Thermal moderator-reflector design of the 24 Hz target station for the High Brilliance Neutron Source

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Abstract. The High Brilliance Neutron Source (HBS) project develops a high current accelerator driven neutron source (HiCANS), aiming to substitute existing neutron research reactors, that reach the end of life. This study focuses on the thermal neutron moderator design for a low frequency, long pulse target station of HBS. We investigate the neutronic characteristics of the D_2O+H_2O mixture moderator material using the Monte Carlo particle transport code PHITS. Our findings show that, compared to D_2O with lower neutron absorption, confinement of H_2O is the dominant factor in achieving a high neutron flux within the moderator and thus a high neutron brightness. We find that surrounding the central thermal water moderator with a D_2O+H_2O mixture can achieve a better balance between confinement and absorption. However, because of multiple angles of reflecting neutron, this design will also increase the divergence of the neutron beam.

1 Introduction

Neutrons are critical in understanding the structure and dynamics of matter and materials, leading to a high demand of neutron scattering and analytical experiments. The advent of high-current accelerator systems launched the development of high-current accelerator-driven neutron sources (HiCANS) utilizing low energy nuclear reactions. High current accelerator-driven neutron sources (HiCANS), are cost-effective to construct and to operate. At current there are mainly three HiCANS projects which are the High Brilliance Neutron Source (HBS) project [1] located in Jülich, the ICONE project developed by Université Paris Saclay [2] and the ARGITU project [3] located in Basque Country area (Spain). These developments can counteract the loss of existing fission-based neutron sources and a resulting decline in available neutron beam days as well as establishing HiCANS as a next generation neutron source.

Despite the lower primary neutron yield of the nuclear reactions compared to reactor or spallation neutron sources, HBS achieves a competitive neutron brightness by a compact moderator and reflector design, which makes a large fraction of the primary neutron spectrum available for thermal and cold neutron applications [1]. The proton power of HBS is 100 kW. The peak current is 100 mA. The HBS project features three target stations with different pulse frequency (24 Hz, 96 Hz and 96 Hz) and proton pulse length (667 µs, 167 µs, 167 µs) [1]. Also, the spectral characteristics are tailored for the instruments hosted at a specific target station. In this work, we will focus on the thermal moderator design for the 24 Hz target station, which provides a thermal neutron beam for many instruments.

Two crucial components of the neutron source design are the moderator, which moderates fast neutrons to the expected energy range, and the reflector, which reflects neutrons, which escape from the moderator, to increase the neutron intensity. The neutron flux, the neutron brightness and time structure of the neutron pulse are important metrics for evaluating the moderator-reflector design. The time distribution of the neutron pulse is determined by the proton pulse shape and the time the neutron spends inside the moderator and in the reflector. When high-energy neutrons collide with nuclei in the moderator, they lose energy until they reach thermal equilibrium. The time spent by neutrons moderating and diffusing inside the moderator can be broken down into two main components: the first is the thermalization time, which is the time taken for the neutron to decrease from the fast energy region to the thermal or cold energy region; the second is the residence time, which is the time the neutron can diffuse inside the material before it leaves the moderator volume or is absorbed [4]. Moderator materials with high elastic scattering cross section, high logarithmic energy reduction, and lower absorption cross section should be considered to achieve high neutron brightness. The nuclides H and D are considered as ideal candidates for moderating neutrons, and H_2O and D_2O are commonly used as moderator materials [4]. Due to its higher elastic cross section, H_2O moderates the neutrons faster and in a smaller volume yielding a higher density of the neutron cloud and a larger neutron flux in the center of the cloud, i.e. the volume, in which the neutrons travel before reaching thermal equilibrium. Compared to H_2O, D_2O has a smaller absorption cross section, making it easier for

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neutrons undergoing multiple collisions to survive longer in D_2O exploring a larger volume. The use of D_2O results in a longer tail for the neutron pulse. Alternatively, the use of H_2O provides a thermal neutron lifetime (time interval from neutron generation to absorption) below 200 μs, which is significantly shorter than the proton pulse length at the 24 Hz target station. That means the neutron lifetime can be relaxed by decreasing absorption. Therefore, using pure D_2O or pure H_2O as thermal moderator materials seems not an optimal solution. Instead, a mixture of D_2O and H_2O is expected to achieve higher neutron cloud density with suitable escaping time and lower absorption.

