Thermal moderator-reflector assembly for HBS

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Abstract. The thermal moderator is the key component in a research neutron source to convert the primary neutrons which typically have energies in the MeV regime into useful neutrons for investigations with energies well below 1 eV. In the case of a HiCANS as HBS, the thermal moderator has to be optimized according to the compact target size and to the proton pulse lengths at individual target stations. Here, the details of a thermal moderator design serving up to 12 instruments at a target station and its neutronic performance are presented. The thermal moderator consists of a complex aluminium vessel filled with light water as moderator material containing 12 thin-walled extraction channels arranged in 2 levels.

1 Introduction

The High Brilliance neutron Source (HBS) design, as an example of a High Current Accelerator-driven Neutron Source (HiCANS) [1], comprises three individual target stations serving up to 12 instruments each with pulse lengths of 167 µs or 667 µs and repetition rates of 96 Hz or 24 Hz, resp., i.e. 1.6% duty cycle. In each target station, the primary neutrons are released by the interaction of a 70 MeV proton beam with a compact tantalum target [2]. The target moderator system has been designed to operate at an average power level of 100 kW at every target station, which imposes an upper limit of the peak current.

The thermal moderator / reflector unit has the purpose of converting the primary neutron energy spectrum to a thermal spectrum and to allow the extraction of neutron beams towards the experimental stations outside the shielding block. The thermal moderator is the first material interacting with the primary neutrons and therefore has to accept the majority of the energy of the primary neutrons. At a source of the power level of HBS this requires active cooling of the moderator, as shown in Section 4, so that water has been chosen as moderator material.

Due to the small target volume (neutron production volume 100 x 100 x 5.8 mm³) of HBS [3], a large fraction of the neutron emission from the target can be covered by a small thermal moderator of only a few litres of volume. This makes it possible to confine the thermal neutrons in this volume, so that the density of the thermal neutron cloud (normalized to the number of primary neutrons produced) is one order of magnitude higher compared to a modern research reactor [4,5].

This paper shows the design of a thermal moderator-reflector unit that is able to feed neutrons to the instruments at an HBS target station according to the paradigms of the HBS concept, providing a high flexibility concerning the assignment and usage of individual neutron beams. The design presented here offers the usage of 12 individual neutron beams,

which offer a well-balanced neutron intensity. Each beam tube, which has a diameter of 60 mm, allows the extraction of a thermal beam or the insertion of a cryogenic moderator [2] to further reduce the energy spectrum of the neutrons delivered to the instruments. This technical design is the proof that the construction and the operation of a suitable thermal moderator for a research neutron source of the HBS type is possible.

The moderator-reflector unit has been designed with materials that are hardly activated in the neutron field (see Section 3) and it has no shielding function outside the operation of the target station. That implies that the moderator-reflector unit can easily be removed and replaced within a few working days, once the activated target has been brought out of the target station. This flexibility allows to use a design that can strongly depend on the current instrumentation being operated at the individual target station with the opportunity to exchange it following future demands. Based on the technical design presented here, variations with different arrangements and geometries can easily be derived without the risk of new technological problems.

