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Design, manufacturing & installation of the high brightness liquid para-hydrogen moderator for the European Spallation Source (ESS)

Yannick Bessler[1]*, C. Happe[1], Eberhard Rosenthal[1] and Ghaleb Natour[1,2]

[1]Forschungszentrum Juelich GmbH, Institute of Technology and Engineering, (ITE), Juelich, Germany
[2] ISF Faculty of Mechanical Engineering, RWTH Aachen University, Aachen, Germany

*E-mail: y.bessler@fz-juelich.de

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, and the first beam on target is planned for the beginning of 2026, with first user operation expected to start in 2026. As a key component of the neutron production, which was developed, built and tested at the Institute of Technology and Engineering, (ITE) of Forschungszentrum Juelich GmbH, the cryogenic moderator slows down high-energy neutrons released from the spallation target. To gain maximum neutron brightness for condensed and soft matter research, an optimized low dimension liquid para-hydrogen moderator has been developed. Hydrogen with a pressure around 10 bar, a temperature around 20 K and a para-hydrogen fraction of at least 0.995 will be utilized to interact with neutrons in a unique moderator vessel arrangement. This paper describes the engineering design, manufacturing and installation of the low dimension liquid para-hydrogen moderator for the ESS.

1. Introduction

The particle accelerator at ESS is a 600 m long linear proton beam accelerator. The ion source feeds protons into the accelerator channel, in which the protons are accelerated to almost the speed of light. The protons are pulsed with an average beam power of 5 MW (design value, currently 2 MW installed), a pulse length of 2.86 ms and a pulse frequency of 14 Hz **[1]**. This long-pulse source delivers approx. $8.9 \cdot 10^{14}$ protons per pulse. The protons exit the accelerator through the proton beam window and hit the helium-cooled, rotating tungsten target, see **Figure 1**. The impact of the protons triggers the spallation reaction, leading to a release of 20–30 neutrons per incoming proton. The neutrons leave the target at an average speed of about 10% of the speed of light. To use these neutrons for scattering experiments, they must first be slowed down (moderated). In the first moderation step, the neutrons are thermalized in a light water moderator. The thermal neutrons can then be used directly or further moderated to a lower energy. For this purpose, a cold moderator, a pressure vessel filled with liquid para-hydrogen, is used. To increase the efficiency of the moderation, a beryllium reflector is installed above the moderators. The moderator- and reflector-unit is surrounded by a stainless-steel support structure that serves for positioning and handling of the components described.

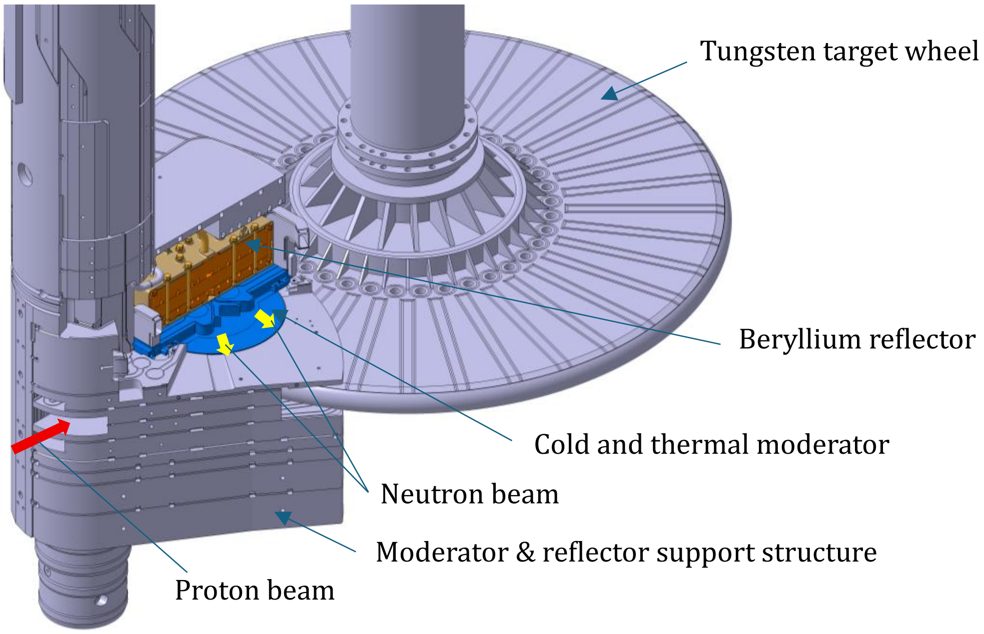

Figure 1. ESS moderator & reflector plug MRP (left) with tungsten target wheel (right). The moderator is highlighted in blue and the Beryllium reflector in orange.