This work will first illustrate the research methods and related geometry, followed by an investigation into the neutronic characteristics for a mixture of materials as a thermal moderator. Finally, a new design of moderator and reflector that places H_2O and the D_2O+H_2O mixture in different geometries is explored.

2 Method

In this study, the Monte Carlo simulation code PHITS 3.27 is used for the neutron transport simulation. The simulations are based on the evaluated neutron cross section library ENDF/B-VII.0 and lwtr.20t and hwtr.20t for thermal scattering kernels [5]. A neutron source generated in advance created with a 70 MeV proton beam distributed over the surface of a cylindrical Ta target with 10 cm diameter and 0.5 mm thickness was used for the simulations, which can avoid tracing of charged particles. Behind the Ta target is a 0.5 cm water (H_2O) layer, which in reality serves for cooling the target. In this study, the ratio of the D_2O+H_2O mixture material is 70% D_2O and 30% H_2O realizing a mean lifetime of approximately 700 μs. Only a mixture 70% D_2O and 30% H_2O has been studied. The energy range for tally is from 1 meV to 500 meV.

For investigating the neutron flux inside H_2O and the D_2O+H_2O mixture material, the following geometry model is used as shown in Fig.1. The moderator has a cylindrical shape. The width and the thickness of the H_2O moderator and the D_2O+H_2O mixture moderator are optimized to maximize the neutron flux in the center of moderator. The width and thickness of the H_2O moderator is 18 cm × 14 cm. The width and thickness of the D_2O+H_2O mixture moderator is 22 cm × 22 cm. There are two [T-Track] tallies [6], one is put at the center of the moderator, called tally 1, the other is placed in the outside area at the same normal distance, but shifted 5 cm outwards within a plane parallel to the target plane, called tally 2, as shown in Fig.1. The maximum neutron flux along the depth direction was investigated initially, indicating an optimal depth of 2 cm for H_2O and 6 cm for the D_2O+H_2O mixture material. Thus, the normal distance from the target of tally 1 and tally 2 is set to 2 cm for H_2O and 6 cm for the D_2O+H_2O mixture material above the target. For investigating the effect of deuterium containing material surrounding a central water moderator, the geometries as given in Fig.2 have been simulated. In this design, a single extraction channel (diameter 6 cm in cylindrical shape) is added into the center of the thermal moderator. The center of the extraction channel is 5 cm away from the target. An additional water cylinder is put in the center of the extraction channel, which acts as "scatterer" to increase the neutron emission along the channel.

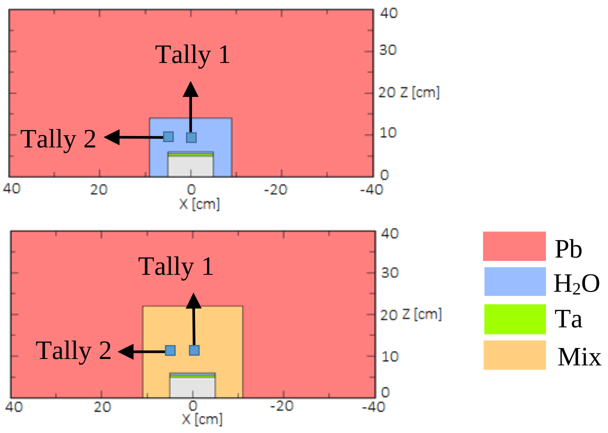
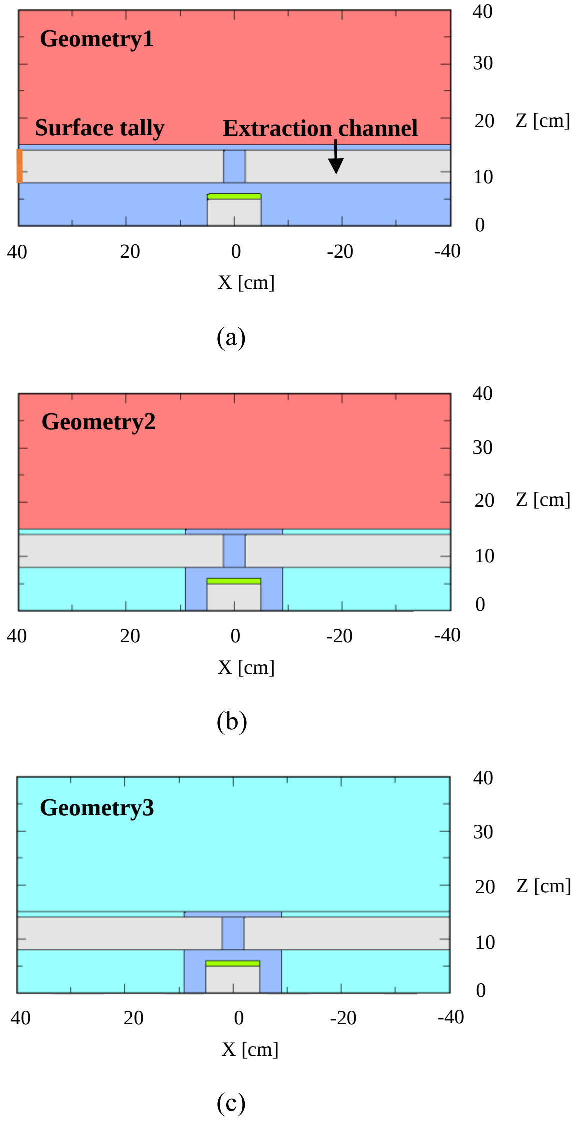


