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An improved elliptic guide concept for a homogeneous neutron beam without direct line of sight

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ABSTRACT

Ballistic neutron guides are efficient for neutron transport over long distances, and in particular elliptically shaped guides have received much attention lately. However, elliptic neutron guides generally deliver an inhomogeneous divergence distribution when used with a small source, and do not allow kinks or curvature to avoid a direct view from source to sample. In this paper, a kinked double-elliptic solution is found for neutron transport to a small sample from a small (virtual) source, as given e.g. for instruments using a pinhole beam extraction with a focusing feeder. A guide consisting of two elliptical parts connected by a linear kinked section is shown by VITESS simulations to deliver a high brilliance transfer as well as a homogeneous divergence distribution while avoiding direct line of sight to the source. It performs better than a recently proposed ellipse–parabola hybrid when used in a ballistic context with a kinked or curved central part. Another recently proposed solution, an analytically determined non-linear focusing guide shape, is applied here for the first time in a kinked and curved ballistic context. The latter is shown to yield comparable results for long wavelength neutrons as the guide design found here, with a larger inhomogeneity in the divergence but higher transmission of thermal neutrons. It needs however a larger (virtual) source and might be more difficult to build in a real instrument.

1. Introduction

Neutron guides are important tools used to deliver ample flux to samples at large distances from the source. Long neutron beamlines lead to low background, and are of particular interest to the planned European Spallation Source (ESS) [1] due to its long pulse and required time of flight resolution. Ballistic guides in which an expanding guide section reduces the beam divergence before the neutrons are transported by a straight guide and then focused by a guide section of decreasing spatial extension have been shown to perform better than conventional straight or curved neutron guides [2], and elliptic or parabolic guide shapes can improve the transmission even further [3].

Hence a currently widely studied guide shape is the elliptic guide profile, which in principle allows neutrons from one focal point to be transmitted to the second focal point with just one reflection. This idealized behavior was recently shown to be true only for a negligibly small fraction of neutrons under realistic conditions [4]. Even though the beam homogeneity after elliptically focusing is in general superior to the one after linear or parabolically focusing guides [5], inhomogeneous divergence distributions are often seen in Monte Carlo simulation studies of elliptical guides [4,6,7]. A further drawback is the difficulty to avoid direct line of sight, which can be solved in certain cases by gravitational bending of the elliptical guide [8], but this solution is limited to long wavelengths in a small waveband around the wavelength for which it was optimized, and cannot be expected to reduce any inhomogeneities of the divergence spectrum. An alternative central beamstop to block the direct line of sight will create a hole in the transmitted phase space.

A double ellipse somewhat improves the divergence profile with only a small loss in transmission [4] if the two ellipses have the same characteristic angle $\psi = \arctan(b/a)$, with a and b the long and short half axis length, and share a common central focal point. Furthermore, a double elliptic guide design provides a natural narrow point, which constitutes a second eye of the needle for a possible chopper placement [9]. This principle is used in the Selene [10] and POWTEX [11] guide concepts, achieving a homogeneous divergence in the respective simulations. While the latter does not avoid direct line of sight, the former does so by using only quarter ellipses acting as elliptical mirrors rather than guides,

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which are inclined and combined with slits and shielding equivalent to an effective central beamstop. This approach sacrifices intensity on the sample because the design is optimized for low background, using only the small fraction of ideal neutron trajectories from an approximate point source. Its use of elliptical guide parts as focusing devices further constrains it to shorter instrument in which gravity effects are small.

This paper describes a kinked double-elliptic guide concept for a 150 m long instrument looking at a small source, which focuses the neutron beam onto a small sample without introduction of beam inhomogeneities. The source can either be a real moderator, or a virtual source created by a preceding slit or focusing device as often considered for beamlines at the ESS, where a small beam spot close to the source is advantageous for the use of a pulse shaping chopper as well as for the placement of shielding. Guide systems intended for direct transportation from large sources will be discussed elsewhere.

Based on the ideas of Cussen [12–14], the motivation for a kinked ballistic double-ellipse, consisting of two elliptically shaped guide parts in the beginning and end connected by a linear guide section, is recalled in Section 2. After a description of boundary conditions and simulation details in Section 3, the principles of the argumentation are verified by simulation and used to design a modified kinked ballistic double-ellipse in Section 4. This new guide design is then compared in Section 5 to two recently proposed alternative approaches that have been shown to give a homogeneous divergence distribution in a focused neutron beam under different conditions or in theory: first, for the special case of a large source and an ellipse with a large opening, a hybrid guide consisting of an elliptically diverging and a parabolically converging part with roughly equal lengths and a total length of about 50 m has been shown to yield an improved divergence profile compared to a full ellipse [7]. Second, an analytical calculation using phase space considerations resulted in a non-linear shape for a focusing guide that retains a rectangular phase space [15]. These approaches are investigated here under the condition of a small (virtual) source, characterizing their performance in a ballistic guide design including a kinked or curved section to avoid direct line of sight.

