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Shielding of elliptic guides with direct sight to the moderator

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ABSTRACT

With the invention of elliptic guides, the neutron flux at instruments can be increased significantly even without sacrificing resolution. In addition, the phase space homogeneity of the delivered neutrons is improved. Using superpolished metal substrates that are coated with supermirror, it is now possible to install neutron guides close to the moderator thus decreasing the illumination losses of the guide and reducing the background because the entrance window of the elliptic guide can be decreased significantly. We have performed Monte Carlo simulations using the program package MCNP5 to calculate the shielding requirements for an elliptic guide geometry assuming that the initial guide section elements are composed of Al substrates. We show that shielding made from heavy concrete shields the neutron and $\gamma-$radiation effectively to levels below $1\,\mu$Sv/h. It is shown that the elliptic geometry allows to match the phase space of the transported neutrons easily to the needs of the instruments to be installed. In particular it is possible to maintain a compact phase space during the transport of the neutrons because the reflection losses are strongly reduced.

1. Introduction

The recent years have witnessed a tremendous increase in the performance of neutron guide systems. Originally, neutron guides were coated with Ni allowing an efficient transport of cold neutrons over large distances. However, their use for thermal neutrons was impaired because the divergence of the neutrons was limited by the maximum angle of total reflection, θ_c, which is given by

$$\theta_c = 0.099\, m\lambda \qquad (1)$$

where θ_c and the wavelength λ are given in degrees and Å, respectively. For Ni, the parameter m is equal to 1. Therefore, the angle of total reflection becomes very small, i.e. smaller than a typical mosaic spread of a monochromator crystal for $\lambda < 4\,$Å. With the implementation of supermirror coatings, the index m can be easily increased to $m=2$ [1]. More recently, a Japanese group achieved $m \simeq 6$ [2] and now, it is possible to produce $m=7$ in mass production [3], thus allowing to efficiently transport even hot neutrons. However, due to the development of roughness at the interfaces of the supermirror with increasing number of layers, which is approximately given by $N=4m^4$ [4], the reflectivity decreases significantly with increasing m. Because typical neutron guides have a length exceeding $L=30\,$m, the number of reflections becomes quite large and the losses become significant.

In order to decrease the reflection losses, elliptic neutron guides have been proposed [5]. They reflect the neutrons typically once per reflection plane, i.e. vertical and horizontal. If the moderator is not point-like additional reflections occur for neutrons with a long wavelength thus enlarging the size of the neutron beam at the focal position. Indeed, the Monte Carlo simulations show that the neutron flux at the sample position of elliptic guides is significantly increased when compared to straight neutron guides [5]. Moreover, the maximum flux of the transported neutrons appears away from the exit of the guide thus allowing to place samples, neutron optical devices (choppers, virtual source of monochromators [6], etc.) directly into the region of maximum flux, where the cross-section of the beam is small. In addition the divergence of the neutrons at the focal point is more homogeneous, i.e. the elliptic concept maintains a rather compact phase space of the neutrons. In fact, the recently installed neutron guide for the powder diffractometer HRPD at ISIS has proven the superior performance of the elliptic concept. The HRPD guide is approximately 90 m long and has led to intensity gains of one to two orders of magnitude [7]. Elliptic guides are now installed at various neutron centers either for the transport of neutrons or for the purpose of focusing [8].

An ellipse is defined by those points P relative to two focal points F_1 and F_2, for which the distance F_1-P-F_2 is a constant. This property implies that neutrons are only reflected once per reflection plane leading to low losses and a homogeneous phase

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space at F_2. However, the elliptic concept requires a direct sight to the moderator if effects of gravitation are neglected. Therefore, in contrast to the commonly used concept of curved guides, elliptic guides allow the transport of fast neutrons and $\gamma-$radiation from the moderator to the end of the neutron guide, which may lead to a high background of radiation. It may be possible to reduce the flux of fast neutrons and the $\gamma-$radiation by introducing a beam stop in the center of the elliptic guide [9] and/or by extending the neutron guide as close as possible to the moderator thus decreasing the aperture of the guide [10]. The extension of neutron guides has recently become possible due to the development of metallic substrates with very low surface roughness that allow to manufacture guides with large critical angles of reflection [11].

In this paper, Monte Carlo simulations using the software package for neutron transport MCNP5 have been performed to calculate the background radiation that appears around a curved and an elliptic neutron guide. The results show that the contribution of fast neutrons and $\gamma-$radiation is indeed higher for the elliptic geometry, however, the dose rate (DR) is still at or below the commonly accepted values. The DR can be further reduced by the installation of additional shielding.

2. Monte Carlo model for MCNP5

As a model system for the MCNP5 simulations we have used the geometry of the beam port SR4 at FRM II that extracts neutrons from the cold source for the beamline for radiography, ANTARES. Similar calculations have been performed by us for the inelastic time of flight spectrometer SEQUOIA at the spallation neutron source at Oak Ridge National Laboratory [12]. The geometry of the beam port SR4 was already implemented into MCNP5 for the optimization of the shielding for ANTARES [13]. The neutrons are extracted from the moderator either by means of a curved neutron guide as it was realized at the spallation neutron source SINQ at Paul Scherrer Institute for the triple axis spectrometer TASP [14] or an elliptic guide. In Ref. [5], the results of detailed Monte Carlo simulations are already available. It was demonstrated that the elliptic design provides an up to a factor of five higher flux and a very homogeneous beam at the sample position. The salient parameters for the curved and elliptic guides used for the MCNP5 simulations are listed in Table 1. In contrast to the parameters used in Ref. [5], we have reduced the distance between the surface of the moderator and the entrance of the elliptic guide from 1.50 to 0.30 m leading to a reduction of the cross-section at the entrance from 35×120 to $15.8 \times 54.4\,\text{mm}^2$, i.e. smaller than the entrance of the curved guide. The maximum cross-section of the elliptic guide is $102.2 \times 350.3\,\text{mm}^2$.

