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Unperturbed moderator brightness in pulsed neutron sources

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ABSTRACT

The unperturbed neutron brightness of a moderator can be defined from the number of neutrons leaving the surface of a moderator completely surrounded by a reflector. Without openings for beam extraction, it is the maximum brightness that can be theoretically achieved in a moderator. The unperturbed brightness of a cylindrical cold moderator filled with pure para-H_2 was calculated using MCNPX; the moderator dimensions were optimised, for a fixed target and reflector geometry corresponding to the present concept for the ESS spallation source. This quantity does not depend on openings for beam extraction and therefore can be used for a first-round optimisation of a moderator, before effects due to beam openings are considered. We find that such an optimisation yields to a factor of 2 increase with respect to a conventional volume moderator, large enough to accommodate a viewed surface of 12×12 cm^2: the unperturbed neutron brightness is maximum for a disc-shaped moderator of 15 cm diameter, 1.4 cm height.

The reasons for this increase can be related to the properties of the scattering cross-section of para-H_2, to the added reflector around the exit surface in the case of a compact moderator, and to a directionality effect. This large optimisation gain in the unperturbed brightness hints towards similar potentials for the perturbed neutron brightness, in particular in conjunction with advancing the optical quality of neutron delivery from the moderator to the sample, where by Liouville theorem the brightness is conserved over the beam trajectory, except for absorption and similar type losses.

1. Introduction

The European Spallation Source (ESS), which entered in the construction phase in 2013 in Lund, Sweden, aims at starting operations and delivering the first neutrons in 2019 [1]. At 5 MW time average power, and 125 MW peak power, ESS will be the most powerful neutron source in the world for neutron scattering studies of condensed matter. Neutrons will be produced by a 2.5 GeV proton beam impinging on a target made of tungsten. ESS will be the first high-power long pulse source [2], the pulse length of the beam will be of 2.86 ms, with 14 Hz repetition rate.

A key for a highly performing neutron source is the optimisation of the configuration of the target, moderator and reflector assembly [3]. The use of tungsten as spallation material will ensure a high neutron yield per incoming proton; the high density of tungsten favours the production of neutrons in a small volume, increasing the probability that neutrons will eventually be slowed down by the moderators placed next to the target. The presence of a reflector surrounding the moderators is essential to increase the neutron intensity from the moderators. For a long pulse facility such as ESS, the recommended moderator type is a coupled, pure para-H_2 moderator [4], because it delivers the highest brightness per proton. The coupling between moderator and reflector (i.e. the absence of any neutron absorbing material to shape the pulse length) guarantees the highest peak flux from the moderator surface; pulses are shaped in time by choppers placed in the beam lines.

The goal of the neutronic optimisation is to determine the configuration that delivers the largest spectral brightness in the wavelength region of interest. The brightness of a neutron source is the number of neutrons emitted per unit time, per unit solid angle, per unit energy (or wavelength), per unit area of the surface. Unlike the flux, the brightness of a neutron beam does not depend on the distance from the source: it is therefore a quantity that characterises the neutron source and depends on its design. Requirements coming from the beam extraction (such as needed viewed moderator surface, and number of beam ports) influence the design choices. In fact, neutrons are extracted via the beam extraction system, consisting of beam ports with neutron guides starting at about 2 m from the moderator surface. Openings in the reflector allow for viewing the surface of the moderators. The angular coverage of the openings, and their positioning, affect the overall performance of the moderator. Other requirements that have an effect on moderator design come from engineering, such as heat load on the moderator cryogenic parts.

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Ultimately, the overall performance of a neutron source depends on the source brightness, the moderator surface area, and the quality of neutron optics, which is inherently poorer than light optics. In case of perfect optics with unlimited aperture, the best solution would be a source of some reasonable size with maximum brightness, which could be imaged without losses to the sample, eventually magnified or reduced. In this paper we aim at discussing and optimising the brightness of a moderator without considering perturbation by the beam extraction system, and the problem of beam optics.

2. Unperturbed moderators

2.1. Unperturbed moderator brightness

Cold moderators in high-power spallation sources such as SNS [5] and JSNS at J-PARC [6] consist of volumes of liquid H_2 surrounded by reflector material, typically Be. In order to extract the neutrons, openings must be placed in the reflector. The ESS baseline configuration foresees two 60° openings for each moderator, placed approximately face-to-face, so that the moderator surface (of 12×12 cm^2) can be viewed by several neutron extraction beam lines [1]. Because of the reduction of reflector material, the presence of these openings has a strong influence on the performance of the moderator. For comparison, the brightness of a moderator surface of 12×12 cm^2 was calculated in two configurations of the openings: (i) baseline configuration with two 60° openings opposite to each other, capable to deliver neutrons to several beam lines, and (ii) configuration with only one 12×12 cm^2 beam line opening of constant cross-section (0° opening angle). The brightness of (ii) is of 50% higher than (i).

