Investigation of the mutual influence of multiple extraction channels for high-current accelerator-based neutron sources

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Abstract. The High Brilliance neutron Source (HBS) project pioneers a High-Current Accelerator-Based Neutron Source (HiCANS), optimizing elements for tailored neutron production. HBS adapts pulse structure and moderators to instrument requirements, focusing on the Target-Moderator-Reflector (TMR) system. Recognizing the need for multiple channels, Monte Carlo simulations are used to compare different models' influence on neutron brilliance and beam divergence.

1 Introduction

Engineering, chemistry, quantum technologies, and nanotechnology are some of the scientific fields employing analytic techniques based on neutrons. Traditionally, nuclear reactors and spallation sources have been key methods for neutron production, but the decommissioning of nuclear reactors has led to the emergence of new technologies [1]. The High Brilliance neutron Source (HBS) project at the Forschungszentrum Jülich is a high-current accelerator-based neutron source (HiCANS), aiming to create a cost-effective facility with peak neutron brightness comparable to medium flux reactor sources [2]. The HBS optimizes its HiCANS elements, including accelerator, target, moderator, reflector, shielding, and instrumentation, to tailor neutron production for individual instruments in a holistic approach. The target-moderator-reflector (TMR) system, with the moderator as a key component, plays a crucial role in accumulating and moderating neutrons to the energy spectrum required by specific instruments. HBS distinguishes itself by adapting the neutron source's pulse structure and moderator according to the instrument's unique requirements. Several extraction channel models have been simulated using the Monte Carlo (MC) particle-tracking code PHITS [3] to observe the effects of the moderator design on the neutron beam divergence and peak neutron flux emitted towards an instrument. Given the necessity for multiple extraction channels to feed few instruments, various arrangements of multiple channels and their influence on neutron flux and beam divergence were investigated in comparison to a single extraction channel.

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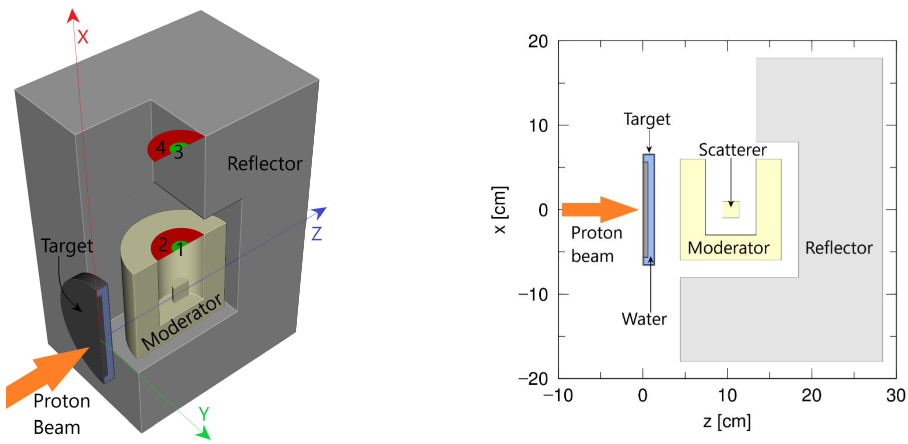
2 Methods

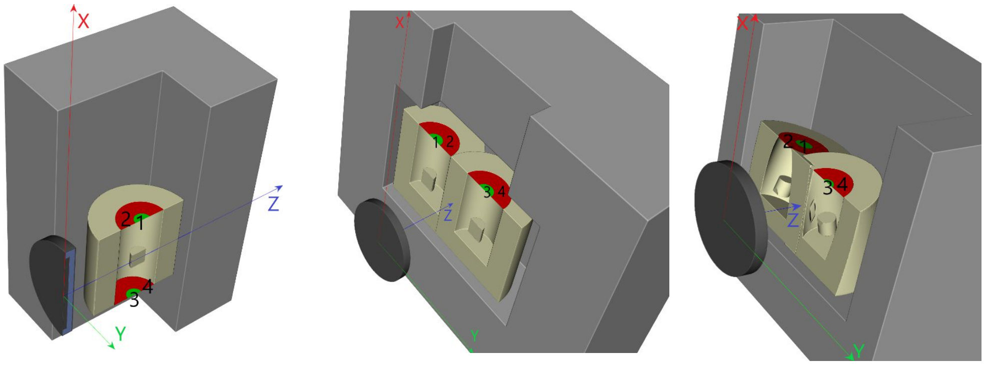
Simulations for this analysis were performed using The Particle and Heavy Ion Transport code System (PHITS), which is a simulation code using MC particle transport. It is capable of simulating the collision and the transport of almost all particles over the energy range from 0.01 meV to 1 TeV by using the Monte Carlo method [3].
To analyze the neutron beam divergence and the neutron brightness emitted towards the instruments, detector surfaces are used. These detector surfaces, shown in Fig.1, are set along the extraction channel, at the end of the moderator cup (1 and 2), and at the end of the reflector (3 and 4) 12 cm away from surfaces 1 and 2. Two types of surfaces are used, circular (1 and 3) with radius of 1 cm and ring (2 and 4) with outer radius of 3 cm and inner radius of 1 cm. The time, energy, and angle at which each neutron passes through these surfaces are recorded for an instantaneous proton beam impinging on the target. The time resolution is linear starting at t=0 up to 2000 μs with timesteps of 200 ns. The energy resolution is logarithmic with 10 levels per decade starting at 10 meV up to 100 MeV. The angular resolution starts from 0° to 10° with steps every 1° and from 10° to 90° with steps every 5°. This type of binning is done to optimize for a shorter simulation time and lower statistical uncertainty.