Fig. 1. Geometry model for the water moderator (upper) and mixture moderator (below).



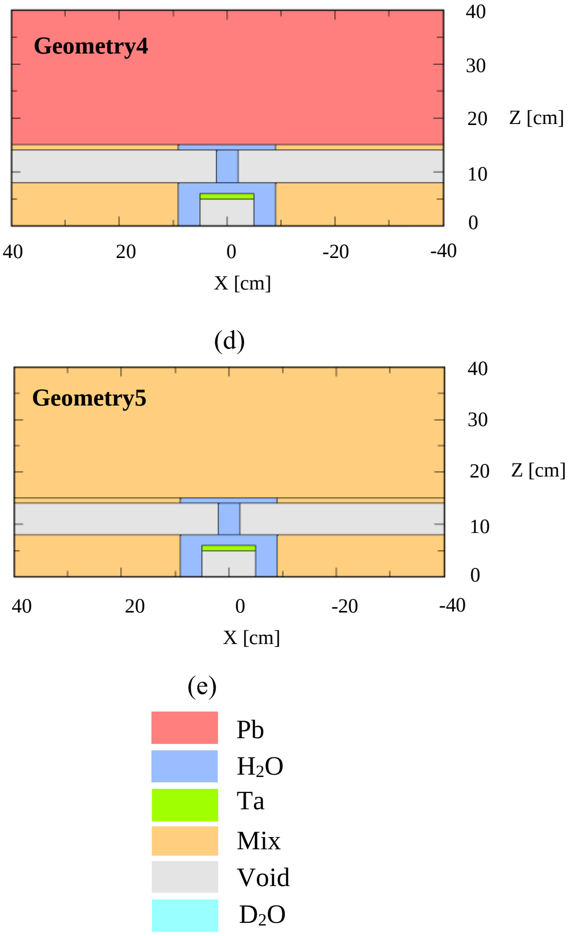


Fig. 2. Different geometry for water and D_2O+H_2O mixture moderator. (a) Geometry 1: water is used as moderator; (b) Geometry 2: D_2O is used around the centered water moderator; (c) Geometry 3: D_2O is used around the center water moderator and D_2O is used as reflector; (d) Geometry 4: D_2O+H_2O mixture material is used around the centered water moderator; (e) Geometry 5: D_2O+H_2O mixture material is used around the centered water moderator and D_2O+H_2O mixture material is used as reflector.

As shown in Fig.2(a) a water layer is surrounding the channel and Pb is used as a reflector. In Fig.2(b)-(e), different surrounding materials and reflector materials are used. In Fig.2(b)-(c), D_2O is used for the surrounding material, whereas in Fig.2(d)-(e) a D_2O+H_2O mixture material is used for it. As for the reflector, Pb is used just above the channel (Fig.2(b) and Fig.2(d)), while D_2O and D_2O+H_2O mixture material is used above and behind the channel (Fig.2(c) and Fig.2 (e)). The surface tally is put at the end of the channel (40 cm from centre). The tally records the neutrons emitted into 0°-90°, i.e. the full space in increasing x-direction, and into 0°-5°, which corresponds to a collimation that we consider a upper limit to be extracted by an instrument.

