Variable focusing system for neutrons

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Abstract. We have developed a variable focusing system for neutrons that allows varying the vertical and horizontal beam size at the sample position independently. It is based on a focusing parabolic neutron guide coated with supermirror $m = 6$ times the critical angle of reflection of Ni. The divergence of the incident beam is adjusted by solid-state collimators with horizontally and vertically arranged absorbing blades. The performance of the prototype set-up has been benchmarked at the beamline BOA at SINQ confirming the expected behavior. In particular we show that the beam size at the sample position can be varied between 0.6 and 2 mm without exchanging the focusing guide or by introducing a beam-defining aperture between the exit of the guide and the sample, i.e. the beam size can be adapted more than half a meter away from the sample.

1. Introduction

The investigation of novel materials using neutron scattering techniques is challenging because these materials are often only available in small quantities, e.g. encompassing a volume of a few mm³. Moreover, special experimental conditions, e.g. high pressure, high/low temperatures and/or high magnetic fields can only be realized for small volumes. Confining the neutron beam to such small areas using slits reduces the number of neutrons delivered by the rather large neutron beams (e.g. 50-100 cm²) significantly because for the minimization of the background, the penumbra must be suppressed too, to reduce scattering of neutrons from the sample environment. Moreover, it would require an aperture that is placed close to the sample which is usually not compatible with the sample environment. Therefore, it is desirable to focus the neutrons precisely to an area corresponding to the given size of the sample. Ideally, the useful neutrons would be selected already far away from the sample area using neutron optical devices.

As already shown in previous works, elliptic mirrors [1]-[4] are well suited to focus neutron and x-ray beams at the sample. With the rather dramatic increase of the reflection angles of supermirrors exceeding $m = 8$ times the critical angle of reflection of Ni [5], neutrons encompassing a wide range of wavelengths and large divergence can be directed towards the sample position. While adjusting the beam size at the sample with Montel mirrors [6] is straightforward using an aperture at the focal point at the entrance of the mirror [6], the selection of the beam size using elliptic or parabolic guides is more complicated and essentially given by the design of the optics [7]. In the following we propose a combination of a focusing parabolic guide with a variable collimation stage in front of the entrance of the guide that allows varying the size of the beam spot at the sample position in the horizontal and
vertical dimension independently thus avoiding the replacement of the focusing guide and its tedious alignment for different setups [7].

2. Experimental Set-Up

It is well known that parabolic mirrors focus beams following parallel trajectories (i.e. beams with a divergence $\psi = 0^\circ$) to a point at the focus of the parabola (see Figure 1). As soon as $\psi$ is increased, however, the size $a$ of the focal spot increases. According to Liouville’s theorem the product $B = a \psi$ is a constant if the volume of the phase space is conserved [2]. Therefore, the beam size $A_f = a_x a_y f$ is directly related to the solid angle $\Omega = \psi_x \psi_y$ of the incident beam for a parabola with a given geometry. Here, the indices $i$ and $f$ designate “incident” and “focal” position and the indices $x$ and $y$ indicate the directions transverse to the flight direction $z$ of the neutrons.

![Figure 1](image)

**Figure 1.** Focusing of neutrons using a parabolic guide segment. By varying the divergences $\psi_{xi}$ and $\psi_{yi}$ of the incident beam the beam size $A_f = a_x a_y f$ at the focal position can be adjusted.

In order to prove the concept of focusing neutrons by adjusting the divergence of the incident neutrons, we installed at the beam line BOA [8] at SINQ a variable focusing set-up comprising two solid-state collimator stages in series (each consisting of 4 individual collimators) for defining the beam divergence independently in the $x$- and $y$-direction followed by a focusing guide. The collimations $\psi_{xi}, \psi_{yi} = 10^\circ, 20^\circ, 40^\circ, 80^\circ$ were defined by the length and the thickness of the Si-wafers, which were coated with absorbing TiGd. The focusing neutron guide with a length of 500 mm has truly curved parabolic profiles in both dimensions, i.e. the curved sides are made from glass substrates with a thickness of 2 mm which can be easily bent. The exact geometry is determined by precise forming parts glued to the backside of the glass substrates, thus the waviness (figure error) of the reflecting surface is only in the order of 10 $\mu$rad (RMS). Four parabolic mirrors are glued together to build the focusing guide. The apertures are 15.00 mm $\times$ 15.00 mm and 5.59 mm $\times$ 5.59 mm at the entrance and exit, respectively. The nominal distance of the focal point of the parabolas is 80 mm away from the exit of the guide. The substrates are coated with supermirror $m = 6$ having an excellent reflectivity of $R = 0.67$ at the critical edge of the supermirror [5].

A monochromatic beam with a wavelength $\lambda = 3$ Å was provided by a double-bounce HOPG monochromator. The neutrons were recorded by a CCD camera imaging detector system (resolution $\approx 30$ μm). All components were aligned by means of a laser that was directed along the optical axis of the neutron beam. The alignment was refined with neutrons. In particular, the vertical and horizontal orientation of the collimators and the focusing guide were adjusted such that a symmetric beam profile was observed. We point out that the horizontal divergence of the beam was restricted by the geometry of the monochromator setup and the horizontal dimensions of the neutron beam to become less than $10^\circ$. Therefore, the horizontal collimators did not affect the beam divergence in the $x$-direction. In the vertical $y$-direction, however, the large opening of the neutron guide of 120 mm in combination with the supermirror coating of $m = 2$ at the top/bottom of the BOA guide provided a beam divergence of about $60^\circ$ [9] allowing a variation of the divergence by the vertical collimators.
3. Results and discussion

**Figure 2a)** shows the intensity distribution versus the x-position on the detector and the z-position of the detector after integrating the data along the vertical y-direction. The horizontal and vertical collimations are 10'. With increasing z, the neutrons reflected from the sides of the converging guide evolve from a double peak structure to a single peak at the focal point. The further increase of z leads again to a double peak structure as expected [2]. The horizontal beam profile at the nominal focal point is shown in **Figure 2b**. The highly symmetric shape confirms the precise geometry and alignment of the beam components. The profile is composed of a sharp component, the focused neutrons, with a FWHM of 0.8 mm sitting on a broad plateau having a width of about 5 mm, which is caused by neutrons that are not reflected by the sides of the focusing guide. These neutrons illuminate the sample environment and increase the background. Therefore, they should be blocked by a beam stop at the centre of the entrance of the guide that covers an area corresponding (or being slightly larger) than the cross section of the guide exit (5.59 mm × 5.59 mm). Clearly, the suppression of the plateau is most efficient for incident beams with low divergence, which yield the best focused beams at the sample position. As mentioned in section 2, the horizontal divergence of the incident beam from BOA is lower than the smallest collimation. Therefore, the horizontal beam profile is independent of the choice of the horizontal collimation and cannot be varied with the present set-up.

**Figure 2.** Horizontal beam profile for a horizontal and vertical collimation of 10'. The measured intensity is integrated along the vertical y-direction of the detector. **a)** Horizontal x-distribution of the neutrons at various distances z from the guide exit. **b)** