ICANS XIX,
19th meeting on Collaboration of Advanced Neutron Sources
March 8 – 12, 2010
Grindelwald, Switzerland

ELLIPTIC GUIDES USING SUPER-POLISHED METAL SUBSTRATES: SHIELDING ISSUES

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ABSTRACT

The neutron flux at instruments can be increased significantly by implementing elliptic guides without sacrificing resolution. In addition, the phase space homogeneity of the delivered neutrons is improved. Using super polished metal substrates coated with supermirror, it is possible to extend neutron guides directly very close to the moderator thus reducing the illumination losses and the background because the size of the entrance of the elliptic guide can be decreased when compared with a conventional guide. This is an important issue because elliptic guides do not interrupt the direct sight to the moderator. We have performed Monte-Carlo simulations using the program package MCNP5 to calculate the shielding requirements for an elliptic guide geometry assuming for the initial guide sections elements composed of aluminum substrates and using the flux spectrum of the moderator of beam line SEQUOIA at SNS. The simulations show that the radiation load on the neutron guides is reduced and that the contribution of the direct radiation from the source can be handled. Summarizing, elliptic geometries out-perform conventional designs for neutron beams with low and high divergence.

1. Introduction

During the past few years the performance of neutron guide systems has tremendously improved by using innovative guide designs and supermirror coatings with large critical angles of reflection. Originally, neutron guides were coated with Ni allowing an efficient transport of cold neutrons over large distances. However, the use of guides for thermal neutrons was impaired because the divergence of the neutrons was limited by the maximum achievable angle of total reflection, θ_c, which is given by

$$\theta_c = mc\lambda \,,$$

where θ_c and the wavelength λ are given in ° and Å, respectively. The constant c has the value $c = 0.099°/Å$ and for Ni, $m = 1$. Therefore, θ_c becomes very small, i.e. smaller than a typical mosaic spread of a monochromator crystal for $\lambda < 4$ Å. With the invention of supermirror coatings, the index m was increased in the 90ties to $m = 2$ [1,2]. More recently, a Japanese group achieved $m \cong 6$ [3] and now, it is possible to produce even $m = 7$ in mass production [4,5], thus allowing to efficiently transport even hot neutrons. However, due to the development of roughness at the interfaces of the supermirror with increasing number N of layers, which is approximately given by $N = 4m^4$ [6], the reflectivity decreases significantly with increasing m. As typical neutron guides have a length exceeding $L = 30$ m, the number of reflections, N_R, becomes large and the losses are significant.

In order to decrease the reflection losses, elliptic neutron guides have been proposed [7]. These guide concepts reduce N_R to essentially one. Indeed, Monte-Carlo simulations show that the neutron flux at the sample position of elliptic guides is significantly increased when compared to straight neutron guides. 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 [8] etc.) directly into the region of maximum flux, where the size 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. The recently installed neutron guide for the powder diffractometer HRPD at the spallation source ISIS has proven the superior performance of elliptic guides. The HRPD guide is approximately 100 m long and led to intensity gains of up to two orders of magnitude [9]. Elliptic guides are now being installed at various neutron scattering centres for the transport of neutrons [10].

An ellipse is defined by those points P relative to two focal points F_1 and F_2, for which the sum of the distances $|F_1\text{-P}|+|F_2\text{-P}|$ is constant. This property implies that neutrons are only reflected once. However, the elliptic concept requires a direct sight to the moderator. Therefore, in contrast to the commonly used curved guides, elliptic guides do not inhibit the transport of fast neutrons and γ-radiation from the neutron source to the end of the guide, which may lead to a high background of radiation. It may be possible to reduce the flux of fast neutrons and γs by extending the neutron guide as close as possible to the moderator thus decreasing the aperture of the guide. The extension of guides has recently become possible due to the development of metallic substrates with very low surface roughness allowing manufacturing guides with large θ_c [12].

