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Optimization of cold neutron beam extraction at ESS

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Abstract

The present study takes its origin in the baseline design of European Spallation Source where a cold and a thermal moderator are situated next to each other enabling bispectral extraction. The study aims at mapping the differences in various neutron distributions depending on the angle and position from which the moderator is viewed. This study does not only show changes in both cold and thermal neutron flux, depending on extraction position, but also shows that there are significant differences in the wavelength spectrum and origin of neutrons depending on the angel of view.

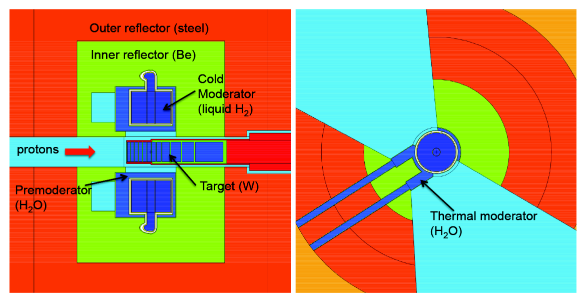


Figure 1: Target-Moderator-Reflector system from MCNPX [2] model. On the left a zy-slice at $x = 0$, on the right a zx-slice, of the moderator reflector system above the target.

Introduction

The European Spallation Source (ESS) is going to be the highest intensity neutron source ever build. Neutrons will be produced by spallation, driven by a 5 MW, 2.5 GeV proton beam impacting on a massive rotating tungsten target wheel. At ESS the neutrons will be thermalized in ambient water moderator placed next to the target, and cooled further in a 20°K tank of liquid para-hydrogen. The moderator will be surrounded by a reflector system, consisting of an inner beryllium reflector, surrounded by an outer reflector made of steel, as shown in Figure 1 or described in [1].

A moderator system will be placed above and below the target, each having two 60° by 12 cm windows where neutrons can be extracted for experiments. The experiments will each be given a 12 cm high and 5° wide instrument window, in one of these 60° beam extraction windows.

Geometry nomenclature

For the ESS geometry, as seen in Figure 1 and 2, we define vertically up as the y-direction $(0, 1, 0)$ (upwards on the left plot of Figure 1), the proton beam to point in the z-direction $(0, 0, 1)$ in a right handed coordinate system (x pointing upwards and z pointing right in the right side plot Figure 1 and in Figure 2). The origin $(0, 0, 0)$ is situated at the spallation hotspot inside the target wheel, which is on the central axis of the cold moderator cylinder.

We define θ as the positive angle in the zx-plane with respect to the proton beam axis ($\theta = 0$ at $(0, 0, 1)$ as seen in Figure 1). This study takes its origin at the point closest to the moderator at which the neutron guides can be placed, namely at the cylindrical beam extraction surface, 2 m from the center y-axis of the para-hydrogen cold moderator. At this 2 m radius cylinder the neutrons position is fully described by y and θ.

We define $\delta\theta$ (in θ-direction) as the relative direction of flight of neutrons with respect to the extraction surface normal.

Neutrons origin plays a vital role in this study. At a given position the neutrons direction of flight $\delta\theta$ can be used to derive if the neutron originated from the cold or thermal moderator or from the reflectors.

The wavelength (λ) will be divided into four categories:
Cold neutrons: $\lambda \geq 2.0$ Å.

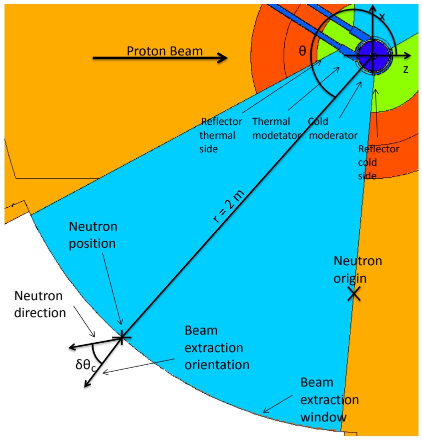
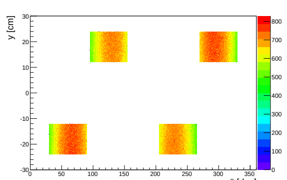


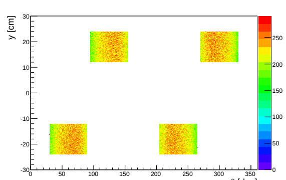
Figure 2: Horizontal geometry definitions. θ is that angle of the neutron position at the 2 m extraction window. $\delta\theta$ is the angle between the 2 m extraction surface normal and the neutrons direction (the horizontal neutron beam divergence).