In this paper the optimized second cold moderator, the so-called butterfly 1 moderator (BF1) will be described in detail. Information about the first ESS cold moderator can be found in **[2]**.

2. Engineering design of ESS cold moderator (BF1)

This chapter describes the final engineering design solution of the BF1 moderator, **[3]**. **Table 1** summarizes the main design parameters of it:

Table 1. Summary of design parameters

Parameter	Value	Unit
Para-hydrogen content	≥99.5	%
Heat load moderator	7.1	kW
Operation pressure	10	bar
Average mass flow	≥420	g/s
Average temperature	20	K
Inlet temperature	18.5	K
Average temperature increase	≤3	K
Moderator vessel material	Al6061-T6	

2.1 Computer aided design of cold moderator (BF1)

The first step in the development of cold moderators is the particle-physics optimization of the geometry as part of parameter studies carried out by the Neutronic team of ESS. The aim here was to slow down as many neutrons as possible released by the spallation target to the required cold energy range and guide them to the scattering instruments. This resulted in the so-called butterfly design (BF1), which is shown in **Figure 2**. This consists of a 1 l liquid para-hydrogen volume surrounded by an aluminium shell. As the hydrogen and the aluminium shell are continuously heated up by the particle interactions, the hydrogen must be circulated and the heat must be dissipated via heat exchangers to a helium cryo-plant, see **[4]** and **[5]**. To ensure an almost homogeneous temperature in the moderator, good flow conditions and heat transfer properties are important, especially in the butterfly-shaped structure. The flow must therefore be directed in such a way, that no large areas of recirculation and flow separation occur.