Monte-Carlo simulations using the software package MCNP5 have already been performed to calculate the background radiation that would appear around a curved and an elliptic neutron guide (Table I) extracting neutrons from the cold source of the research reactor FRM II in Munich [13]. The results show that the contribution of fast neutrons and γ-radiation at the end of the elliptic guide is approximately 15 times larger then for a curved guide. However, at the same time, the elliptic guide provides a five times higher flux [7], therefore the ratio of useful neutrons to fast neutrons is similar. Moreover, the calculations have shown that the beam stop does not (unfortunately) effectively interrupt the direct sight to the moderator [13].

At a spallation source, the maximum energy of the neutrons ($E_n \cong 1$ GeV) is much higher than at a reactor based source ($E_n \cong 20$ MeV). Therefore, to explore the feasibility of elliptic guide systems, we have performed Monte-Carlo simulations using the source spectrum of the beam line SEQUOIA at SNS in order to investigate the influence of the contribution of the high-energy neutrons to the performance of curved and elliptic guides. The results show that the dose rate (DR) is typically a factor of 5-10 larger than at a medium flux reactor; however, it is still close to the commonly accepted values.

2. Monte-Carlo Model for MCNP5

As model for the geometry for the beam tube and the biological shielding a Monte-Carlo model for beam tube SR4 at FRM II was applied [13,14]. Instead of the cold source at the entrance window of the beam tube, a neutron source characteristic for a spallation source, i.e. from the beam line SEQUOIA at SNS, was included in the MCNP5 model [15]. This "virtual" source at the entrance window of the beam tube has an area of 12 cm x 10 cm (height x width). Between the source and the sample position a curved neutron guide as it was realized at the spallation neutron source SINQ at Paul Scherrer Institute for the triple axis spectrometer TASP [16] or an elliptic guide are implemented. The curved guide starts 1.5 m from the entrance of the beam tube (Fig. 1). The same guide parameters have also been used for the Monte-Carlo simulations (McSTAS) in Ref. [7] and are listed in Table I. For comparison, we have implemented an elliptic guide that starts 300 mm from the entrance of the beam tube (Table 1). Its cross section is with 35 x 120 mm^2 at 1.5 m from the entrance identical with the aperture of the TASP guide [7]. The maximum cross section of the elliptic guide is 102.2 x 350.3 mm^2.

Tab. I: Geometrical parameters for the curved (TASP) and elliptic guide as used for the MCNP5 simulations.

Item	**Curved guide**	**Elliptic guide**
Distance source-entrance of guide	1.5 m	0.3 m (Al substrate)
Cross section at entrance	35×120 mm^2	15.8×54.4 mm^2
Cross section at exit	35×120 mm^2	32.7×111.9 mm^2
Length of guide	46.8 m	48.0 m
Radius of curvature	2063 m	NA
Beam catcher	NA	$L = 402$ mm, 20.6×70.6 mm^2
Miscellaneous	$m = 3$	$m = 3$, 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 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 first 10 m of the elliptic guide are manufactured from Al (3 m) and float glass (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. It is made from boral (2 mm), steel (200 mm), and polyethylene (20 mm).