3 Results

The neutron flux versus time related to the geometry in Fig.1 is shown in Fig.3. For tally 1, the flux reached at saturation for H_2O is two times larger than in the mixture case. For tally 2, the saturated value for H_2O is 1.6 times larger than in the mixture case. This result indicates that with H_2O one can obtain a larger neutron flux even though the neutron pulse decays faster than in the D_2O+H_2O mix's case. As described above, H_2O confines the neutron cloud stronger. This effect cannot be compensated by the lower absorption during the pulse due the lower macroscopic absorption cross section of D_2O. In other words, the absorption in the central area is of minor importance. Thus, for the geometry shown in Fig.1, the confinement effect of H_2O plays a leading role for the neutron flux around the central area.

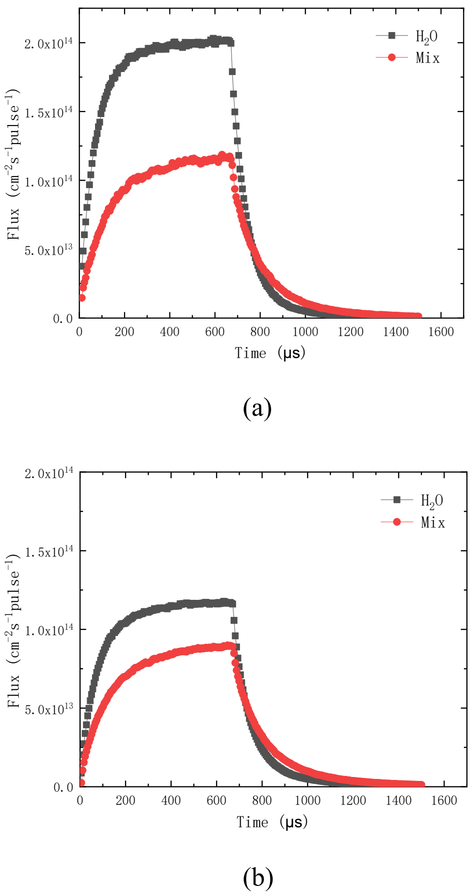
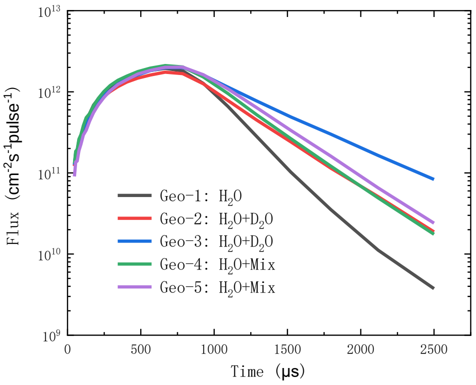


Fig. 3. Neutron flux versus time for geometry in Fig.1. (a) The result of tally 1. (b) The result of tally 2.

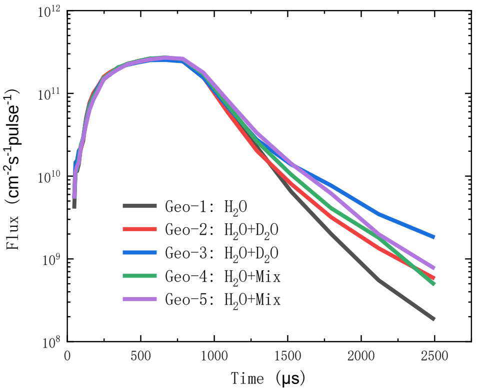
In order to take advantage of the lower neutron absorption of D_2O without diluting the neutron cloud around the central area, H_2O and D_2O+H_2O mixture material should be placed at different positions. For confining the neutron cloud, H_2O should be put at the center of the moderator to confine the neutron. To store more neutrons in the whole moderator and reflector structure, deuterium containing material is used, which decreases the absorption in this volume. The D_2O+H_2O mixture material surrounding the H_2O cannot influence the neutron cloud in the central area. Thus, the geometries as presented in Fig.2 are investigated.

The results for the different geometries introduced in Fig.2 are shown in Fig.4. Fig.4(a) presents the output of the surface tally into an emitted angle 0°-90° and Fig.4(b) is the result related to the tally emitted into an angle of 0°-5°, for which most of the events originate from the volume in the center of the extraction channel. Table 1 shows the related time integral value and decay time for these two tallies. The decay time is obtained by fitting an exponential decay function from the curve shown in Fig.4 [5]. The integration time range in Table 1 is from 0 ms to 1.5 ms.