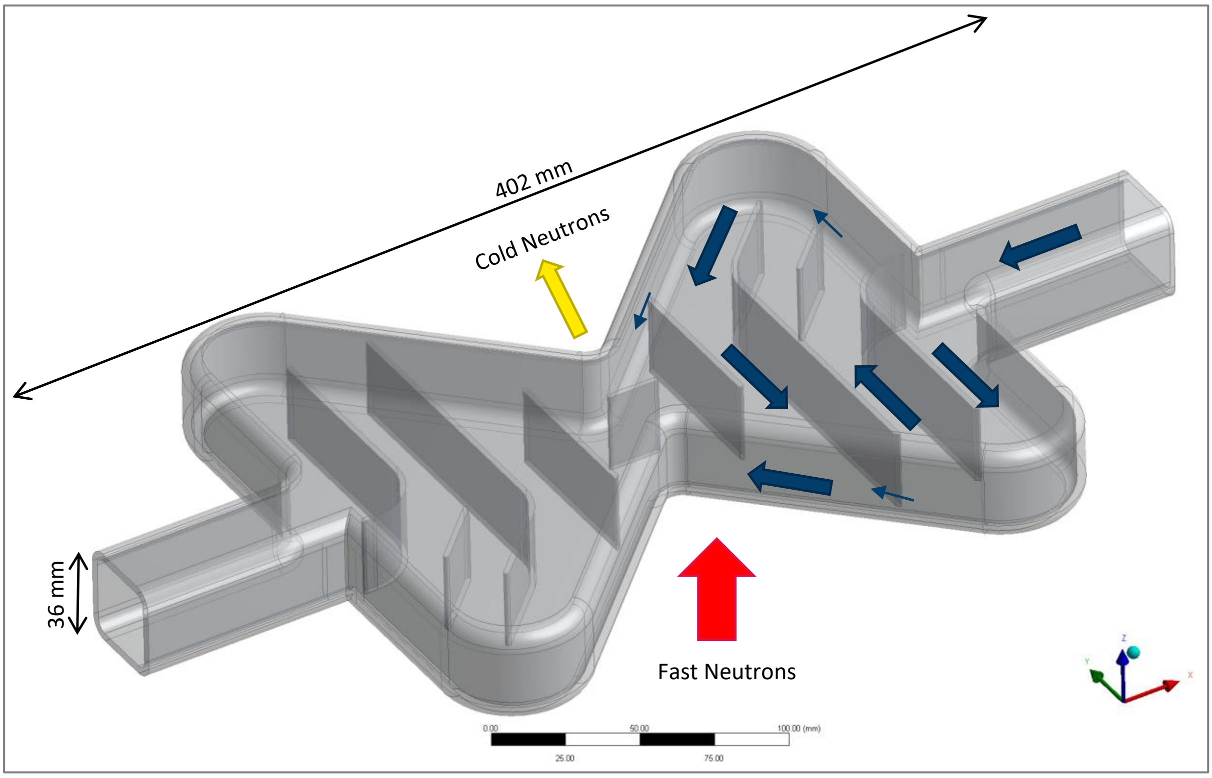

Figure 2. Design and dimensions of ESS low dimension liquid para-hydrogen moderator (BF1)

For these reasons additional guiding structures inside the moderator volume are needed. However, these are associated with losses in neutronic performance, because neutrons are absorbed. In addition, the volumetric heat flux density in aluminium is around four-times higher than in hydrogen. In this respect, the lowest possible proportion of inner structural material and sufficient heat transfer from aluminium to hydrogen are important factors in the design.

The fluid guide plates were modelled on a channel flow, in which an attempt was made to position the guide plates in such a way that the cross-section was as constant as possible (30 x 30 mm^2). To avoid dead zones, bypasses were also required (small arrows in **Figure 2**), which guide a partial flow (approx. 10% of the main flow) through the sharp corners.

2.2 Fluid dynamic design of cold moderator (BF1)

The main purpose of the flow simulation is to optimize the flow pattern, so that the hydrogen dissipates heat optimally without evaporating. Furthermore, the temperature and pressure fields are required as boundary conditions for the subsequent mechanical simulation, see chapter 2.3. **Figure 3** shows the resulting temperature curve as a function of the proton beam power, pulse frequency and a pulse length.