Model 1

Fig. 1. 3D and 2D view with a cut along the xz-plane of the one extraction channel.

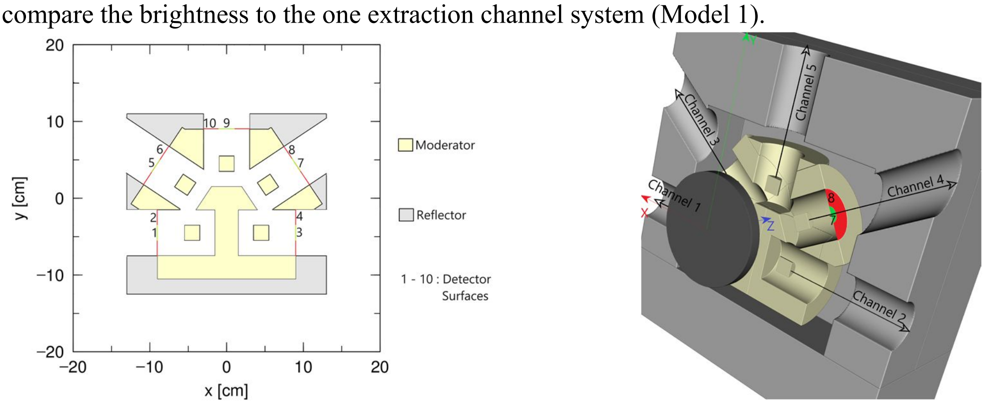
The models that are analyzed comprise of a tantalum (Ta) target with cooling water behind; a polyethylene (PE) cup and scatterer, as thermal moderator; lead (Pb) as reflector. The target has a surface area of 100 cm^2 and is hit by a 70 MeV proton beam. The water behind the target serves as a target coolant. The thermal moderator is in a shape of a cup with a diameter of 3 cm and contains a scatterer in the middle, which is a PE cylinder with a radius of 1 cm and height of 2 cm. The scatterer is introduced to analyze whether it increases the neutron flux in the forward direction. The Pb reflector has a thickness of 10 cm and it is 2 cm away from the moderator in all directions. Three different models for a two channel TMR geometry have been analyzed. These models have detector surfaces for both channels, as shown in Fig.2, to analyze the difference in the brightness between these two channels. These detector surfaces are positioned along the extraction channel at the end of the moderator cup. Detector surfaces further away from the moderator cup were also analyzed but not shown in this paper.



(a) Model 2 - channels at 180° (b) Model 3 - channels in parallel (c) Model 4 - channels at 30°

Fig. 2. 3D view of the two channel models with cuts along xz-plane (a), and xy-plane (b and c)

Model 2 consists of a hollow cylinder which will allow the extraction of the neutrons in the +x and -x direction. Model 3 consists of two intersecting moderator cylinders which would provide neutrons in the +x direction. Model 4 also consists of two intersecting moderator cylinders which are slanted at 15° around the +x direction. In this model the top part of the reflector was removed and the distance from the moderator was slightly increased, to allow for the opening of the slanted channel.
Additionally, a moderator system consisting of five channels, shown in Fig.3, is analyzed. Because of the five channels, the moderator system of this model is bigger than the rest. This requires a repositioning of the moderator system at the center of the target. The moderator system consists of 5 PE scatterers and 5 moderator cups intersecting at the center of the moderator system. Each of these channel contains two detector surfaces that are used to compare the brightness to the one extraction channel system (Model 1).



Model 5

Fig. 3. 3D and 2D view of the five-extraction channel model with a cut along xy-plane at z = 10.4 cm.

