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Multiple reflections in elliptic neutron guide tubes

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ABSTRACT

Neutron guide tubes are widely used to transport neutron beams over long distances. The neutron mirrors used to line the guide tubes have imperfect reflectivity and, in long conventional guides, the average number of reflections for neutron rays becomes large thus reducing the transmission. This issue is extremely important for modern spallation sources, especially for the proposed long pulse European Spallation Source to be constructed in Lund, Sweden, where technical constraints require many instruments to be far from the source. Several solutions to the problem of transporting neutrons over long distances have been proposed and currently the most favored model is that of guides with elliptic shapes. It is widely believed that elliptic guides transport neutron rays from source to sample with a single bounce, a near perfect solution for long neutron guides, and a view which is true in ideal circumstances. This article uses computed Monte Carlo ray tracing simulations (VITESS) and other techniques to demonstrate that transport of neutrons by realistic elliptic guides usually involves many reflections, contrary to the usual expectations. These multiple reflections explain the irregular divergence distributions observed in computer simulations of transmission by some elliptic guides.

1. Introduction and literature review

Neutron guides [1] are used to transport beams from sources to distant locations and have greatly enhanced the ability to use neutron sources effectively by making it possible to site larger numbers of instruments far from the source where background is lower. The guides are constructed as evacuated tubes with the inner walls coated to reflect neutrons. For many years, neutron guides used pure ^{Nat}Ni or isotope ^{58}Ni mirrors for which the limiting "critical" angle for total external reflection depends on the neutron wavelength, λ, and is $\lambda\theta_C$ where $\theta_{C,Ni}=0.10^\circ$ and $\theta_{C,Ni-58}=0.117^\circ$. Multilayer "super-mirror" coatings [2–4] have been the subject of intense development work and increase the effective critical angle to $m\theta_{C,Ni}$ where at present m may be as large as 7. Increasing the critical angle increases the angular acceptance of neutron guides and hence the integrated transmitted intensity. However, the reflectivity of super-mirror coatings, R_{SM}, is constant at about 99% up to $m=1$ but then falls roughly linearly with increasing m (corresponding to increasing angle of reflection) at between 6 and 10% per unit in m. This falloff in R_{SM} has a dramatic effect on guide transmission (τ) if the number of reflections exceeds 2 or 3. Neutrons traveling through long (>40 m or so) conventional guides undergo many reflections and then super-mirror coatings give total τ little better than that for simple Ni mirrors.

In this context, the idea of "ballistic" guides [5] was a most significant advance. A ballistic guide reduces the beam divergence by using a tapered guide entry to expand the guide cross-section. The now low divergence beam is transmitted with a reduced number of reflections through a long straight guide of large cross-section before a linearly tapered converging section recompresses the beam spatially and restores the initial beam divergence. Simple ballistic guides with linearly tapered entry and exit tend to produce relatively inhomogeneous intensity distributions with divergence, γ, $\tau(\gamma)$. Alternative ballistic geometries have been explored and using parabolically rather than linearly tapered guide ends improves the beam characteristics. Among associated ideas, that of the elliptic guide has generated great enthusiasm [6–38] both for short focusing devices to converge a beam onto a sample and for long distance neutron transport. Schanzer et al. [6] seem to have first introduced the idea of elliptic guides and their simulation results showed a more homogeneous phase space distribution than that from linear ballistic guides with the added advantage of moving the most intense beam spot away from the guide end. It is widely believed that a neutron source placed at one focal point of an elliptic guide will be imaged at the second focal point with the transported neutrons undergoing a single reflection (e.g. [14]). For practical guides, which usually have rectangular cross-sections, this becomes one bounce per dimension [27]. This one bounce transmission almost completely overcomes the problem of reduced mirror reflectivity for $m>1$. The

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new European Spallation Source (ESS) [39], to be constructed at Lund in Sweden, promises to be a large step forward in neutron scattering by providing a clean, sustainable and, most significantly, very high intensity source. Technical issues associated with the long pulse nature of the ESS source mean that many instruments will be at extremely large distances of 150 m or even 300 m from the source. Conventional straight or curved guides of such length would give very low transmission indeed. Especially for the ESS then, one reflection elliptic guides are currently expected to be a central requirement for effective instruments.

A number of articles have studied elliptic guide performance and many report significantly improved beam transport by comparison with conventional straight or curved guides. A systematic study [36] using Monte Carlo ray tracing computed simulations (MC) to compare the performance of guide geometries concluded that elliptic geometry and ballistic guides with parabolic entry and exit perform almost equally well and are strongly superior to other design geometries (except for low-divergence, long wavelength neutrons for which all guide types work well). The improved transport efficiency by elliptic guides arises from increased solid angle acceptance and delivery and it has been noted that the transport efficiency of elliptic guides increases with increasing guide length [36].