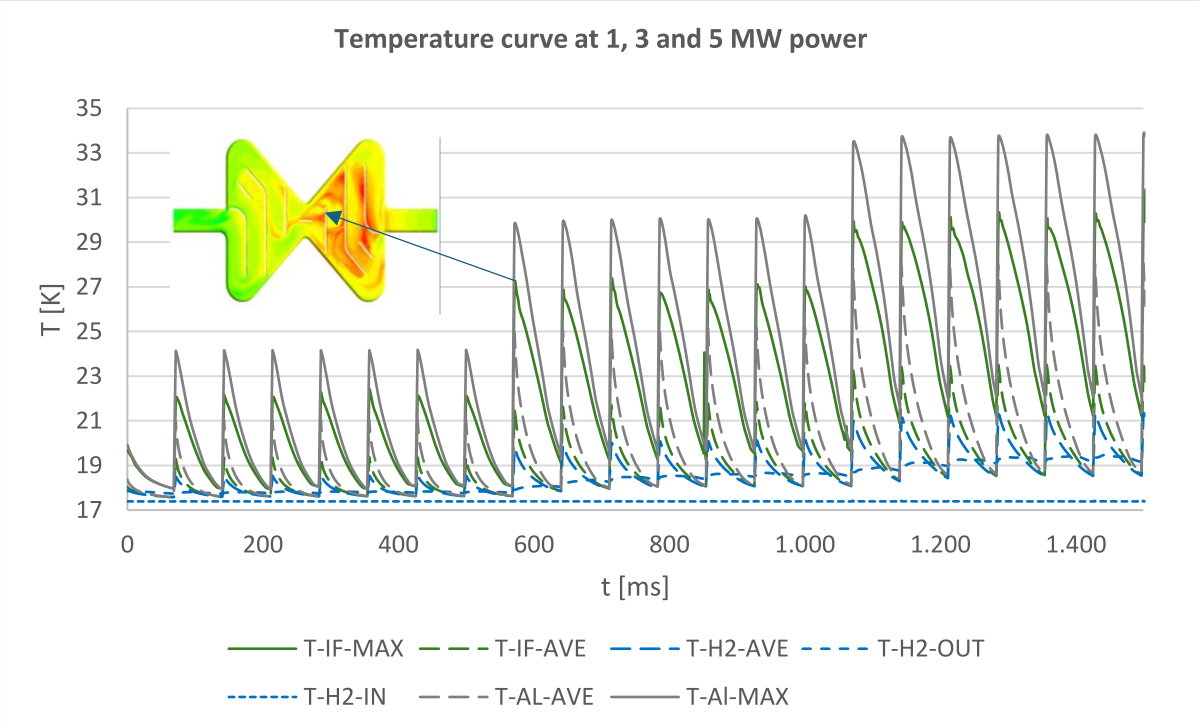

Figure 3. Temperature curves at an average proton beam power of 1 MW (0.0≤t≤500 ms), 3 MW (500≤t≤1000 ms) and 5 MW (1000≤t≤1500 ms). Plotted are aluminium (Al), interface (IF) and H_2 temperatures

The average and maximum temperature in the aluminium (T-AL-AVE and T-AL-MAX) and in the first boundary layer (T-IF-AVE and T-IF-MAX) are plotted, as well as the average (T-H2-AVE), the inlet (T-H2-IN) and the outlet temperature (T-H2-OUT) of LH_2.

In general, the temperature curves are stable over time. The same temperatures are always reached in both the cooling- and warm-up phases. A gradual temperature increase due to a too short cooling phase between the consecutive heat pulses can therefore be ruled out. Also, the boiling temperature of hydrogen, which is T_s(p=10 bar)=31.2 K is not reached, even at 5 MW. However, the peak temperature in the first boundary layer (T-IF-MAX) at 5 MW is already 30.2 K without considering the simulation uncertainties. With uncertainties a beam power of about 4 MW would already lead to local boiling of hydrogen, which means that the goal of 5 MW would not be possible under the given requirement **[3]**.

However, the ESS will not directly start with 5 MW beam power and many of the uncertainties are related to the particle transport simulation and to the operation of the proton beam accelerator, that can be more precisely verified by operational experience at lower beam power. In addition, the main flow is well subcooled, even when a small amount of hydrogen locally exceeds the boiling temperature, which is why the requirement that no boiling is allowed should be discussed further.

2.3 Structural mechanics of cold moderator (BF1)

The design guideline used for the mechanical design of the BF1 is the French nuclear code RCC-MRx **[6]**, which contains design and construction rules for mechanical components of nuclear installations. The moderator vessel is made of the tempered aluminium alloy Al6061-T6. It contains of two halves welded together. The reduction of the permissible stress S_m in the heat affected zone of the welds must therefore be considered. The design criteria are: 1) the membrane stress P_m should not exceed S_m, 2) the local membrane stress P_L should not exceed $1.5 \cdot S_m$, and 3) the sum of local membrane stress and bending stress P_L+P_b should be less than $1.5 \cdot S_m$. For Al6061-T6 the values are S_m=87 MPa and for welds S_{mW}=55 MPa, see **Figure 4**.