Two of these moderator cups are positioned opposite to one another, along the +x and -x direction; two of them at 45°; and one is pointed in the +y direction. Similar to other models, the reflector is 10 cm thick and 2 cm away from the moderator system in all directions.

3 Results

The comparison in neutron intensity for integrated time range for two different circular detector surfaces and one ring detector surface for Model 1 is shown in Fig.4. The difference

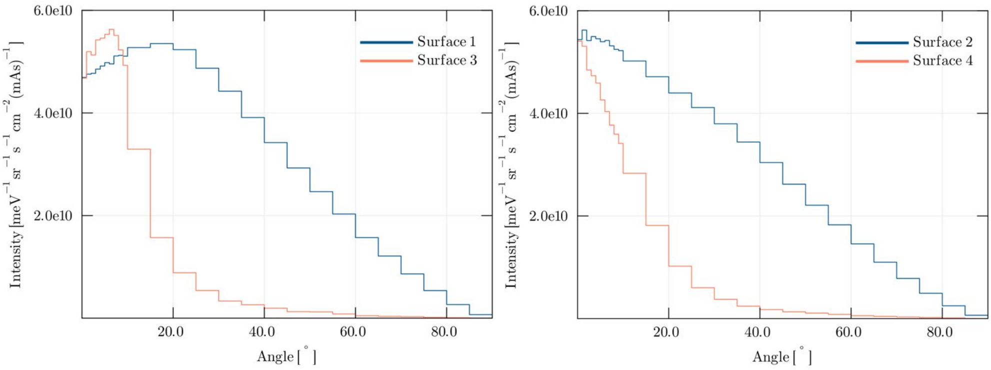


Fig. 4. The angular spectrum of thermal neutrons (10-500 meV) passing through the one extraction channel (Model 1) at circular detectors (left) and ring detectors (right).

between the circular (Surface 1 and 3) and ring (Surface 2 and 4) detectors is immediately observed at 0°, where about 15% more neutrons are going through the ring detectors. This means that there are more neutrons moderated in the base of the moderator cup than in the scattere. Additionally, the differences in the spectrum between surfaces 1 and 3 show where the thermalized neutrons are coming from. There is an increase in the spectrum for surface 1 up to 20°, which is not observed for surface 3, meaning that the walls of the moderator cup are responsible for such an increase.

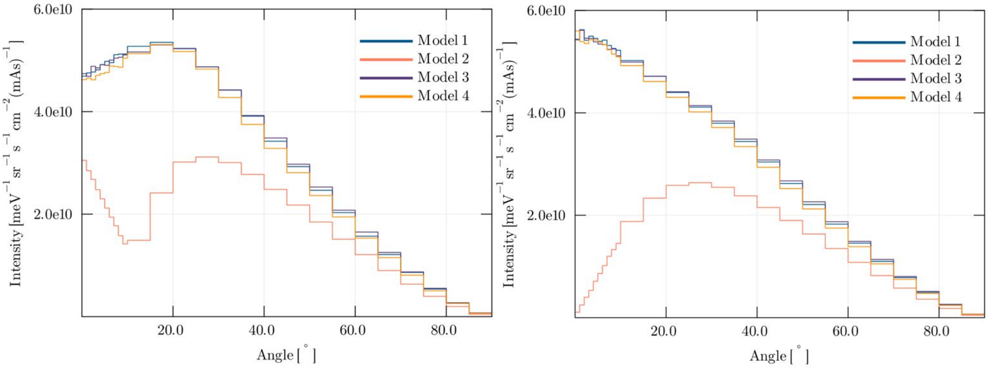


Fig. 5. The angular spectrum of thermal neutrons (10-500 meV) passing through the circular detector surfaces (left) – Surface 1 and ring detector surfaces (right) – Surface 2 for Models 1-4.

The angular spectrum of thermal neutrons for Models 1 to 4 is shown in Fig.5. The only noticeable difference is observed between Models 1 and 2. It is observed that throughout the channel there is about 70% loss of neutrons in the two extraction channels at 180° compared to the one extraction channel, which comes as a result of the removal of the moderator cup base. However, the angular spectra of the two channels in parallel and two channels inclined at 30°, show that the neutron brilliance is almost identical to the single extraction channel, with the small differences attributed to the increased space between the moderator and the reflector. The comparison between the one extraction channel and five extraction channels is shown in Fig. 6. From this comparison it is observed that the neutron brilliance at 0° for the circular detector surface is decreased by about 20%, due to the repositioning of the moderator system.