2 Position and geometry inside the TMR assembly
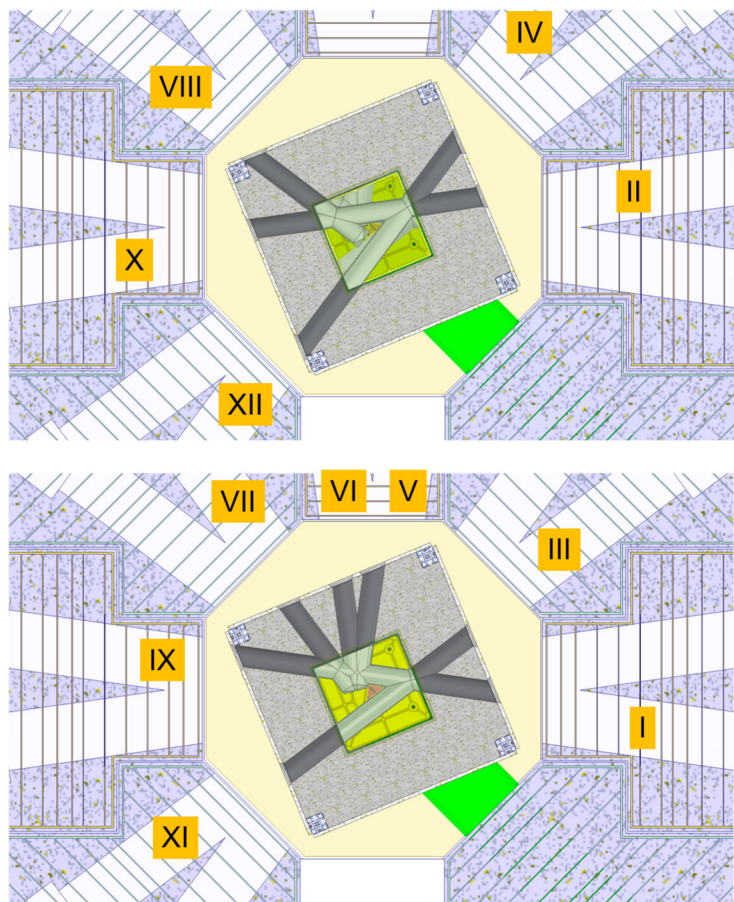
Fig. 1. Horizontal cut through the upper level (top) and the lower level (bottom) of the moderator-reflector assembly within the target station shielding. The extraction channels are enumerated with Roman numerals. The green structure below is the evacuated target exchange tube that extends to the centre of the target station and contains the tantalum target just below the thermal moderator.

The thermal moderator-reflector assembly is integrated in the shielding block with the target assembly and the proton beam tube. The proton beam impinges on the target from below, and the neutron beam tubes have been arranged in two levels ultimately close above the target, so that the voids of the beam tubes are sufficiently distributed to have every beam tube surrounded by thermal moderator material to feed thermal neutrons into it (see also Fig. 5 for a vertical cut through the entire structure showing the stacking of the extraction channels above the target).

Figure 1 shows the horizontal cut through the two layers of extraction channels. The yellow area is the volume filled with light water for moderation of the fast neutrons. Its size is 265 x 265 x 190 mm³. The grey square around it is the lead reflector with outer dimensions of 700 x 700 x 1000 mm³ which almost entirely encloses the thermal moderator and the target chamber. Both are penetrated by the twelve extraction channels, which each have 60 mm diameter and are arranged in two layers of 60 mm and 130 mm distance above the target. As can be seen from figure 1, a geometry has been created where every beam port in the shielding matches with one extraction channel in the moderator-reflector assembly. The extraction channels are displaced from the axes of the beam ports in order to preserve more moderator material in the centre of the moderator volume close to the flux maximum to increase the intensity of the neutron beams extracted. The geometry has been optimized to guarantee equivalent flux conditions on all beam ports on the expense of a somewhat reduced flux on all positions (see section 6).

This moderator design has four continuous extraction channels (II-X, IV-XII in the upper level and I-IX and III-XI in the lower level) where each of them can be equipped with a cold moderator (e.g. with an elongated para-hydrogen cold source) serving two instruments at both ends of the extraction channel. The other four extraction channels (VIII in the upper level and V, VI, and VII in the lower level) are blind and can be used to extract thermal beams or three of them (V, VI and VII) may share a short cold source, e.g. using a solid methane cold moderator insert.

3 Materials

Light water (H_2O) has been chosen as the thermal moderator material because it has a high proton density yielding efficient moderation of neutrons and it can be circulated in a cooling loop to remove the heat imposed by the strong radiation close to the target. The activation in the strong neutron field is low, but the activity concentration of tritium reaches 200 Bq/g after one year of operation and is higher than the value for unrestricted release of 100 Bq/g, so treatment or regular exchange of the moderator water is required.