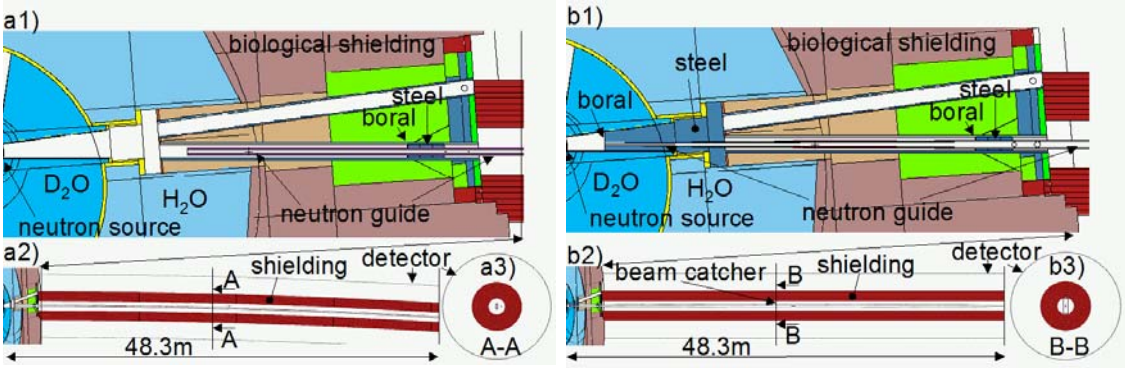

Fig. 1: Horizontal cut through the Monte Carlo models of the curved (a1) and the elliptic (b1) neutron guide inside the biological shielding. a2) and b2) show respective horizontal cuts through the whole Monte Carlo models. The guides end at a distance of 48.3 m from the beam tube entrance. a3) and b3) show vertical cuts through the curved and elliptic guide and the surrounding shielding, respectively.

The guides are surrounded by a cylindrical shielding of heavy concrete with a density ρ = 4.68 $\mathrm{g/cm}^3$. It contains a mixture of hematite, colemanite, and granular steel. In contrast to a shielding manufactured from pure lead or iron, the contribution of photo neutrons produced by the Fe grains in the concrete is negligible outside the shielding. The inner and outer radii of the shielding are 200 mm and 600 mm, respectively. The detectors for monitoring the neutron and γ–radiation are placed on the surface of a cylinder with a radius of 1.3 m, i.e. the background 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:

- fast and epithermal neutron background radiation that is scattered through the entrance window into the beam tube
- γ-radiation from neutron capture and inelastic neutron scattering in structure elements as there are: a) coating of neutron guide (Ni/Ti, *m* = 3), b) guide walls (float glass, borofloat glass, aluminum), and c) shielding within the biological shielding and the heavy concrete around the guide outside the biological shielding.

2. Dose Rates for the Curved Neutron Guide

Contour plots of the dose rate (DR) for neutron and γ-radiation of the curved guide are shown in Fig. 2. Outside the direct line of sight, the DRs are strongly reduced, while close to the biological shielding, the DR exceeds 5μSv/h. The maximum allowed DR varies for the various facilities in a range of typically 1μSv/h – 5μSv/h. Therefore, additional shielding is necessary. Fig. 3 shows the dependence of the DR for the various energy groups as measured with the detector located 1.3 m away from the optical axis of the guide. It is clearly seen that the fast neutrons ($E > 0.1$ MeV) are mostly responsible for the DR of the neutrons. This group is emitted by the spallation target and enters the guide by inward scattering of the moderator. The DR decreases up to the line of sight due to the decreasing solid angle. After the line of sight, the fast neutrons are moderated and scattered by the guide walls and the shielding thus leading to a fast decrease of the DR. The moderated neutrons show up in the two energy groups with $E < 0.1$ MeV.