Table 1
Geometrical parameters for the curved and elliptic guide as used for the MCNP5 simulations.

Item	Curved guide	Elliptic guide
Distance source–guide	1.5 m	0.3 m (Al substrate)
Cross-section at entry	$35 \times 120\,\text{mm}^2$	$15.8 \times 54.4\,\text{mm}^2$
Cross-section at exit	$35 \times 120\,\text{mm}^2$	$32.7 \times 111.9\,\text{mm}^2$
Length of guide	46.8 m	48.0 m
Radius of curvature	2063 m	NA
Beam catcher	NA	$L = 402$ mm $20.6 \times 70.6\,\text{mm}^2$
Miscellaneous	$m = 3$	First 3 m made from Al
Materials around guide in biological shielding and moderator vessel	1 mm boral, 300 mm steel	1 mm boral, 300 mm steel, space around entrance of guide is filled with steel

The beam catcher consists of 2 mm boral, 200 mm steel, followed by 200 mm polyethylene.

The details of the composition of the shielding close to the moderator are shown in Fig. 1. The first 10 m of the curved guide are manufactured from boron-free float glass. The area between the moderator and the entrance of the guide contains He. The first 10 m of the elliptic guide are manufactured from Al (3 m) and float glass (6.7 m). In order to interrupt the direct line of sight, a beam stop is placed 24.8 m upstream from the entrance of the guide. The guides are surrounded by a cylindrical shielding of heavy concrete with a density $\rho = 4.68\,\text{g/cm}^3$. It contains a mixture of hematite, colemanite, and granular steel. In contrast to a shielding manufactured from plain lead or iron, the photo neutrons produced by the Fe grains in the concrete are moderated and absorbed within the shielding. Its inner and outer radii are 200 and 600 mm, respectively. The detectors for monitoring the neutron and $\gamma-$radiation from the guide are placed on the surface of a cylinder with a radius of 1.3 m, i.e. the background radiation is measured 700 mm away from the surface of the shielding.

The implementation of the MCNP5 code takes the following sources of background radiation into account: (i) the moderated, epithermal, and fast neutrons from the cold source and the

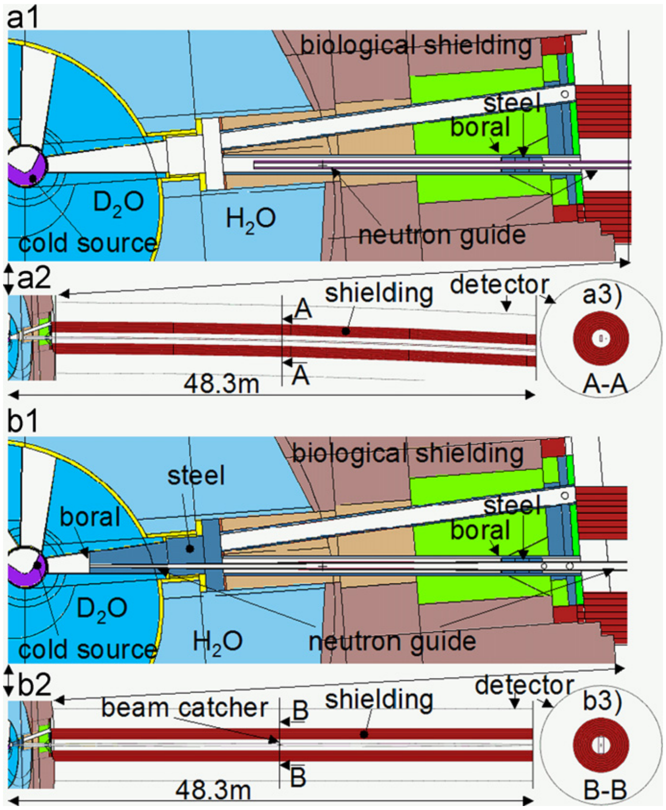

Fig. 1. (Color online) (a1) Horizontal cut through the Monte Carlo model of the curved neutron guide inside the biological shielding. The curved guide begins at a distance of 1.5 m from the cold source. (a2) Horizontal cut through the whole Monte Carlo model of the curved neutron guide. The guide ends at a distance of 48.3 m from the cold source. The first 10 m of the guide consists of float glass, then borofloat glass is applied. The shielding around the guide has an inner radius of 200 mm and an outer radius of 600 mm. The shielding is surrounded by a cylindrical detector with a radius of 1.3 m from the beam axis. (a3) Vertical cut through the curved guide and the surrounding shielding. (b1) Horizontal cut through the Monte Carlo model of the elliptic neutron guide inside the biological shielding. The elliptic guide begins at a distance of 0.3 m from the cold source. Up to a distance of 3.3 m from the cold source it consists of Al. Between 3.3 and 10 m float glass is used. For larger distances borofloat glass is used. (b2) Horizontal cut through the whole Monte Carlo model of the elliptic neutron guide. Close to the center of the ellipse a beam catcher made from boral (2 mm), steel (200 mm) and polyethylene (200 mm) is applied. (b3) Vertical cut through the elliptic guide and the surrounding shielding.