The structural materials of the water vessel and the extraction channels inserted are made of aluminium alloys with magnesium addition. These materials are reasonably machinable, weldable, castable, and drawable to realize the complex geometry which is required, while they are not very sensitive to irradiation, have a reasonable thermal conductivity and do not produce long-lived radioisotopes by activation in the neutron field. The profiles and screws used for the assembly as well as the water connection tubes are also fabricated from aluminium alloyed with magnesium and silicon.

As the reflector material, pure lead for the massive parts and an alloy of lead with calcium or tin as addition for the casted parts around the extraction channels have been chosen. Lead has high scattering and (n,2n) cross sections for fast neutrons and a low moderation effect, so that the mobility of the scattered neutrons remains high on their way back to the thermal moderator region to avoid elongation of the neutron pulse length.

4 Radiation heating and cooling requirements

To assess the necessity of moderator and reflector cooling, simulations of the energy deposition of prompt neutron and gamma radiation within the thermal moderator and the first layer of the lead reflector surrounding the moderator were of particular interest.

For that purpose, a simplified model of the TMR assembly has been prepared where the beam extraction channels, cold moderator inserts, and constructional parts have been neglected. Only a thin 10 mm aluminium layer was added between the proton beam tube and the thermal moderator to simulate the energy deposition in the moderator housing. The simulation was performed using the FMESH energy deposition tally of MCNP6 [6] where the mesh was set to cuboids of 35 x 40 x 45 mm³.

As it can be seen from figure 2, the highest energy load is to be expected within the first few centimetres of the moderator above the target where the maximum of the fast neutron flux arrives. Directly above the target a radiation power of ca. 700 mW / cm³ is deposited in water. The water moderator volume receives an integral power below 2 kW, of which 1 kW is deposited in the 40 mm thick water layer above the target. A cooling circuit with forced circulation is required to remove this heat. The heat deposition due to delayed gamma-ray emission from activated materials can be neglected.

The integral heat deposition in the lead reflector is about a factor 20 lower and can be removed by convectional cooling at the surfaces of the reflector.
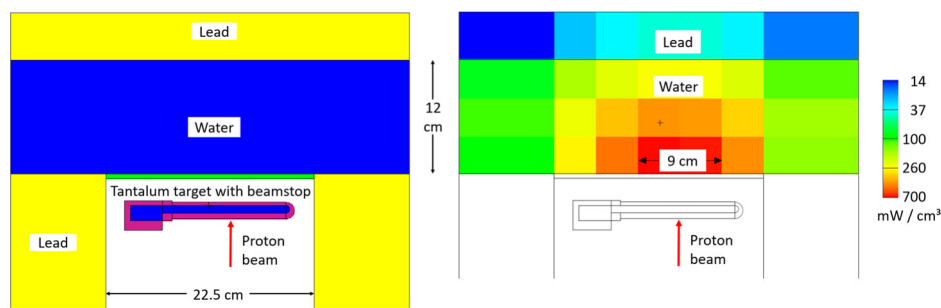

Fig. 2. MCNP model geometry (left) and spatial distribution of the energy deposition (right)

5 Design concept

5.1 Thermal moderator

The light water thermal moderator needs a container to keep the liquid in the desired geometry for the proper shaping of the thermal neutron field. This tank consists of the outer vessel, the extraction channels penetrating the vessel, a void towards the target used for feeding the primary neutrons more efficiently into the upper layer of extraction channels and service elements for connecting the water cooling circuit.