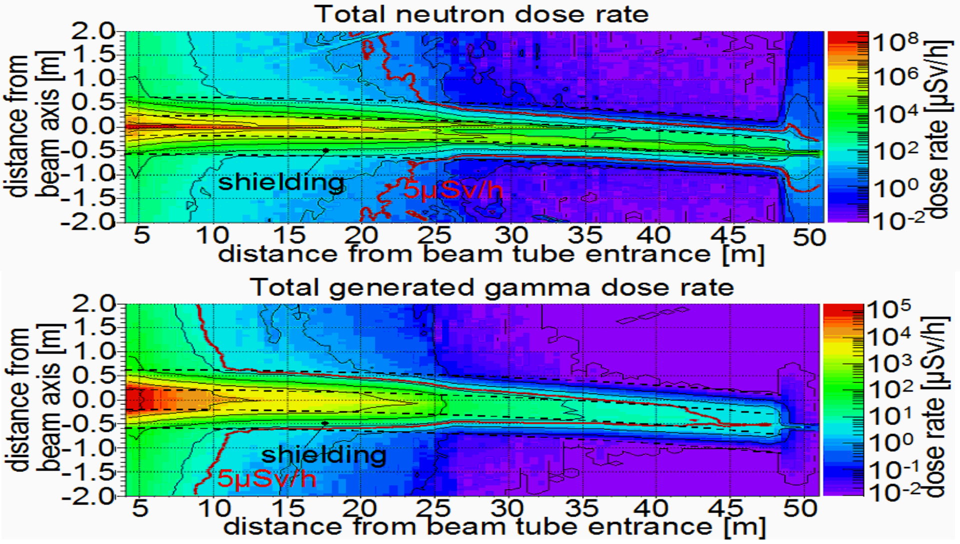

Fig.2: Contour plot of the total DR for neutrons (top) and γ-radiation (bottom) of a curved guide. Outside the direct line of sight (25.6 m), the radiation levels drop quickly to below 1μSv/h. The outer radius of the heavy concrete shielding is 0.6 m (broken line in black). The red contour indicates the DR-level of 5μSv/h.

The simulations show that the guided (low energy) neutrons are not relevant for the neutron-DR outside the shielding. Similarly, the DR of the γ-radiation drops also significantly downstream of the line of sight. The major contribution to the γ-DR is due to the two energy groups $E > 0.5$ MeV. The γs are mostly produced by the interaction of the neutrons with the neutron guide. It is in particular the Ni/Ti coating $m = 3$ that produces hard γs with an energy around 7 MeV. It is clear that this contribution increases if coatings with even larger critical angles are used due to the rapidly increasing amount of Ni and Ti. Presently, supermirror with m approaching 7 is being manufactured [4,7] thus N increases up to ≅ 10'000. When compared to the neutron-DR, the γ-DR is small.

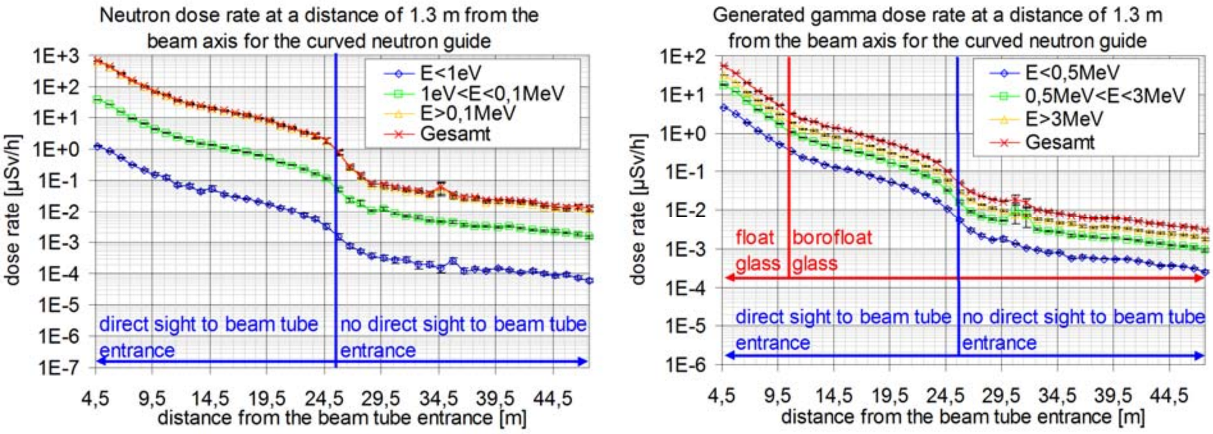

Fig. 3: Dose rate of the neutron (left hand side) and γ-radiation (right hand side) versus distance from the cold moderator for a curved guide as measured in the detector surrounding the guide at a distance of 1.3 m. The results show that the high energy contributions are mostly responsible for the DR. Beyond the line of sight, the DRs drop to very low levels < 1µSv/h.