2. Theoretical considerations

This section derives a double-ellipse with a linear kinked connecting section and central narrow point from ellipse properties in combination with non-ideal behavior of neutrons not coming from a focal point, summarizing considerations made in Refs. [12–14] in context of a guide design for an ESS extreme environment (ESSEX) instrument.

2.1. General guide shape

The second ellipse in a double-elliptic guide as drawn in Fig. 1(a) principally reverses neutron trajectories and thereby partly reverses unwanted aberration effects of the first ellipse only under idealized conditions of neutrons emerging from a point source. Under realistic conditions, i.e. with an extended source (millimeters and larger), gravity altering neutron trajectories (and thereby reflection angles) and a possible non-perfect elliptic guide shape constructed out of straight pieces, most neutrons will undergo multiple reflections already in the first ellipse and the neutron beam cannot be expected to be perfectly focused at the central focal point. The transmission compared to a single ellipse will decrease even more than expected from the ideally only doubled number of reflections. Hence a straight forward modification to the double elliptic guide design is to replace the converging part of the first ellipse as well as the diverging part of the second ellipse by a straight guide, to obtain the ballistic double-ellipse in Fig. 1(b). Note that differently to most ballistic guides with elliptically focusing ends, the elliptic guide parts still share a common focal point in the center of the straight guide.

2.2. Avoiding direct line of sight

The constant connection between elliptic guide parts in the ballistic double-ellipse allows to introduce two kinks at the connection points. Most neutrons enter the guide with a divergence large enough to undergo at least one reflection in the first half of the ellipse, leading to a smaller divergence in the central part of the guide and making this an advantageous position to place a mirror to reflect the neutron beam out of direct line of sight. The kink angles are demanded in Refs. [12–14] to be such that the common central focal point lies on the reflecting guide wall, as illustrated in Fig. 1(c), and a central narrow point as shown in Fig. 1(d) is introduced to provide a suitable position for frame overlap choppers and to be further out of line of sight. The study in Refs. [12–14] further states that extending the used part of the ellipses while narrowing the maximal guide width improves the divergence profile further. An example of such a guide is schematically shown in Fig. 1(e) and will be referred to as *extended kinked ballistic double-ellipse A*.

This design is improved here to an *extended kinked ballistic double-ellipse B* schematically drawn in Fig. 1(f): The condition of the kinked guide wall going through the central focal point causes kink angles larger than necessary to avoid direct line of sight, therefore this condition is dropped. The guide width at the central narrow point, which is fixed in Refs. [12–14] to 4 cm, will be chosen here such that the guide walls opposite to the mirror wall are parallel to the guide axes. This is illustrated by the light blue lines in Fig. 1(f). This way the central guide width as well as the kink angle are determined by the transition point between ellipse and linear guide. The optimal transition point is found by simulation in Section 4.

3. Boundary conditions and simulation details

The distance from the source to the $1 \times 1\ \mathrm{cm}^2$ sample is fixed to 150 m. A dedicated study of pinhole beam extraction [16] revealed that efficient neutron transport as well as a satisfying beam

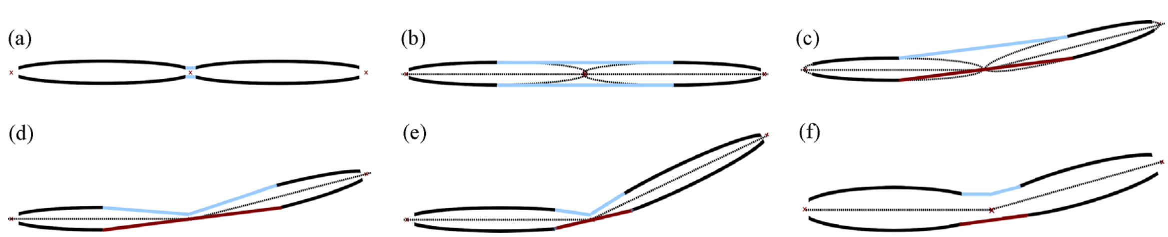

Fig. 1. Derivation of a kinked ballistic double-ellipse with narrow point, schematic drawing. (a) Double-ellipse, (b) ballistic double-ellipse, (c) simple kinked ballistic double-ellipse, (d) kinked ballistic double-ellipse with narrow point, (e) extended kinked ballistic double-ellipse A and (f) extended kinked ballistic double-ellipse B. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)