Figure 3 shows the main elements of the water vessel for the thermal moderator. The outer vessel consists of three shells (6, 7, and 8) which meet each other at the centre of the lower level of extraction channels, or at the centre of the upper level of extraction channels, respectively. To achieve thin walls while keeping sufficient mechanical strength and stiffness, a layout with reinforcing ribs (5) and weight reduction pockets (4) in between is foreseen. This can be manufactured by mechanical milling of the main body and chemical milling of the pockets. In the lower shell one can see a deep drawn void shell (10) as a guide for fast neutrons towards the moderator surrounding the upper level of extraction channels.
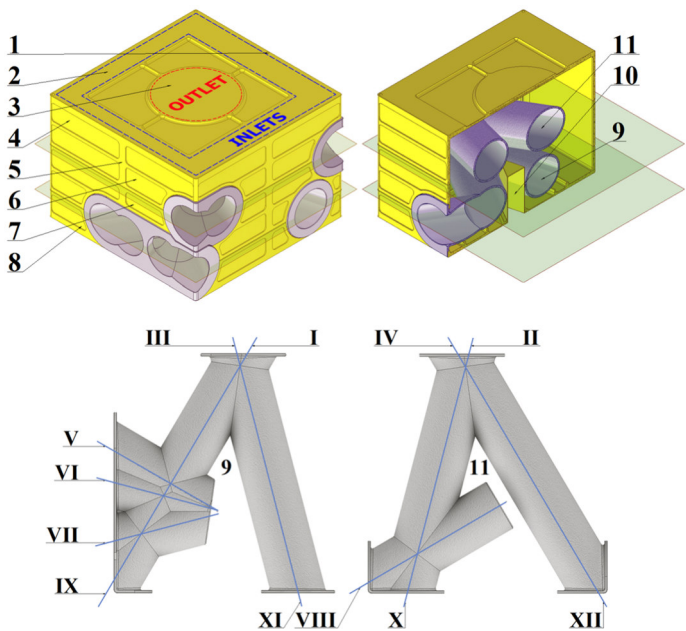
Fig. 3. Water vessel for the thermal moderator and its tube structures for the two levels of extraction channels. The Arabic numerals are explained in the text, the Roman numerals refer to the individual extraction channels as in figure 1.

The extraction channels of both levels are manufactured separately (9 and 11). Lost-wax casting is used to define the outer geometry of the complex channel systems. A deep drilling of the cast body realizes the desired precision of the thicknesses of the thin walls of the extraction channels. Mechanical milling defines the welding surfaces towards the shells.

For the adjusted assembly of these six parts for welding, openings (1) for assembly pins and locking screws are foreseen to be able to properly assemble all these parts with the desired precision, where they are welded to form a single closed tank.

During the welding of the channels to the shell, a removable auxiliary construction will define the precise position of the axes of the inner channels with respect to the base of the shell. Welding between the different aluminium alloy parts will be performed under inert gas.

The connections for the water circulation will be mounted to the top surface in the areas indicated (2 and 3).