Concluding, beyond the line of sight of the curved guide, the dose rates are very small and the thickness of the shielding may be reduced. However, the shielding close to the biological shielding must be improved to achieve radiation levels of the order of 1µSv/h.

3. Dose Rates for the Elliptic Neutron Guide

Fig. 4 shows the contours of the DR for the neutron and γ-radiation. The comparison with the DR of the curved guide shows that the background is higher in the second half of the guide section, i.e. for $x > 25$ m. Obviously, the present design of the beam catcher does not help to reduce the background significantly: Most of the fast neutrons from the moderator pass the beam stop and hit the guide structure downstream of the catcher. Simulations show that even a beam stop with a length of 2 m does not reduce the radiation significantly, i.e. it is superfluous. The position of the catcher can be identified by the spot of enhanced γ-radiation around $x = 25$ m.
Similarly as for the curved guide, it is only the DR of the fast neutrons $E > 0.1$ MeV and of the γ-radiation with $E > 0.5$ MeV, which contribute mostly to the background (Fig. 5). The background caused by the guided cold and thermal neutrons is irrelevant outside the shielding. The results show that the background as produced by the elliptic guide is close to the acceptable limits of a few µSv/h. By adding a small amount of shielding, the contribution of the fast neutrons can be reduced such that the DR drops below 1µSv/h.

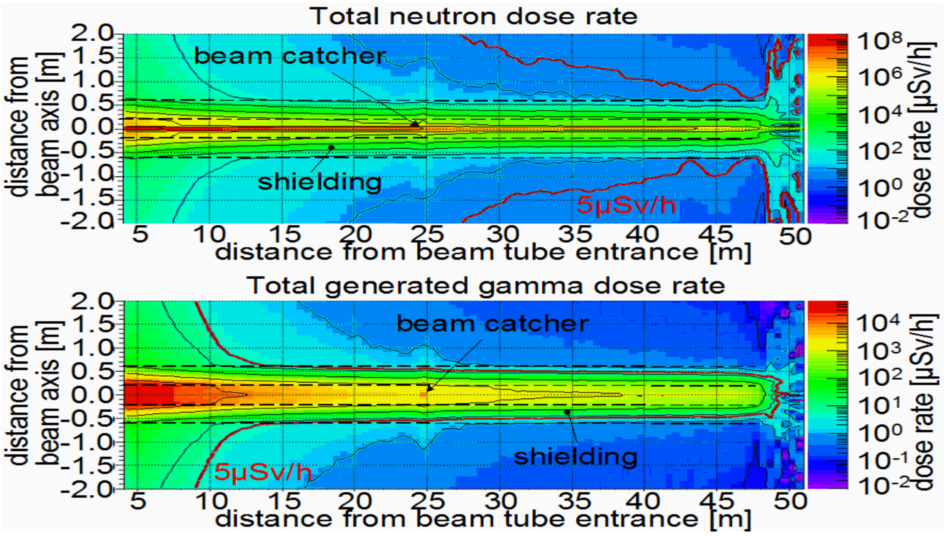

Fig. 4: Contour plot of the total dose rate (DR) for neutrons (top) and γ-radiation (bottom) of an elliptic guide. The outer radius of the heavy concrete shielding is 0.6 m. Its outer contour is indicated by broken lines in black. The dark red contour indicates the DR-level of 5µSv/h.

