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Enhancing neutron beam production with a convoluted moderator

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ABSTRACT

We describe a new concept for a neutron moderating assembly resulting in the more efficient production of slow neutron beams. The Convoluted Moderator, a heterogeneous stack of interleaved moderating material and nearly transparent single-crystal spacers, is a directionally enhanced neutron beam source, improving beam emission over an angular range comparable to the range accepted by neutron beam lines and guides. We have demonstrated gains of 50% in slow neutron intensity for a given fast neutron production rate while simultaneously reducing the wavelength-dependent emission time dispersion by 25%, both coming from a geometric effect in which the neutron beam lines view a large surface area of moderating material in a relatively small volume. Additionally, we have confirmed a Bragg-enhancement effect arising from coherent scattering within the single-crystal spacers. We have not observed hypothesized refractive effects leading to additional gains at long wavelength. In addition to confirmation of the validity of the Convoluted Moderator concept, our measurements provide a series of benchmark experiments suitable for developing simulation and analysis techniques for practical optimization and eventual implementation at slow neutron source facilities.

1. Introduction

Slow neutron beams are used in a variety of research techniques in the study of condensed matter, nuclear physics, and nuclear engineering. These slow neutron beams are produced by a remarkably inefficient slowing-down and thermalization process, in which very few of the fast neutrons produced appear in the useful neutron beam. The most inefficient step in this process occurs when neutrons are emitted from the face of the neutron moderator assembly with weak angular dependence, and only the small fraction that happen to be going in the right direction (i.e., along the neutron beam line) are exploited. Historical efforts to improve this situation include the “grooved” moderator concept, implemented at IPNS [1], KENS [2], and ISIS Target Station 2 [3], in which neutrons leaving the bright “groove” surfaces in the wrong direction (that is, any direction but along a beam line viewing the moderator) are scattered from the “fins,” possibly back into the moderator, and get another chance to be usefully emitted; the “V” moderator concept implemented at IBR-2 [4]; and re-entrant cold sources such as NIST [5], the ILL [6], and HFIR [7,8].

The effectiveness of the grooved and re-entrant moderator concepts implies that any neutron scattering event that redirects the neutron towards a neutron beam line can result in a gain in beam brightness comparable to the ratio of that event's probability to the fractional solid angle subtended by that beam line. As the fractional solid angle subtended by a typical beam line entrance is 10^{-5}, even a small additional probability could have dramatic effects. Such events might include neutron refraction, reflection, surface scattering and scattering from single crystals.

The gains attainable via this fundamental concept are dramatic, and can be roughly assessed by considering the microscopic processes going on within the moderator. Once a neutron has reached the desired energy range within a conventional thermalizing moderator, it has approximately a 10^{-6}–10^{-8} chance per scattering event of going directly into a neutron beam line. A neutron in this energy range will scatter many times, and thus have many opportunities to be emitted in a useful direction with an acceptable time-delay. The time-delay (or lack thereof) is only of significant interest for a pulsed neutron source. The enhanced brightness over a monolithic moderator, in which the surface brightness is reduced significantly over the inaccessible central

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brightness, is of equal interest for both continuous and pulsed sources. If we can provide alternate routes for a neutron undergoing a scattering event to come out in a useful direction, comparable in likelihood to the direct route described above, we significantly increase the brightness of the neutron beam. This enhanced path of egress from the moderator interior is, of course, accompanied by a loss in moderating material; the relevant gain in brightness for the modified moderator assembly is the gain over a separately optimized system without that modification.

1.1. The Convoluted Moderator

We define a Convoluted Moderator as a moderator assembly with alternating layers of moderating material and largely transparent non-moderating material (possibly void) arranged in such a way as to illuminate neutron beam lines with neutrons coming out of the interfacial layers at angles (to those surfaces) far from the perpendicular. Fig. 1 shows such a concept (the angles and dimensions shown are not to scale), in which gains accrue to a beam exiting the moderator assembly to the right.