Thermal neutrons: .5 Å $\leq \lambda <$ 2.0 Å.
Hot neutrons: .01 Å $\leq \lambda <$ .5 Å.
Any wavelength/all neutrons: .01 Å $< \lambda$.
Note that no neutron with .01 Å $\geq \lambda$ will be included in this study.

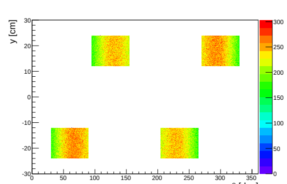
Spatial distribution



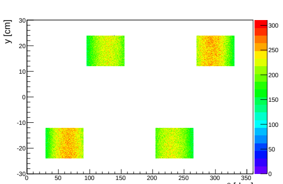
(a) Any wavelength ($\lambda >$ 0.01 Å)



(b) Cold neutrons ($\lambda \geq$ 2.0 Å)



(c) Thermal neutrons (.5 Å $\leq \lambda <$ 2.0 Å)



(d) Hot neutrons (.01 Å $\leq \lambda <$ .5 Å)

Figure 3: Neutron distribution on the beam extraction surface at 2 m radius, with different wavelength requirements. The main part of the excess neutrons in the two forward pointing windows ($\theta \in [30°; 90°]$ and $\theta \in [270°; 330°]$) are thermal and hot, a visualization of this is shown in Figure 4. Most instrument will be given a single slot of 5°x12 cm. Note that all of these distributions are flat in y and symmetric in θ around the beam axis (180° or 0°).

The TDR model of ESS [1] consists of a thermal moderator and a cold moderator positioned near the center of four 60° beam extraction windows. Some of the neutrons emitted from the thermal/cold moderator or from the reflectors arrive on one of these four 2 m beam extraction windows, as seen in Figure 3. Each of these 60° beam windows will be subdivided into twelve 5° beam slots, most of which will host an extraction instrument. These slots have been indexed in increasing order with θ, first slot being slot 0 at $\theta \in [30; 35]$.

Looking at a flat moderator surface, one will discover that the neutrons emitted in an angle with respect to the surface will be suppressed because they need to traverse more material in order to reach the surface. Traversing more material, causes more absorption and more re-scatter. This means that the maximum intensity from a moderator surface is expected to be directly in front of it, then falling off as something cosine-like as the surface is viewed at an angle wrt. the surface normal. This is also the case for the thermal neutrons from the thermal moderator at ESS, even though this is not how it looks from Figure 3 and 4. This is due to the two figures showing all neutrons arriving on the extraction surface, and as a trivial consequence thermal neutrons from the reflectors and from the cold moderator are included. The reason why this is asymmetric is that there are more neutrons in the reflector on the cold moderator side of the moderator-reflector system (due to the forward pointing proton beam and the reflector being closer to the spallation hot spot), this can be seen from Figure 5.

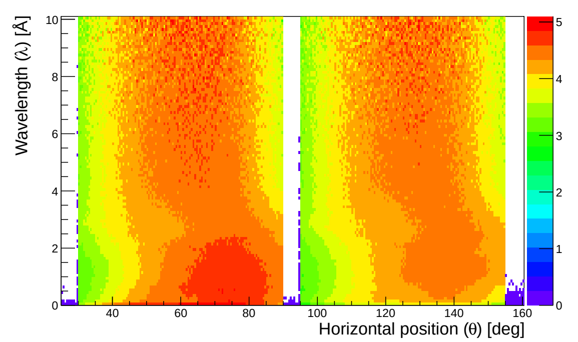
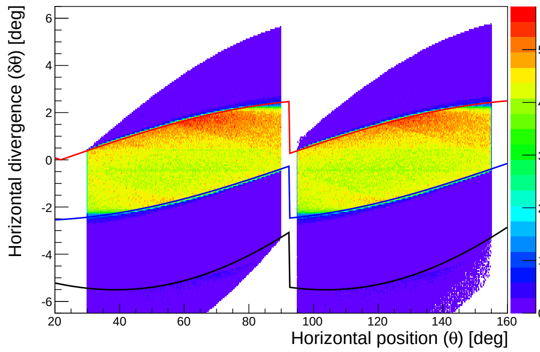