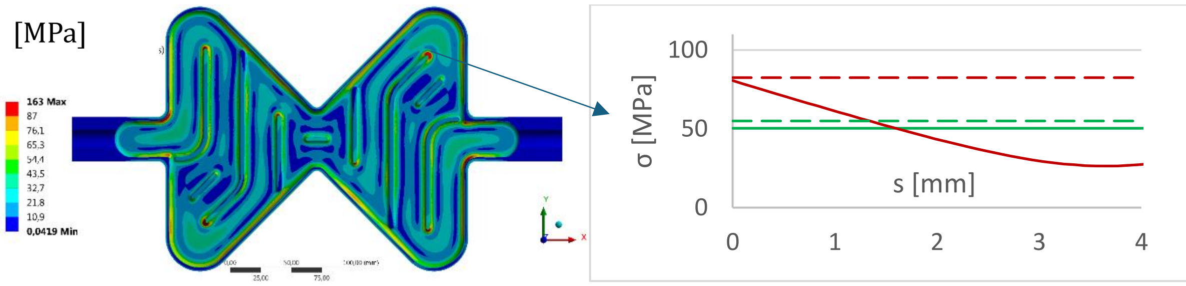

Figure 4. Von Mises stress distribution (left) and linearized membrane (green) and bending (red) stresses (continuous lines) and limit values (dashed lines)

The fatigue utilization percentage is in the present case <1, as it can be seen in **Figure 5** (red cross). Therefore, the criterion for avoiding fatigue failure is fulfilled as well.

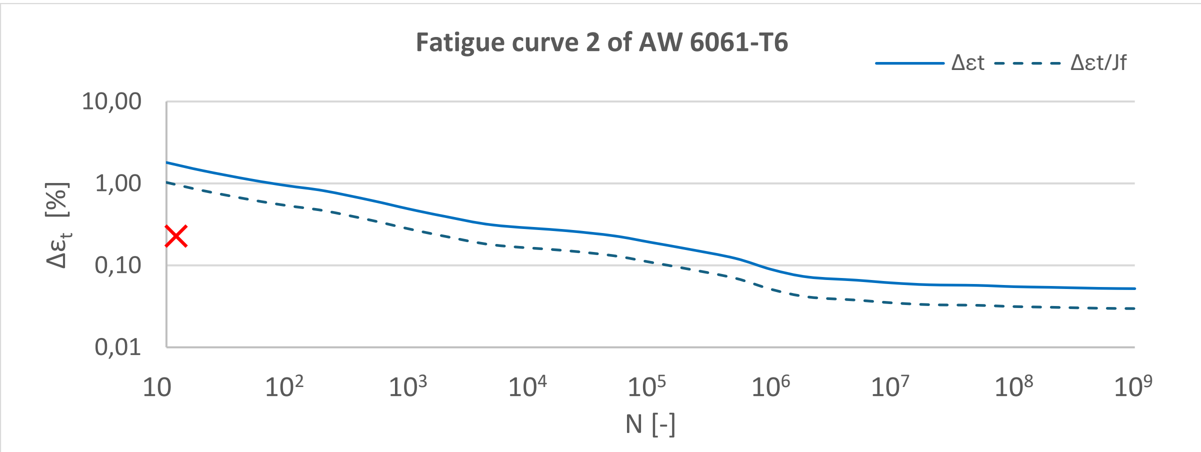

Figure 5. Fatigue curve of AW 6061-T6 at 20 to 125°C (continues) and for weld seams (dashed) taken from **[6]**

The mechanical design of the BF1 moderator, based on the RCC-MRx code, has shown that the pressure vessel can be used in the specified form, as it fulfills all strength criteria. Even if some material data had to be taken from another source, it can be assumed that the pressure vessel will withstand the operating conditions due to the conservative assumptions and the selection of the very high design pressure (1.7 times the operating pressure). It was shown that the pressure load dominates. The secondary stresses, caused by the thermal loads, are very low. In addition, the fatigue of the aluminium vessel is not critical due to its relative short lifetime of 13 month at full proton beam power of 5 MW, caused by radiation. **[3]**

3. Cold moderator manufacturing & testing

The moderator is prepared from two milled halves made of Al6061-T6. The first half contains the top plate with the fluid guide plates, and the second half is the ground plate with the butterfly shaped frame. The two halves are then inserted into each other and welded together using electron beam welding. A continuous butt-weld is provided on the top side (**Figure 6**, left) and T-joint welds are provided on the bottom side (**Figure 6**, right). To prevent heat cracks during welding, the silicon-containing filler Al4047 is used. After welding, the outer contour is machined out by wire erosion (EDM). Finally, the in- and outlet pipes are TIG welded to the main body.