Conventionally, the design process of the target–moderator–reflector configuration takes into account the presence of the openings from the beginning of the optimisation study: the figure of merit used in Monte Carlo calculations for the neutronic performance is the brightness of the moderator surfaces viewed through the openings, calculated with point detector tallies placed at a distance. This kind of optimisation process is certainly effective. However, one could consider as a starting point in the moderator design the ideal case where the moderator is completely surrounded by reflector, without considering the beam openings that decrease its efficiency. Such an *unperturbed* neutron brightness corresponds to the maximum theoretical brightness that can be delivered by the moderator and it is therefore a very interesting quantity to look at: it is a fundamental quantity that does not depend on how the neutrons are extracted, but nevertheless can be expected to be related to the final performance of the neutron source.

Unperturbed neutron fluxes are commonly calculated to estimate the performances of research reactors. In the framework of pulsed spallation sources, unperturbed flux was computed in a few cases in order to compare with the performance of research reactors [7]. In Refs. [7,8] it was pointed out that the ratio between perturbed and unperturbed flux is different in reactors and spallation sources. However, up to now unperturbed moderator brightness has not been used as a parameter in moderator design of pulsed spallation sources.

3. Unperturbed moderator optimisation

We have performed moderator studies by Monte Carlo simulations using the MCNPX 2.7.0 [9] code coupled with ENDF/B-VII data libraries [10]. The nuclear interactions outside the libraries energy range were modelled using the standard Bertini model in MCNPX [11].

We considered a basic model geometry of target–moderator–reflector based on the present ESS concept [1]. The spallation target is a wheel containing pure tungsten in the neutron-producing zone (See Fig. 1). The thickness of tungsten is of 8 cm, the outer diameter is of 2.5 m. The tungsten is enclosed in an iron shroud. The simulated beam footprint is rectangular with dimensions of 16×6 cm^2 and a parabolic shape. The moderators are placed above and below the target. They consist of cylindrical aluminum vessels containing pure para-hydrogen at 20 K. A light water premoderator surrounds each moderator, with the function of partially thermalising the neutrons that will undergo final thermalisation inside the liquid-H_2 of the moderator. The inner reflector is a cylinder of Be of 60 cm diameter and 90 cm height. The outer reflector is a large volume of iron surrounding the inner reflector.

Since the goal of this work is to study the *unperturbed* moderator performance, we had to score neutrons exiting the whole side surface of the moderator. So, we could not make use of conventional scoring by a point detector and benefit from its variance reduction biasing. Instead, we used the surface crossing tally, and scored neutrons exiting the moderator side surface within a narrow cone of 5° angle around the axis, oriented towards the surface normal vector at the point where a particular neutron exited it. The sector angle value was intentionally chosen to be small in order to select neutrons which will potentially arrive to the neutron guide openings (as in a conventional estimation with a point detector) and at the same time large enough to be able to collect enough statistics in reasonable time.

The performance of the moderator was estimated as the number of neutrons with $E < 5$ meV integrated over all moderator side surface and time, within 5° sector angle, normalised to the solid angle Ω formed by this cone, and the moderator side

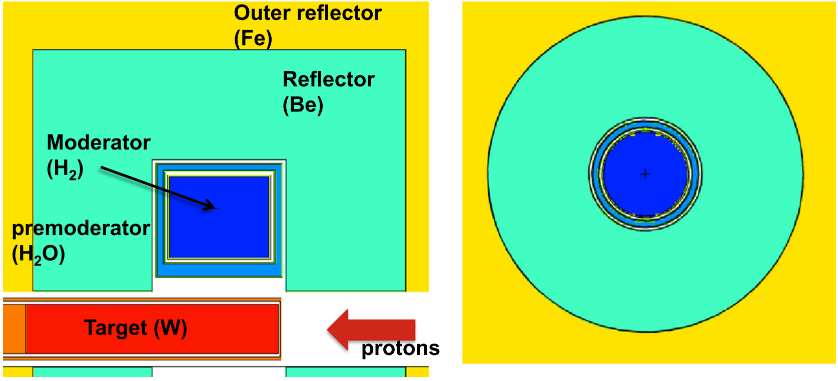

Fig. 1. Side view MCNPX model of the unperturbed moderator (left). Top view of the unperturbed moderator (right).