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A study on optical aberrations in parabolic neutron guides

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ABSTRACT

It is widely believed that a neutron beam can be focused to a small spot using a parabolic guide, which will significantly improve the flux. However, researchers have also noted challenges for the neutron inhomogeneous phase space distribution in parabolic focusing guide systems. In this paper, the sources of most prominent optical aberrations, such as an inhomogeneous phase space distribution and irregular divergence distribution, are discussed, and an optimization solution is also proposed. We indicate that optimizing the parabolic guide geometrical configuration removes almost all of the aberrations and yields a considerable intensity gain factor.

1. Introduction

Neutron scattering is well-known as one of the most powerful experimental techniques for simultaneously investigating the static structure and dynamical state of materials in a Fourier space. However, certain neutron scattering experiments, especially for novel materials under extreme conditions with small samples, are restricted by a low neutron flux. Neutron focusing is an indispensable technique used to increase neutron intensity and extend the feasibility envelope of experimentation; it is important that all neutron instruments and existing facilities can be upgraded with relatively low effort.

It is universally accepted that neutron guide [1] systems with ballistic geometry [2] can significantly focus a neutron beam based on total reflection by the supermirror. The term “ballistic” refers to the middle section of the guide systems, which is wider than the entrance and exit. The converging and diverging sections include three types of geometry: a linearly tapered geometry [3–8], elliptic tapered geometry [9–17], and parabolic tapered geometry [9,14,18–20]. In the present study, we only consider the parabolic tapered focusing neutron guide.

Many total-reflectivity and focusing studies on parabolic guides have been performed and have demonstrated that parabolic guides perform beam transport significantly better than conventional straight guides. Hils et al. [18] developed a small focusing guide tube that includes parabola-shaped walls coated with supermirror $m=3$, and experiments using the neutron reflectometer TOPSI at SINQ demonstrated that an intensity gain of 6 can be easily generated. McStas Monte Carlo simulations demonstrated gain factors up to more than 50 for a spot size with an approximately 1.2 mm diameter. Thereafter, also Christian et al. [9] investigated parabolic guide properties using McStas. The data demonstrated a flux gain on the order of 5 but an inhomogeneous neutron intensity profile. In 2005, to investigate the parabolic guide focusing properties, especially the intensity phase space distribution, Nikolay et al. [19] performed experiments using the V12b instrument at HMI with a standard, high-resolution radiography detector. The results demonstrated that the maximum intensity gain is approximately 25. However, the intensity distribution is inhomogeneous; thus, the parabolic guide is unsuitable for neutron radiography applications. Finally, the results suggested that the large gain may be used for other applications, for instance PGAA (prompt gamma activation analysis). Satoru et al. [20] developed a multichannel parabolic guide for PGAA of JRR-3M in JAEA, which yielded peak flux gains of 9.6 and 4.1 compared with using a vacuum tube and straight guide, respectively. Until then, researchers considered parabolic guide optical aberrations serious impediments to their application in neutron scattering experiments due to complicated resolution functions and consequent difficulties in analyzing the data. Conversely, the latest results were generated by Komarek et al. [14] in 2011, and the inhomogeneous divergence distribution attributed to the parabolic focusing guide improved to a certain extent. Currently, we conclude that the inhomogeneous spatial intensity distribution phenomenon is sensitive to the parabolic guide geometrical configuration but not its intrinsic features. In this paper, based on geometric optics theory, the origin of the optical

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aberration is analyzed, and a method to relieve or even eliminate aberrations is provided. Monte-Carlo simulations were used for the experiments and to verify the method.

2. Geometric optical analysis of the inhomogeneous phase space distribution origin

To simplify our explanation, we only address the inhomogeneous distribution of the neutron beam intensity and divergence in the horizontal direction; the vertical is similar. The counterclockwise rotation angle was defined as positive, and only the positive angle range was considered for the symmetric geometry.

Fig. 1 shows a typical profile for neutron source+straight guides+parabolic guides (top view). For any point *N* on the focal plane around focal point *O*, the neutrons that reach it originate from three parts, including the direct incident from the neutron source, the reflection neutron beam from the straight guide walls and the reflection neutron beam from the parabolic guide walls. First, we analyze and discuss the uniformity of neutron intensity distribution at a certain distance from focal plane due to each part, the combined effect is then comprehensively considered.

(1) The neutron directly incident from the neutron source

Neutrons from the neutron source are evenly distributed in the 4π direction and angular range, over which the neutrons can travel through the point *N*, which is $[0,\alpha]$, as shown in Fig. 1. Their corresponding intensity–divergence distribution is shown in Fig. 2(a); the left indicates the angular range and intensity of the incident neutrons from the source, and the right indicates the angular range and intensity of the reflected neutrons that hit point *N*. Because no reflection occurs, both figures are similar.