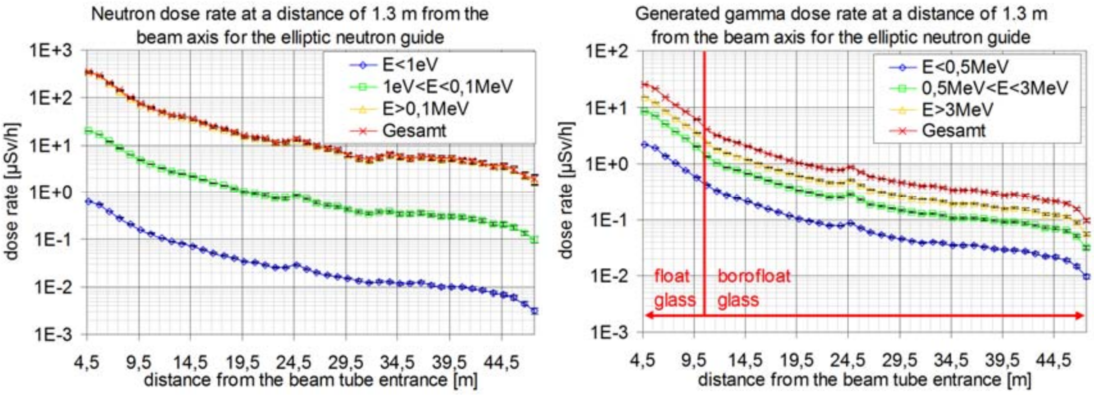

Fig. 5: Dose rate of the neutron (left hand side) and γ-radiation (right hand side) versus distance from the beam tube entrance for an elliptic guide as measured in the detector surrounding the guide at a distance of 1.3 m. The results show that the high energy contributions are mostly responsible for the DR

4. Discussion

Fig. 6 shows that the DR close to the biological shielding is smaller for the elliptic guide than for the curved guide due to the more compact shielding near the moderator. In contrast, the DR is reduced for the curved guide when compared with the elliptic guide by approximately an order of magnitude downstream of the position $x = 25$ m. Both guide concepts yield small DRs of below 10µSv/h at large distances from the biological shielding. It is clear, however, that the shielding for the elliptic design should be improved to approach the low levels of the curved design. The DR for the γs is with DR < 1µSv/h at an irrelevant level. Of course the DRs can be further reduced by adding more shielding.

The simulations show that the major background is produced by by the inward scattering of fast and epithermal neutrons by the moderator and the γ-radiation from neutron absorption in the neutron guide structure and the shielding surrounding the guides.

The γs from the neutron source do not contribute to the background because they propagate mostly parallel to the axis of the neutron guide. When they hit the guide walls, they are scattered by the Compton effect under small angles with respect to the guide axis. Therefore, the γs from the moderator see effectively a very thick shielding.