Figure 6. Final manufactured BF1 cold moderator top side (left) and bottom side (right)

3.1 Destructive testing of BF1 cold moderator

In addition to the usual non-destructive tests, such as X-ray testing of all welds, dye penetration testing, helium leak testing and visual inspection, another identically manufactured moderator was subjected to a burst test at liquid nitrogen temperature. The setup used is described in **[7].**

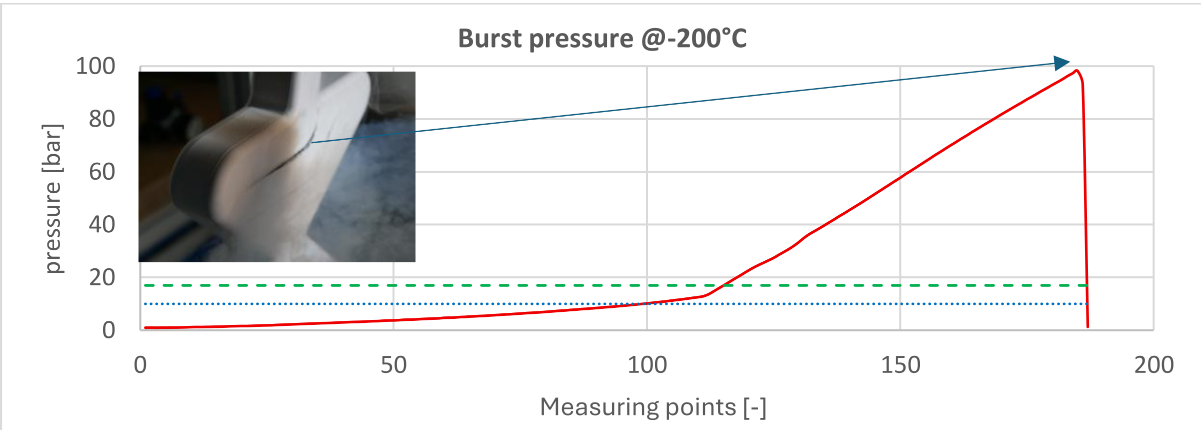

Figure 7. Destructive testing of BF1 cold moderator at LN_2 temperature. Burst curve (continuous red line), operating pressure (dotted blue line) and design pressure (dashed green line)

As can be seen in **Figure 7**, the burst pressure is about ten times higher than the operating pressure, which means there is sufficient safety margin to operate the moderator safely.

4. Moderator & Reflector Plug (MRP) installation at ESS

After the moderator was manufactured and tested, it was mounted into the support structure with the thermal moderator and beryllium reflector, which in turn is welded to the shaft. With that, the first moderator and reflector plug (MRP) for the ESS was ready for the final installation into the ESS target monolith. The final installation took place in 2024. **Figure 8** shows how the first MRP was lifted to its final position, next to the spallation target. The MRP is surrounded by approximately 1000 tons of water-cooled stainless steel for shielding reasons.