Figure 4 shows the water flow velocity and temperature distribution in the light water thermal moderator and the walls of the tank. The geometry has been simplified to 2 dimensions to reduce the calculation time. The outer dimensions of the moderator tank, the deep-drawn void and two penetrating extraction channels in each level have been modelled together with one (case II) or two (case I) inlets at the boundaries of the container's top plate and the only outlet in the centre. These represent two different possible positions of 2D cuts through the vessel. Case II resembles the extreme case of placement of the water inlet connection with very inconvenient access for the water flow. In both cases, the water at the inlet is assumed to flow with 0.5 m/s and have an initial temperature of 294 K.
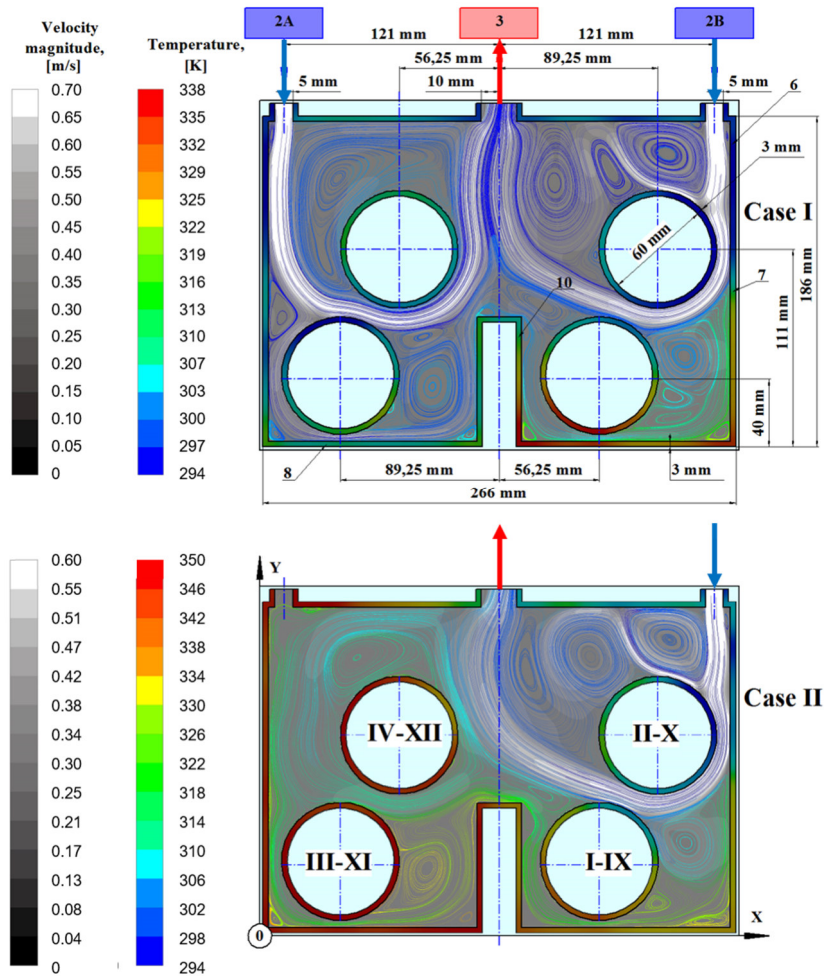
Fig. 4. Pseudo-2-dimensional CFD / FEM simulation of water flow and temperature distribution inside the (simplified) thermal moderator. Case I (top) shows fully connected water input and output, case II (bottom) is the extreme case where the water input is connected only at one side far away from the extraction channels III-XI. The Arabic numerals are the components from figure 3, the Roman numerals indicate cross-sections through the penetrating extraction channels with the enumeration according to figure 1.

Two-way coupled pseudo-2-dimensional CFD / FEM-simulations of a stationary distribution of temperature fields with flowing masses and thermal conductivity were carried out using the ANSYS Fluent package [7] where the thermal load has been assumed to be 30% above the MCNP simulation results presented in section 4. The pseudo-2-dimensional flow simulation makes assumptions about the flow velocity components perpendicular to the plane shown. The input value of 0.5 m/s is only the in-plane component, so that the values shown in the figure are higher.

These simulations prove that, although all water connections are mounted only at the top plate, the water flow reaches the entire volume including the lower surface of the moderator tank with sufficient velocity to remove the heat. The moderator water will not start boiling, the maximum temperature reached in case II is 350 K between the lower surface of the moderator tank and the extraction channel most far away from the inlet connector. All heat deposited by the radiation can be removed properly.
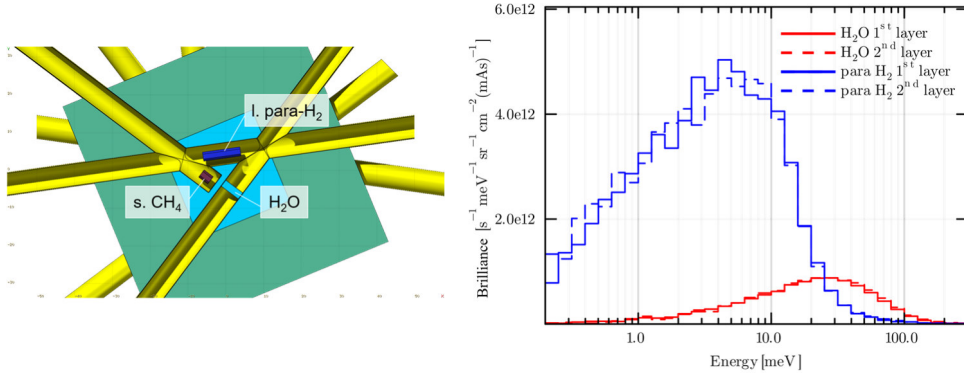
5.2 Reflector
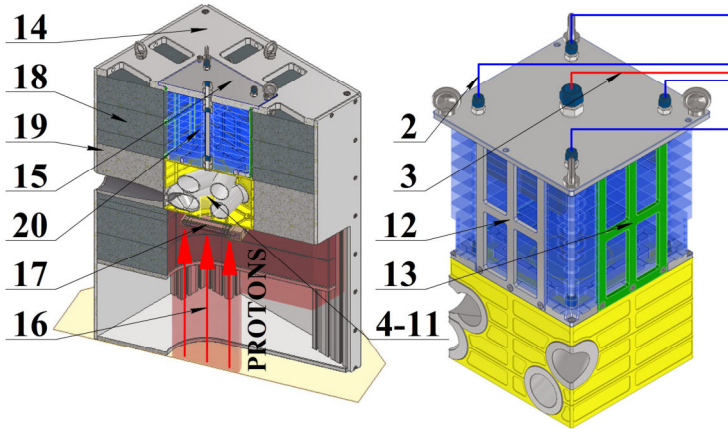
Fig. 5. Vertical cut through the target – moderator – reflector assembly (left) and view of the Cargo cabin containing the thermal moderator and the top part of the lead reflector. The blue and red lines represent the water connections, the numbers are explained in the text.

