the TMCP II. The main components of the CDMS Cold Box itself are the heat exchanger, the circulation pumps, the ortho–para catalyst vessel and the pressure control buffer. The circulation pumps are installed in the CDMS Cold Box to supply the moderator with the liquefied deuterium in a closed circuit. In addition, the natural conversion of para-deuterium to ≥99% ortho-deuterium is accelerated by using a catalyst in the cryostat. A high ortho content is needed since it has better moderator properties and a higher heat conductivity. An active heated pressure control buffer is also installed in the cryostat to compensate pressure changes caused by the pulsed proton beam and beam trips. The CDMS Cold Box provides the needed LD_2 to the moderator via the DTL, where the deuterium is heated up and returned to the heat exchanger to cool the deuterium down again. In addition, a storage tank for the deuterium will be necessary since deuterium produces tritium under irradiation. Therefore, the deuterium cannot be vented like hydrogen when incidents occur, or maintenance work needs to be carried out. For this reason, it is foreseen to heat up the deuterium and then feed it into the storage tank using a heater and compressor. Then, when the system shall return to operation, the deuterium can be refilled into the CDMS. The size of the storage tank is determined by the total inventory of the circuit, cryostat and moderator, which must be kept as small as possible for safety and costs reasons. Therefore, it is very important to place the CDMS Cold Box as close as possible to the moderator to reduce the total amount of deuterium. Since selecting the final location of the CDMS components based on the available options was not possible within the framework of this design study, this will be necessary in the final design phase. The estimation of the total deuterium inventory and with that the estimation of the storage tank size were due to the unknown locations of the CDMS components also not possible at this time.

4. Moderator design

The target geometry of the moderator vessel for the engineering design resulted from the particle transport simulations, performed by ESS neutronic team, using Monte-Carlo N-Particle Transport Code (MCNPx) [1]. The result with the best neutronic performance including particle heat was used for the presented engineering design, shown in **Figure 3**.

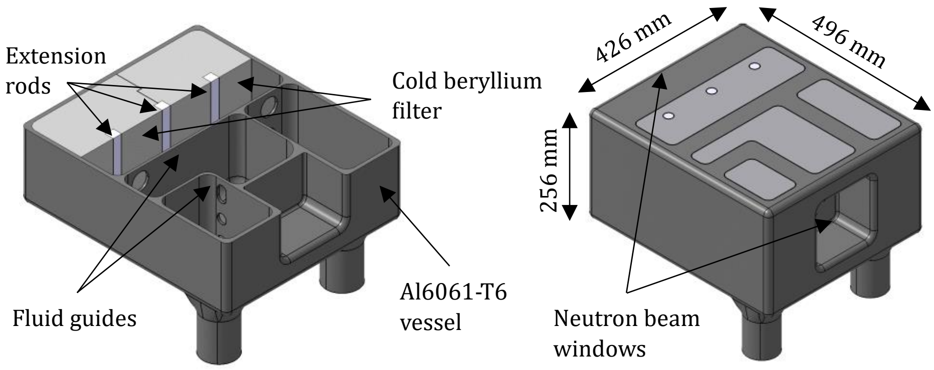

Figure 3. Preliminary engineering design of the LD_2 moderator

The major engineering challenge here is to handle the enormous heat load of around 60 kW. Several iterations led to the preliminary engineering design of the LD_2 moderator, shown in **Figure 3**. The moderator vessel will be made of high-strength aluminium alloy Al6061-T6, which allows local stresses up to 87 MPa in the not heat effected zones and 55 MPa around welds of the vessel according to the RCC-MRx code [6]. The high strength values of the alloy are given by the tempering process (T6), which allows thinner wall thicknesses of the moderator vessel, compared to non-temperable aluminum alloys. Another reason for the material choice is long operating experience under irradiation. All design criteria, from the structural mechanics point of view, according to the RCC-MRx code are fulfilled with the presented design [1].

The moderator will be surrounded by a vacuum jacket followed by a light water pre-moderator and a warm beryllium reflector around. In addition, a cold beryllium filter is installed inside the cold moderator vessel. The fluid guides ensure that flow separation, dead areas and swirls do not occur. The extension rods ensure additional mechanical stability since the vessel walls are flat and need to be as thin as possible to minimize neutron losses. The moderator will be milled, and partially Electrical discharge machined (EDM) from a solid block, and the cover will be finally welded to the main body with electron beam welding to minimize distortion.

