Nuclear Instruments and Methods in Physics Research A 777 (2015) 6–14

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A new guide concept for a homogenous neutron beam without direct line of sight

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ARTICLE INFO

Article history:
Received 20 August 2014
Received in revised form
28 November 2014
Accepted 1 December 2014
Available online 19 December 2014

Keywords:
VITESS
Monte Carlo simulation
Neutron instrumentation
Neutron guides
Elliptic guides
European Spallation Source

ABSTRACT

Neutron guide tubes are used to transport neutrons efficiently from the source to distant instruments. Ballistic neutron guides, which have an expanding section in the beginning and a contracting section in the end, reduce the total number of reflections and improve transport efficiency in long guides. Long pulse spallation sources like the European Spallation Source require very long guides. Challenges in ballistic guide design are imposed by the need for small virtual sources and the prevention of direct line of sight to the source, because both tend to produce inhomogeneous beam distributions, and the latter reduces transmission for short wavelengths.

This article describes a novel ballistic guide design based on elliptic profiles. It incorporates a carefully positioned and angled kink to avoid line of sight to the source and a narrow point to position a chopper. This design reduces the number of reflections in long guides and improves transmission, especially at short wavelengths, compared to other solutions avoiding a direct line of sight.

1. Introduction

Neutron guide tubes transport neutrons by reflections from mirrored walls inside evacuated tubes. Guides have greatly improved the efficiency of usage of neutron sources by delivering relatively high flux to instruments at large distances from the source. This permits a larger number of instruments to use the source and to operate in a low background environment. The longer flight paths can be used to improve resolution on pulsed sources. Modern sources require beam transport over even longer distances. It has been found advantageous to replace conventional straight and curved guides by ballistic guide geometries of various sorts where the guide spatial cross-section in the middle is expanded from narrow ends. This reduces the beam divergence in the middle of the guide which simultaneously reduces the number of reflections and the angles of reflection thus increasing transmission [1].

For many years it was believed that ballistic guides with an elliptic profile permitted single bounce transport of rays from guide start to end. This belief suggested that elliptic guides were as near perfection as possible. Note that in this view the ellipse is not acting as a guide (where multiple reflections are normal) but as a neutron focusing device. This single bounce view has now been demonstrated to be untrue except for extremely small sources and near perfect elliptic guide wall profiles [2]. This new understanding explains the ugly divergence distributions often seen in Monte Carlo (MC) computer simulation studies of elliptic guide transmission. This new understanding of the paths followed by neutrons in elliptic guides also suggests a way to improve their performance.

The driving force for this study was the guide design for an instrument at the proposed European Spallation Source (ESS) [3], namely the "Extreme Environment Instrument," to be used for diffraction, SANS and spectrometry [4]. The requests from the instrument responsible for the beam-line properties were

1. Wavelength range: 1–6 Å
2. Length about 150 m
3. Small virtual source (to position a chopper to generate short pulses)
4. High flux at the sample
5. Symmetric and smooth divergence profile (up to 2.0°) in the final beam, preferably Gaussian-like
6. A spatially uniform final beam
7. No direct line of sight through the guide
8. Narrow point for a beam chopper in the middle of the instrument

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http://dx.doi.org/10.1016/j.nima.2014.12.003
0168-9002/

However, it is clear that a guide design fulfilling these needs should have more general applicability for other sources and instruments. Therefore we have avoided any ESS specific features and tried to draw general conclusions for all instruments with similar properties.

2. Guide design

It is usual to build guides with rectangular cross sections perpendicular to the beam propagation axis with all mirror surfaces either vertical or horizontal. This is assumed here and, in such an arrangement, the beam behavior vertically and in-plane can be discussed separately.

Elliptic neutron guides, first suggested by Schanzer et al. [5], have been shown to work in practice and are now the preferred choice for many long guides. However, elliptical guides have some drawbacks:

1. Large cross-sections give the highest transmission for single elliptical guides [6] and this makes it difficult to position a chopper cascade along the guide.
2. Neutron rays starting in a focal point of an ellipse undergo an "angle inversion" after reflection

$$\gamma_{out}\gamma_{in} \approx -\psi^2 \quad (1)$$

where γ_{in} and γ_{out} are the incident and transmitted ray divergences from the propagation axis and ψ is the ellipse "characteristic angle" with $\psi \approx \text{atan}(b/a)$ and a and b the ellipse semi major and semi minor axis lengths. ψ is typically small ($\approx 0.1^\circ$). This angle inversion means that the angular distribution in the beam at the end of the ellipse differs from that at the source for neutrons undergoing only one reflection.
3. The image has low intensity at very small divergences $\gamma_{out} < \psi$, because the value of γ_{in} which can be reflected near the guide entrance is limited by the reflectivity of the coating.
4. If the source has finite size, even very small, or the elliptic profile is composed of linear segments, as is usual, then these geometrical imperfections lead to a "coma" aberration [7] and multiple reflections. In designing or simulating such segmented elliptic guides it is necessary to have surprisingly short segment sizes near the highly curved ends of the ellipses to reduce aberrations and maintain transmission [2].