Some challenges in the use of elliptic guides have also been noted, e.g. that the effectiveness of elliptic guides is very sensitive to alignment [6,19]. While several authors describe the phase space distribution from elliptic guides as "superior" (presumably to linear ballistic designs), others, notably Stahn et al. [30,34] and Komarek et al. [27], note that the transmitted beam has an irregular phase space distribution and that coma aberrations occur. Significantly, Harjo et al. [10] simulated the transmission of an elliptic guide which showed a clear four peak structure in the two-dimensional divergence distribution. Some authors have noted or suspected that finite sources produce a coma aberration [31,35] and multiple garland reflections [10,15]. Janoschek et al. [24], actually observed multiple zigzag reflections in a simulation of a short elliptic guide. But the idea of one bounce transmission in an elliptic guide has been strongly held in spite of contradictory evidence [24,35].

It is extremely important that neutron guides remove the direct line-of-sight to the source to reduce radiation from the source due to fast neutrons and gamma rays. This remains most problematic for elliptic guides where curvature destroys the optical behavior of the devices. There has been some discussion of the use of two ellipses in series to partially remove the coma aberration [31,38] and it may be possible to use a gap between ellipses to site beam choppers [14] or to introduce a kink to remove line of sight.

A series of papers [13,32,33,37] have proposed the use of Wolter optics for neutron guides to improve the properties of the transmitted beam. In particular a hybrid elliptic–parabolic shape found using MC simulations offers good transmission and smooth divergence distribution for a particular set of source and guide parameters [37]. These authors also noted that multiple reflections take place, but concluded that their contribution to the transmitted intensity can be neglected.

In summary, it is widely believed that elliptic guides increase beam angular acceptance and give single reflection transport leading to improved transmission over other guide types. There has been some comment on inhomogeneity in the transmitted phase space but this appears to be regarded as of little practical significance with scattering through an instrument expected to smudge out the effects enough for them to be unimportant.

2. Example of MC simulation results for a single elliptic guide

The elliptic guide designs discussed seem to separate into two distinct classes. The first class uses a large source and very wide entry and exit where the guide focal point is typically well behind the source. The second class uses relatively small entries and exits with source and image at the ellipse foci. Our interest was in transporting relatively large divergence beams with low background starting from a narrow beam point suitable to host a pulse shaping chopper. So this work concentrates on this second type of elliptic guide.

MC computer simulation studies using VITESS [40] showed that the beam transported by a single guide with square cross-section and elliptic profiles in each perpendicular dimension differed from expectations with significant structure in the beam distributions at the image point. Fig. 1 illustrates the output for such a guide. The guide had a 1×1 cm^2 source and image monitor sited at the ellipse foci separated by 150 m. The maximum guide width was 0.3 m with entry and exit 20 cm from the foci (so approximately 2.2 cm wide and subtending an angle of $\pm 3.13^\circ$ at the focal points). Gravity effects were ignored in this simulation. The spatial distribution appears relatively smooth but note that it is cross like rather than uniform over the whole area.

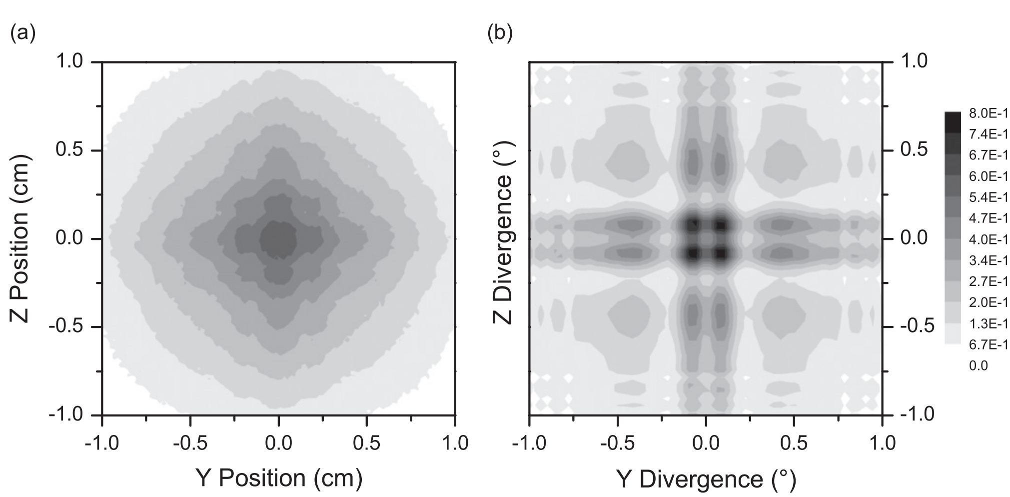

Fig. 1. Intensity for 1.5 Å neutrons as a function of position (a) and divergence (b) for a single elliptic guide 150 m long and 30 cm wide composed of 40 cm long segments, entry and exit 2.2 cm wide and 20 cm from focus, $m=6$ coating. Gravity effects are ignored. Note the cross like form in the spatial distribution and the large degree of complex structure in the divergence distributions.