5. Summary & outlook

A liquid deuterium moderator system for the ESS appears feasible from the engineering point of view. It could be shown that a volume moderator, including all necessary process lines, can be integrated into the existing Twister structure under the given limitations. Furthermore, the design shows that the moderator can withstand all mechanical loads [1] and that manufacturing and welding, although very complex, seems possible. The cooling process concept design shows all extra infrastructure needed to realize such a moderator upgrade. A key point is to reduce the deuterium inventory as much as possible. On the one hand, this can be done placing the cryostat as close as possible to the moderator and, on the other hand, by reducing the heat load. The reduction of the heat load is also decisive from a thermomechanical point of view, in order to be able to use the presented moderator at full proton beam power. However, the first optimizations have already shown that the separation of the cold beryllium filter already leads to significant improvements. In contrast to the shown box shaped moderator (worst case), slightly shaped vessel walls would allow thinner walls, which means that less heat is generated (heat caused by particle in aluminium is about 3-4 times higher than in deuterium) and the neutronic performance of the moderator is improved as well.

The Twister assembly has a radiation-related lifespan of 14 months at full beam power and must then be replaced [7], since the permissible radiation of the Al6061-T6 components in the Twister of ≤40 dpa is reached after this period. Replacing of the Al6061-T6 components and reuse the remaining Twister support structure made of stainless steel is also not possible at reasonable costs, due to the strong activation, which is why the entire component must be replaced regularly. However, this opens up the possibility to continuously optimize and further develop the moderator system at ESS and to be able to implement always the newest developments promptly into the source. Due to this possibility, in addition to the presented liquid deuterium moderator concept, initial considerations for the following moderator generation are already being made, that contains very cold neutron (VCN) moderators based on solid deuterium for example [8].

References

[1] V. Santoro, O. Abou El Kheir, D. Acharya, M. Akhyani, K.H. Andersen, J. Barrow, P. Bentley, M. Bernasconi, M. Bertelsen, Y. Beßler, A. Bianchi, et al. (2023): HighNESS Conceptual Design Report, physics.ins-det, DOI: 10.48550/arXiv.2309.17333

[2] Y Bessler, C Henkes, F Hanusch, P Schumacher, G Natour, M Butzek, M Klaus, D Lyngh and M Kickulies (2017): Final design, fluid dynamic and structural mechanical analysis of a liquid hydrogen Moderator for the European Spallation Source, IOP Conference Series: Materials Science and Engineering, DOI: 10.1088/1757-899X/171/1/012131

[3] Roland Garoby, A Vergara, H Danared, I Alonso, Y Bessler, et al. (2018): The European Spallation Source Design, Physica Scripta, DOI: 10.1088/1402-4896/aa9bff

[4] Y. Beßler, G. Natour (2022): Cryogenic hydrogen Moderator infrastructure at ESS, Journal of Neutron Research, DOI: 10.3233/JNR-220033

[5] Y Beßler, M Klaus, C Henkes, G Natour and J Ringnér (2018): The Cryogenic Moderator System Cryostat Design for the European Spallation Source, Journal of Physics: Conference Series, DOI: 10.1088/1742-6596/1021/1/012080

[6] AFCEN. RCC-MRx DESIGN AND CONSTRUCTION RULES FOR MECHANICAL COMPONENTS OF NUCLEAR INSTALLATIONS. 2012 Edition. Lyon : AFCEN, 2012. ISBN: 2-913638-40-6

[7] M Kickulies, Y Beßler, Y Lee and D Lyngh (2018): Lifecycle of the ESS Moderator and Reflector System, Journal of Physics: Conference Series, DOI: 10.1088/1742-6596/1021/1/012069

[8] Nicola Rizzi, Ben Folsom, Mina Akhyani, Mads Bertelsen, Peter Böni, Yannick Beßler et al. (2024): An intense source of very cold neutrons using solid deuterium and nanodiamonds for the European Spallation Source, Nuclear Instruments and Methods in Physics Research Section A, DOI: 10.1016/j.nima.2024.169215