Such a moderator assembly is a directionally enhanced neutron source, emitting neutrons along the plane defined by the transparent layers with a higher probability (per unit solid angle) than it does into other directions, making brighter beams from a fixed fast neutron production rate. Such a moderator offers three avenues for potential gains in overall source intensity, as quantified by the integrated phase space density of neutrons arriving at the beam lines in question per primary source neutron produced:

1. *Geometric effect*: The geometric effect comes from illuminating the neutron beam line(s) with low-angle views of the large surface areas between the moderating layers and the non-moderating layers. This effect will be present with any transparent material used as the non-moderating layer (including void). Typical neutron transport analysis methods do not address grazing-incidence surface crossing in a particularly robust manner [9], and may not adequately describe this effect.
2. *Bragg effect*: Should the non-moderating layer be made from a crystalline material (either polycrystalline or single crystal), neutrons traveling through the layer will be subject to Bragg scattering. As the flight path through such a layer might extend several tens of millimeters, these effects must be considered even should they prove disadvantageous. If such Bragg scattering can be exploited, however, it might result in dramatic enhancement of beam intensity at specific wavelengths. Single crystal scattering is usually ignored in neutron transport calculations, and so is difficult to model with existing tools.
3. *Refractive effect*: Neutrons crossing the interface between dissimilar materials are subject to refraction. This refraction can be exploited by taking neutrons that would be almost within the desired angular emission range and refracting them into the direction of the neutron beam line. This effect would be more pronounced at increased neutron wavelength, and would involve small changes in angle, which we hope to leverage into significant increases in beam intensity at long wavelengths. Refractive effects will increase as the difference in the refractive indices of the moderating and non-moderating layers, and will of course be present even when the non-moderating "layers" are in fact void. Neutron refraction is also not treated in a general fashion in widely available neutron transport analysis tools.

The geometric effects can be considered as increasing the viewed surface area of the moderating material more rapidly than the brightness falls off with viewing angle by enough to counteract losses coming from the reduction in the moderating material effective density. The Bragg gains combine an array of correlated directions relative to the interface and wavelengths into highly collimated beams. The refractive gains combine a wide array of correlated directions and positions along the moderating material/non-moderating material interface(s) into highly collimated beams exiting the moderator.

A convoluted moderator is conceptually different from a grooved moderator—in a grooved moderator, one attempts to optimize beam extraction from the base(s) of the grooves, tolerating the secondary beam coming from the tip(s) of the fins. In a convoluted moderator, one attempts to optimize beam extraction from the sides of the fins. While subtle, this distinction results in large differences in the observed performance. A convoluted moderator is different from the re-entrant moderators (cold sources) often implemented at continuous neutron source facilities as well—the reentrant cold source is intended to optimally thermalize the emitted neutron beam by containing the neutrons for many collisions, bringing them into better thermal equilibrium with the moderator material at the cost of significant time-dispersion in the neutron emission, which is unacceptable in a short-pulsed source system. The brightness gains for a convoluted moderator concept apply to continuous sources as well as pulsed sources; although the advantage of smaller time-dispersion for the convoluted moderator will be unimportant, the enhanced

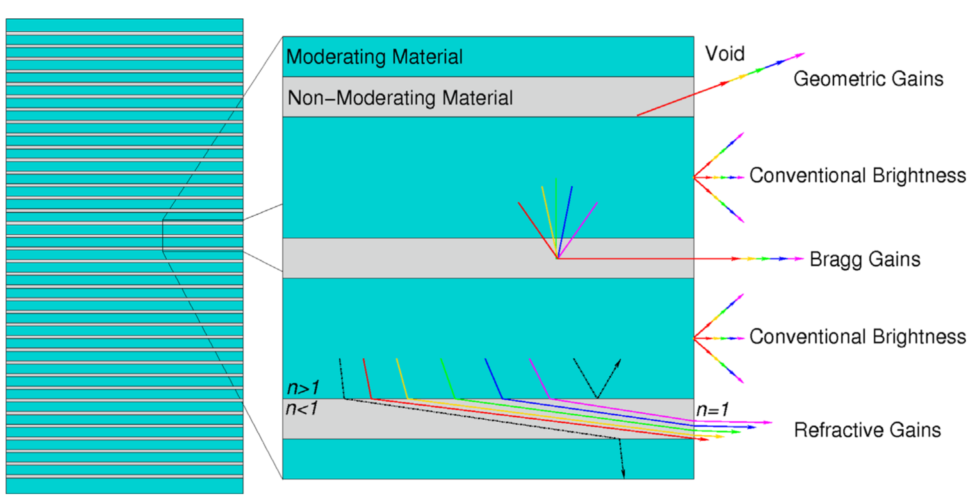

Fig. 1. A convoluted moderator, showing the origin of potential brightness gains. The figure is not to scale, and only one-half of each (symmetric about the normal) set of gains is shown.

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