As for the emitting angle 0°-90° shown in Table 1, the time integral value of geometry 2 is almost the same as geometry 1 (difference is smaller than 5 %). The maximum time integral value is for geometry 3, which increases by 18 % compared to geometry 1. It indicates that the neutrons can travel for a long time in the D_2O volume to reach the surface tally. However, from the time distribution curve of geometry 3, the added neutrons contribute mostly to the tail of the neutron pulse. This is also demonstrated in Table.1. The decay time of geometry 3 in the emitting angle 0°-90° is 1.7 times larger than that of geometry 1. Furthermore, the time integral value of geometry 4 is 14 % higher than geometry 1. This means in the D_2O+H_2O mixture material the thermal neutrons can survive and be confined into the channel. The decay time of geometry 4 is just 1.3 times longer than that of geometry 1, which is smaller than the case using pure D_2O in geometry 3.



(a)



(b)

Fig. 4: Neutron flux versus time for an energy range of 1 meV to 500 meV for geometry in Fig.2. (a) Neutron flux versus time for emitting angle 0°-90°. (b) Neutron brightness versus time for emitting angle 0°-5°.

That means the D_2O+H_2O mixture material along the extraction channel achieves an optimal balance between absorption and confinement. The time integral value of geometry 5 is also 14% higher than geometry 1, which is the same as in geometry 4. Thus, the neutron is not scattered back from the D_2O+H_2O mixture material. For the emitting angle 0°-5°, Table 1 indicates that the neutron flux varies less than 8 % between geometry 1 to 5. This difference is smaller than that when the geometry is not larger than 14 %. Fig.4(b) shows the emitting angle 0°-90°. The difference in the decay time for each peak value among different geometries is similar to each other. These results indicate that the emission of a collimated beam is only weakly affected by the properties of the reflector for the HBS TMR geometry. The neutrons scattered back from the D_2O+H_2O mixture material do not contribute to the neutron pulse emitted into a narrow angle of 0°-5°.

Table 1. Time integral neutron brightness and decay time for the geometries shown in Fig.2 for an energy range of 1 meV to 500 meV. The integration time was 1500 μs.

Emitting angle : 0°-90°		
	Time integral × 10^9 (cm^{-2} pulse^{-1})	**Decay time (μs)**
Geo-1: H_2O	1.35 ±0.03	318 ±20
Geo-2: H_2O+D_2O	1.31 ±0.02	400 ±23
Geo-3: H_2O+D_2O	1.64 ±0.03	536 ±26
Geo-4: H_2O+Mix	1.57 ±0.02	396 ±27
Geo-5: H_2O+Mix	1.57 ±0.02	456 ±31

Emitting angle : 0°-5°		
	Time integral × 10^9 (cm^{-2} pulse^{-1})	**Decay time (μs)**
Geo-1: H_2O	1.78 ±0.03	255 ±13
Geo-2: H_2O+D_2O	1.75 ±0.04	238 ±13
Geo-3: H_2O+D_2O	1.74 ±0.04	250 ±12
Geo-4: H_2O+Mix	1.86 ±0.04	257 ±14
Geo-5: H_2O+Mix	1.88 ±0.04	276 ±10

4 Conclusion

In this study, we have investigated the neutronic characteristics of a thermal water moderator and a mixture material of D_2O and H_2O for a moderator-reflector design for a long pulse target at the HBS. It was found that confining the neutron cloud is more important than reducing the absorption even for a rather long neutron production time of nearly 700 μs.

Comparing the neutron flux emitted into a limited collimation cone, we find, that the reflector material affects mainly the tail of the neutron time distribution. That means that neutrons scattered back from the reflector contribute hardly to the instantaneous neutron flux through the emission surface into the forward direction. Due to the small target volume, basically all neutrons are coupled into the light water moderator and only a tiny fraction of not-equilibrated neutrons escape towards the reflector at the HBS. Therefore, we observe an effect of the reflector mainly in the tail of the thermal neutron pulse, in particular if we consider the collimated emission at the extraction surface. This allows to optimize the reflector for the HBS based on different aspects, e.g., to shorten the pulse tail by appropriate thermal neutron absorbers, which decouple the reflector from the moderator to maximize the signal-to-noise ratio for the instruments.

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