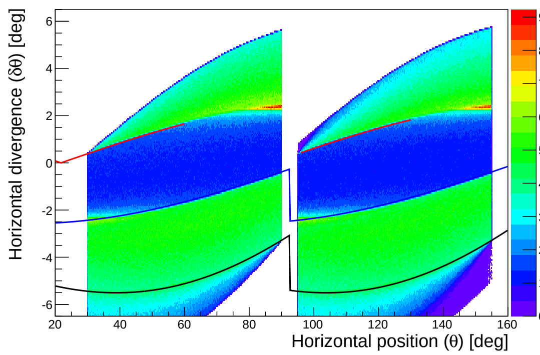
Figure 4: Horizontal wavelength spectra for a forward (30°-90°) and a backward (95°-155°) extraction window on the beam extraction surface at 2 m radius (slice-wise normalized in λ to enhance horizontal structure). Cold neutrons have equal distribution in both forward and backward window, however, there are more cold neutrons centrally in the extraction window. Thermal and hot neutrons are mainly forward directed.

Angular distribution

The horizontal divergence ($\delta\theta$) for cold and thermal neutrons observed from different extraction positions (θ), can



(a) Cold neutrons ($\lambda \geq 2.0$ Å)



(b) Thermal neutrons ($.5$ Å $\leq \lambda < 2.0$ Å)

Figure 5: θ vs $\delta\theta$ for cold and thermal neutrons. The lines represents edges between characteristic areas: cold side reflector - red - cold moderator - blue - thermal moderator - black - thermal reflector. The red line have been removed from a region, to obtain better view the thermal hotspot near $80° - 90°$ and $145° - 155°$ in (b).

be seen in Figure 5. The Figure shows quite a few differences from extraction position to extraction position. These differences might be exploited by instruments depending on their demands on wavelength spectrum and beam footprint, a couple of ideas/examples of this is found in the next section. The structure of the cold spectrum, shown in Figure 5a, can be explained by the properties of para-hydrogen: scattering on the spin-singlet state of para-hydrogen becomes unavailable at 15.2 meV, and in turn the moderator becomes transparent. As a result of this transparency neutrons are (to first order) emitted from the point where they scattered below this energy ($\lambda \sim 2.3$ Å). As thermal neutrons entering a cold moderator will be down scattered in very few collisions, with a short mean free path, they are observed near the interfaces where they enter the cold para-hydrogen moderator. This effect is not very visible for central extraction positions, as there is no such interface in line of sight of the moderator (see Figure 1). The effect is enhanced for instruments opposite the cold moderator, as they are viewing the interface between the reflector and the cold moderator, where more neutrons enter the moderator compared to the interface between the thermal moderator and the cold moderator.

As seen in Figure 5b, the thermal neutrons are fairly evenly distributed over all of the thermal moderator. However, when observing thermal neutrons from the reflector next to the cold moderator, one discovers a hotspot near the interface between the cold moderator and the reflector, but only when viewed from the opposite side of the beam extraction window. The reason is that most neutrons, emitted through a surface are forward directed, and as the surface is viewed at the lowest angle from the opposite side of the extraction window ($\sim 30°$ wrt. the surface normal) most neutrons are observed here.

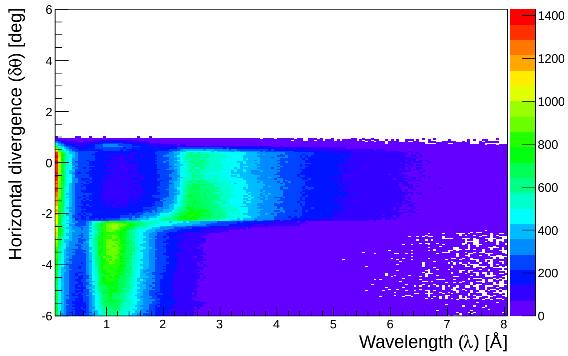
Figure 6 shows a more detailed view of the angular distribution of neutrons in different wavelength regions, for three specific extraction locations. Namely the most forward pointing slot, on the cold moderator side of the extraction window (6a); one of the 2 central slots in the extraction window, directly in front of the thermal moderator surface (6b) and the slot at the thermal moderator side of the extraction window, where the thermal neutron hotspot at the reflector next to the moderator is most intense (6c).