Two elliptic guides in succession (a double ellipse) with a shared focal point at the middle of the guide length may seem at first glance to offer a simple way to avoid these disadvantages, as the second ellipse undoes the angle inversion introduced by the first. MC simulations show that a double ellipse partly restores the beam distribution. However, any multiple reflections within either ellipse (as seem to be common in practice) destroy this effect so the double ellipse can only work in particular cases, that is, with point-like sources, very good guide shape and reflections not too close to the focal points [2]. These are the conditions which are exploited in the SELENE design [8]. Significantly, for an "equivalent" system with equal ψ, a double ellipse halves the maximal width for a given design thus reducing the cost of the guide for equal accepted incident beam divergence (although delivering a smaller beam area). This approach has been successfully used for the design of the guide system of the instrument PowTex [9].

MC simulations show that the main problem area for multiple reflections is near the focal point in the center of the double ellipse. This suggested a line of thought which led to the new guide design described in this article. The next section of the article describes this line of thinking. Following this approach seems to improve the situation in several ways.

Conventional straight and curved guides have near perfect transmission for neutrons of "small enough" divergence (which is proportional to wavelength). "Small enough" in this context is set by the limitations of the neutron super-mirrors used in the guide. For natural nickel mirrors the reflectivity at the walls is uniformly 99% for glancing angles of reflection less than the critical angle, $m\lambda\theta_C$ where $\theta_C \approx 0.1^\circ/\text{Å}$ and here $m=1$. Mirrors with higher critical angles (larger m) can be constructed but the reflectivity falls off more or less linearly for glancing angles above the $m=1$ limit up to the cutoff angle, thus reducing the reflectivity for neutrons of large divergence. For a neutron ray undergoing only one reflection this is not so important but, in a long guide, neutrons often undergo many reflections and then this falloff in reflectivity greatly reduces transmission. The result is that long conventional guides with high m mirrors have transmission little different from that of simple nickel guides. So we seek to reduce the average number of reflections for rays in the beam. Increasing guide transmission by using ballistic geometries and high m mirrors is then the pursuit of usable increased beam angular divergence at the guide entrance and exit.

Starting with a double ellipse design, note that the angle inversion, Eq. (1), means that neutron rays incident with large divergence (relative to the angle ψ), $\gamma_{In} > \psi$, bounce first in the first half of the first ellipse and have small divergence at the midpoint while rays with small incident divergence, $\gamma_{In} < \psi$, bounce first in the second half of the first ellipse and have large divergence at the midpoint. For the very long guides considered here, ψ is quite small compared to the beam divergence we wish to transport, so these initially small divergence rays represent only a small fraction of the total beam intensity. Let us then consider first only the "large" divergence ($\gamma_{In} > \psi$) part of the incident beam which is reflected first in the first half of the first ellipse.

Rays originating away from the source center will not be reflected towards a spot of source size at the center of the double ellipse, if reflections occur in the first half of the ellipse; instead the focal area is much larger. This results in multiple reflections near its exit, if the first ellipse has an exit equal in size to the entrance [2]. The effect is most pronounced for guides starting close to the source.

In the case considered here, most of the desired beam intensity has incident divergence greater than ψ. So the second half of the first ellipse contributes little to intensity by reflecting neutrons coming directly from the source; but it causes a lot of multiple reflections. Furthermore, the initially large divergence rays (from the center of the source) must bounce in the first half of the first ellipse and the second half of the second ellipse to be focused to the sample. Thus, keeping only these two elliptic segments and omitting the entire midsection of the guide (or replacing it with a straight guide section as shown in Fig. 1a) should improve the total transmission and beam character of the bulk of the beam intensity. Liouville's theorem shows that the effect of the second half ellipse at the guide end is to transform a small divergence beam to a larger divergence with a corresponding spatial compression. The guide design largely ignores the optics of the transmission for the small fraction of the beam with initially small divergence, but these rays may find their way through the guide anyway especially since guides usually transmit small divergence rays well.

So the first step in the new design is as shown in Fig. 1a. Initial simulations of this design showed great promise and it turns out that other groups ([10,6]) had reached similar design ideas based solely on simulation work.

Simulations of guide systems with guides of constant cross-section connecting two partial ellipses – half axes *a* and *b* – show best performance for the case of two half ellipses and a constant guide of maximal width and height *2b* and length *2a* in between