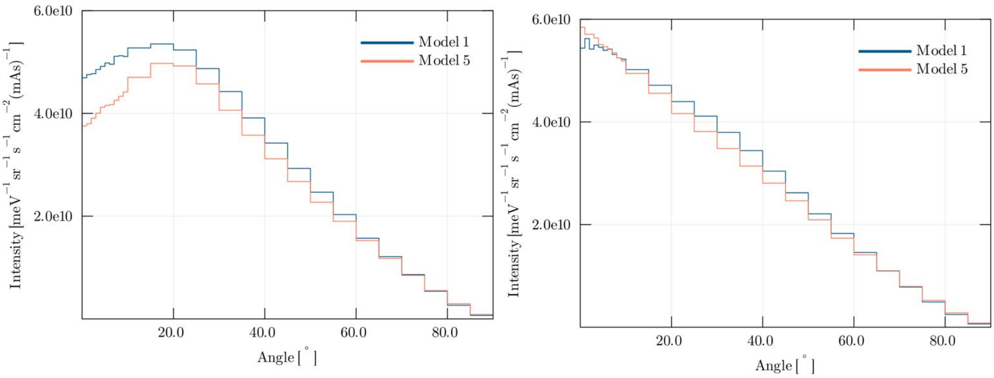


Fig. 6. The angular spectrum of thermal neutrons (10-500 meV) passing through the circular detector surfaces (left) – Surface 1 and ring detector surfaces (right) – Surface 2 for Models 1 and 5.

Whereas, for the ring detector surface no decrease is observed. The brilliance at 0° for all 5 channels lies within a 5% range.
The data in Table 1 shows the thermal neutron flux in the forward direction within 0-5° angle for all the models and their best and worst performing channel. The addition of the fluxes of the circular and ring detectors gives the total flux through the channel.
It is observed that throughout the channel there is about 70% loss of neutrons in the two extraction channels at 180° (Model 2) compared to the one extraction channel (Model 1), which comes as a result of the removal of the moderator cup base. These neutrons are almost completely recovered, when the two channels in parallel and inclined at 30° (Models 3 and 4) are considered, at which point the neutron flux data are almost identical to the one extraction channel. Additionally, in the five extraction channels (Model 5) the average thermal neutron flux is decreased only by 9%, despite the repositioning and the additional extraction channels.

Table 1. Neutron flux in forward direction at different detector surfaces of all models.

Neutron Flux (*10^9 n/cm^2/mAs)						
Surfaces		*Model 1*	*Model 2*	*Model 3*	*Model 4*	*Model 5*
Circular detector	*Min*	-	0.59	1.13	1.07	0.90
	Max	1.14	0.59	1.14	1.10	0.94
Ring detector	*Min*	-	0.12	1.28	1.18	1.26
	Max	1.29	0.12	1.28	1.27	1.32
Total flux	*Avg*	2.43	0.71	2.415	2.36	2.21

4 Conclusion

In this paper the results obtained from the simulations performed by PHITS for different arrangements of extraction channels are presented. For the simulations, the Ta target with water cooling, time resolution, energy resolution, angular resolution and the types of detectors are identical. The source definition was the same for all the simulations, which provided the moderator-reflector system with the same neutron intensity in each case making the comparison between the models more accurate. The results from the addition of one extra extraction channel show some differences between different arrangements.
The thermal neutron flux with 5° divergence for the two extraction channels at 180° from one another is about 70% lower compared to the one extraction channel due to the removal of the base of the moderator cup.
The thermal neutron flux obtained for the two extraction channels in parallel with 5° divergence is almost identical to the one extraction channel system, showing that two different instruments can be provided with the same neutron flux. The disadvantage of this system is that it provides two neutron beams only 7 cm away from one another.
Similarly, the thermal neutron flux obtained for the two extraction channels at 30° from one another and 5° divergence is <1% less than that of the single extraction channel system. In this arrangement the channels provide slightly different fluxes (about 3% difference). This arrangement provides two neutron beams further apart from one another allowing for an easier instrument placement.
The moderator system for five extraction channels is bigger compared to the ones with less extraction channels. The thermal neutron flux obtained for this system with 5° divergence is about 9% less than the one extraction channel system, meaning that five instruments can be provided with a slightly lower thermal neutron flux.
In conclusion, the influence of multiple extraction channels on the thermal neutron flux is minimal depending on the amount of the moderator used and the arrangement of the channels. This means that a total of five different instruments can be ”fed” with similar thermal neutron fluxes. Since the HBS project aims to produce neutrons at different energies demanded by the instruments, the addition of cold moderators to these models would give further possibilities to tailor the neutron beams to the instrument requirements for different extraction channels.

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