(2) Neutrons from total reflection by the straight guide walls

The neutron guides were constructed as evacuated tubes with inner walls coated to reflect neutrons. The limiting critical angle for total external reflection depends on the neutron wavelength, λ, namely $\lambda\theta_C$, where $\theta_{C,\ Ni}=0.10^\circ$, $\theta_{C,\ Ni\text{-}58}=0.117^\circ$, and $\theta_{C,\ Supermirror}=m\theta_{C,\ Ni}=m\times0.10^\circ$. In this paper, supermirror is considered the guide coating. Currently, m may be as large as 7. A profile of the neutron guide reflectivity as a function of the reflection angle is shown in Fig. 3.

The angular range is shown in Fig. 1, over which the neutrons can be reflected by the straight guide walls and reach the point *N*, which is $[\alpha, \beta]$. For the straight guide wall reflection, the incidence angle θ is the divergence angle of the incident neutron beam, and the reflection angle is θ based on the reflection law. As a result, the divergence angle of the reflected neutron beam was unchanged after the reflections. Clearly, as the reflection angle θ increases, the reflectivity gradually decreases with a variation trend similar to the supermirror neutron guide reflectivity as shown in Fig. 3. The intensity–divergence distributions of the incident (left) and reflected (right) neutrons for the straight guide wall are illustrated in Fig. 2(b).

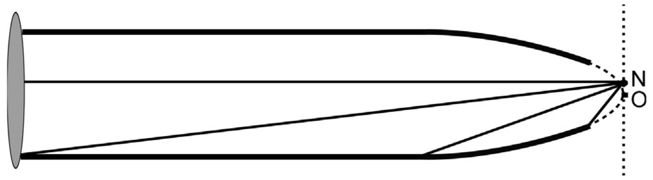

Fig. 1. Profile of the typical source-straight guides-parabolic guides system.

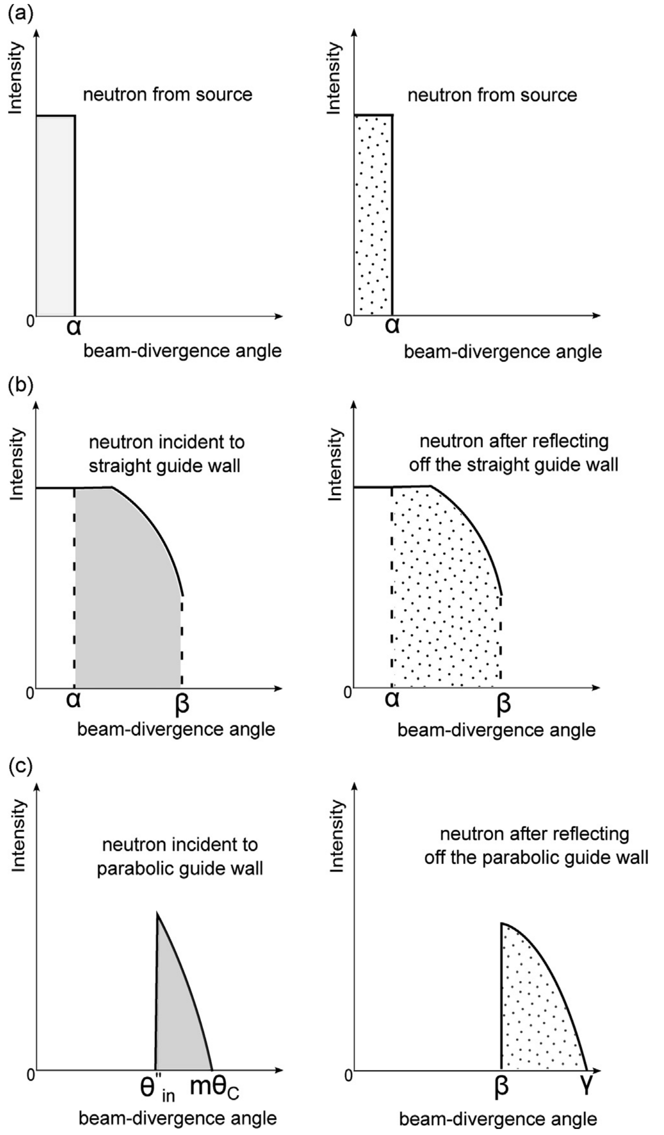

Fig. 2. The intensity–divergence distribution of the neutron passing through the point *N*, (a) directly incident from neutron source, (b) from straight guide wall's reflection, (c) from parabolic guide wall's reflection.

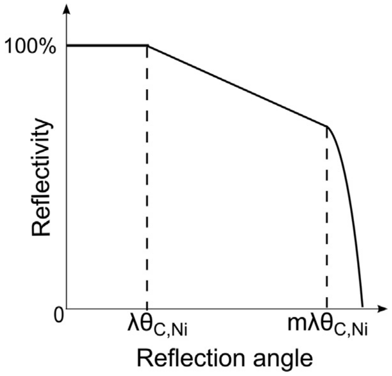

Fig.3. Profile of the reflectivity of super mirror neutron guide.

(3) Neutrons from total reflection by the parabolic guide walls

Fig. 4 shows a profile for a typical parabolic neutron guide (top view). This type of geometry has been heavily exploited in photon optics. The parabolic formalism can be written as follows:

$$z=-Ax^2 \tag{1}$$