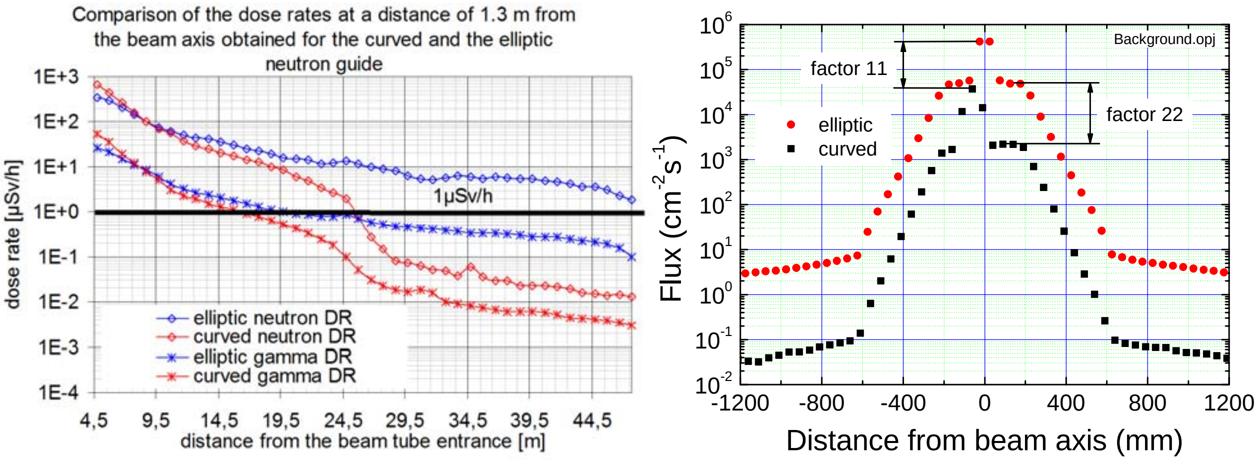

Fig.6: Left: Comparison of the total dose rates (DRs) for the curved (red symbols) and elliptic (blue symbols) guide. The diamonds and the stars indicate the DR for neutrons and γ-radiation, respectively. Right: Flux of epithermal and fast neutrons at the sample position for the elliptic (circles) and curved (squares) guide.

When compared with the simulations, which we performed for a cold neutron moderator at the research reactor FRM II [13], we see as major difference that the much harder spectrum of neutrons with energies up to more than 1 GeV as it occurs at a spallation source leads to a roughly 5 – 10 times higher DR for neutrons and γs along the neutron guides. This is the reason why the shielding at spallation sources is predominantly made from Fe and not from heavy concrete as assumed in our simulations. To cope with the fast neutrons, the shielding is arranged as close as possible to the neutron guide. With the availability of super polished steel substrates coated with large-*m* supermirror, it will become possible to remove the gaps between shielding and the supermirror coating completely and to extend the neutron guide very close towards the surface of the moderator thus reducing the streaming of neutrons and decreasing the area where fast neutrons can enter the neutron guide.

Of most concern are the fast and epithermal neutrons that enter the neutron guide and appear at the exit of an elliptic guide. Fig. 6 shows that the peak flux is 11 times higher for the elliptic guide when compared with the curved guide. However, considering that the useful flux of neutrons is increased also by at least a factor of five for the elliptic design, the ratio of thermal to fast neutrons, Q, is only increased by approximately 2. It should be noted, however, that the maximum of the fast neutrons for the curved guide occurs always away from the optical axis of the guide (Fig. 6). Hence, the effective Q may be larger than two. Q may be decreased by adding more shielding near the exit of the elliptic guide.

During the course of the simulations we have assumed that the complete elliptic guide is coated with supermirror $m = 3$. However, the angle of reflection θ_c is only large at the beginning and the end of the guide. For most areas, θ_c can be reduced. By optimizing, the m-value [9], the amount of Ni/Ti as source of photo neutrons is reduced, hence the DR of a real guide system will be lower than the above simulations indicate. Last but not least, the small entrance of the elliptic guide may be further reduced thus reducing the flux depression in the moderator leading to a higher flux.

5. Conclusions

We have shown that elliptic guides do not lead to a problem with increased radiation or contamination of the neutron beam at the sample position despite the direct line of sight to the moderator [17]. With respect to the aging of neutron guides, elliptic guides are favourable too, because the number of fast neutrons from the moderator is reduced as is the radiation damage by the guided neutrons that are scattered into the glass by the non-perfection of the supermirror because the neutrons are essentially only reflected once. Therefore, cheap borofloat glass instead of the precious borkron glass N-ZK7 can be used.

A further advantage of elliptic guides is the ease of adjusting the beam size and the divergence depending on the needs of the beam line [11,13]. Presently, research is going in the direction of developing guides with adaptive optics. This may allow adjusting the phase space of neutrons during the pulse of neutrons according to their wavelength. An active phase space transformation will increase the phase space density while not violating Liouville's theorem. Although, the alignment of an elliptic guide is more involved than the alignment of a conventional guide, laser trackers facilitate the task tremendously and it is possible to install elliptic guide systems quickly and reliably. Moreover, the alignment can be regularly checked during operation. The combination of non-linear tapering of neutron guides with large-*m* supermirror will indeed guarantee a bright future for neutron scattering.

Acknowledgement: Part of the work was supported by the Swiss National Science Foundation through the National Centre of Competence in Research MaNEP and by the project 226507-NMI3 within the seventh framework program FP7 of the EU.

6. References

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