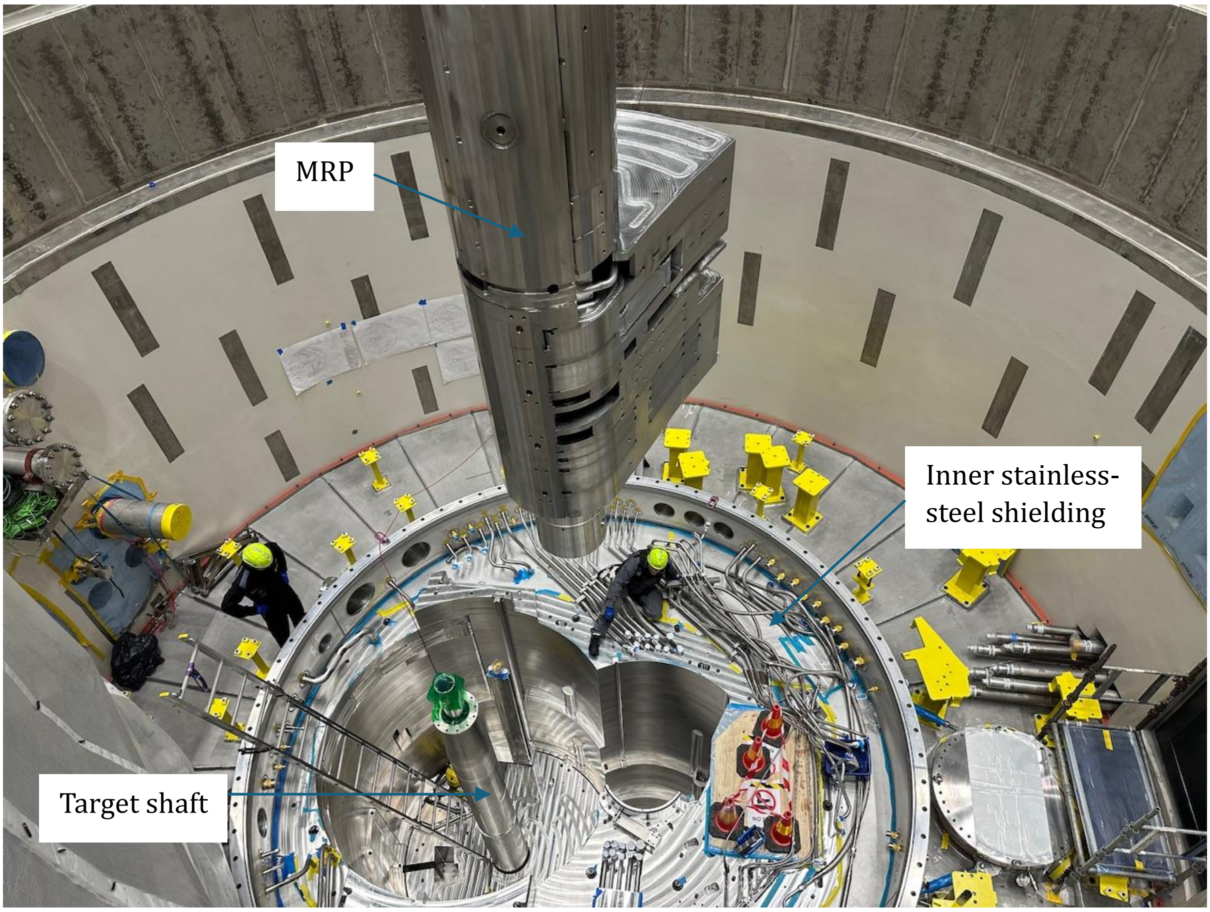

Figure 8. Installation of moderator & reflector plug at ESS target monolith, Photo by ESS

All water-cooling circuits of the MRP are already commissioned. The hydrogen test operation is planned for the second half of 2025. The MRP is then ready for the operation of the spallation neutron source ESS. Currently it is foreseen to start operation at low beam power in spring 2026 (first beam on target). First scientific experiments are scheduled for 2026 and the steady state operation at 2 MW proton beam power is expected in 2028.

Due to the high radiation damage caused by particle interactions, the lifetime of the MRP is very limited (13 months at full beam power), **[8]**. On the one hand, this is a major cost factor and a challenge for production, but on the other hand, it also makes it possible to continuously develop new moderators based on the results and experience of operation, ensuring the best possible setup for - current research.

5. Summary & outlook

5.1 Summary

It was shown that a complex liquid para-hydrogen moderator for the ESS is theoretically and practically feasible and that the partial load operation of the world's most powerful neutron source can start with the presented moderator and reflector system. Even though some operational experience still needs to be gained before the full proton beam power of 5 MW can be reached, this appears to be achievable.

5.2 Outlook

A challenge for the operational phase is the short radiation-related lifetime of the MRP. The production time is among other things due to tendering and material delivery time being about twice as long as the lifespan, even if an exact copy of the previous MRP should be manufactured. In addition, it is to be expected that no MRP will be the same as the previous one, since optimized moderators will always be used in the successor versions to meet the current needs of science. For example, it is currently being investigated, whether a high-intensity very cold neutron source filled with liquid ortho-deuterium, or a supra-fluid helium ultra-cold neutron source can be installed in the third generation of the MRP **[9]**.

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