Optimization of instruments position and orientation

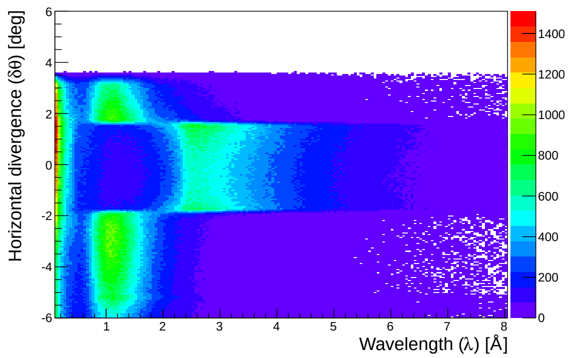
For most instruments the first thing to consider from the knowledge obtained in this study, is background. Moving from a forward pointing extraction window to a backward pointing window, reduces high energy background, along with hot and thermal neutron flux, it does however not change the cold neutron intensity significantly. This means that instruments which only concerns with cold neutrons, should be position them self in backward pointing slots. For thermal or bispectral instruments, it should be carefully considered if more thermal neutrons are worth the extra background.

One example, of a more complex utilization of a more specific feature of the spatial and angular distribution of neutrons could be for bispectral extraction. At first glance it would seem reasonable to pick an extraction slot near the center of the extraction window where both cold flux and thermal flux from the thermal moderator is at its maximum. However, moving the bispectral instrument to the thermal moderator side of the extraction window, aligning it to look at the interface between the reflector and the cold moderator, will allow the instrument to extract both cold neutrons and thermal neutrons, even without the use of a bispectral supermirror. The bispectral mirror can then be added to enhance cold neutron extraction, and in case of failure, due to radiation damage or its like, the mirror can be removed and the instrument will still accept quite some cold neutrons.

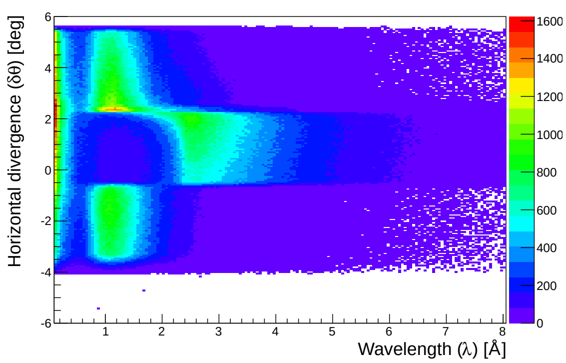
Also the instruments interested in neutrons with wavelengths near 2 Å should consider the extraction slots near the sides of the extraction window, as these positions have far more neutrons in this intermediate wavelength range ($\lambda \in [1.8$ Å$; 2.2$ Å$]$), originating from the interface be-



(a) Slot 0: Cold moderator side



(b) Slot 5: Central slot



(c) slot 11: Thermal moderator side

Figure 6: $\delta\theta$ vs λ for three different forward pointing extraction slots. Note how the optimal extraction angle for thermal neutrons, changes for different slots.

tween the cold and thermal moderator or the cold moderator and the reflector.

Conclusion

The present studies have mapped the differences in various neutron distributions for different angles of view and position of extraction. This study showed that there are quite some differences from slot to slot in the origin and spectrum of neutrons. Any experiment should chose their beam slot carefully and heavily consider which direction to align their guide. Changing orientation or moving position changes which ranges of neutrons are accepted by a guide. Such optimizations can not only be used to enhances the intensities of wanted neutrons and help shape the beam footprint, but it can also be used to suppress unwanted background.

References

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[2] Laurie S. Waters, Gregg W. McKinney, Joe W. Durkee, Michael L. Fensin, John S. Hendricks, et al. The MCNPX Monte Carlo radiation transport code. *AIP Conf.Proc.*, 896:81–90, 2007.