Figure 5 shows the lead reflector assembly with the thermal moderator in its centre. To avoid mechanical load on the thermal moderator vessel and to allow mounting and maintenance of the moderator assembly, the thermal moderator and the part of the reflector above it are designed as a Cargo cabin (figure 6 right) which is hanging in the centre of the main part of the reflector. The Cargo cabin has been designed as a self-supporting structure transferring all weight forces onto the top holding plate (14). The cabin is structurally realized in the form of a frame made of demountable (13) and fixed (12) aluminium plates connected from above by the support platform (15). The surrounding part of the lead reflector consists of machined plates (18) and cast pieces (19) surrounding the extraction channels. The top part of the reflector (20) consists of several machined plates that can easily be disassembled if maintenance of the thermal moderator is required. Everything is aligned on top of the target (17) in the direction of the proton beam (16).

More information about the design of the reflector assembly can be found in Ref. [2].

6 Neutronic performance

To assess the neutronic performance of the thermal moderator a MCNP model [6] of the target-moderator-reflector has been prepared where the channels have been filled either with a cryogenic moderator or a water layer providing scattering of the neutrons along the channel, as shown in figure 6 (left). The neutron beams' brilliances have been determined at the surfaces of the cryogenic moderators or the water scatterer, respectively. In the right part of figure 6 it is shown that the brilliance of the neutron beams emitted into the channels of the two layers is very comparable, in the thermal extraction channels as in the channels equipped with cold sources. The spectra of the CH_4 moderator have been omitted for the clarity of the figure. They are comparable to the para-H_2 spectra shown. The aim to provide equivalent neutron extraction properties and a high flexibility concerning the placement of cold moderators at all positions has been satisfied.

Fig. 6. Left: MCNP model of the moderator-reflector assembly together with cryogenic moderators or water scatterers inserted into the extraction channels. Right: Brilliance of the cold or thermal neutron beams extracted from the respective channels in both moderator layers.

Still, other optimizations serving less beam ports allow a higher flux on some of them (up to 2 times higher) and can be realized using the same technical design approach. In a later stage, when the instrumentation suite of a target station is being finalized, one will have to rearrange the channels to reduce the complexity of the arrangement and the amount of void in the thermal moderator to deliver the optimal neutron flux to the instruments being built. As the moderator region is easily accessible during service periods of the target station, a modification of the thermal moderator necessary due to upgrades of the instrumentation suite is not a penalty. Here, we describe the technologically most demanding solution, from which all other configurations can be derived.

7 Conclusion

This design shows the feasibility to manufacture a light water thermal moderator with a complex assembly of extraction channels that serves up to 12 instruments with equally distributed neutron flux. The arrangement in two layers allows the installation of individual cryogenic moderators that are shared by max. 2 beamlines. The design can be understood as a blueprint that allows to derive optimized arrangements for a scope of instruments to be realized at a dedicated target station.

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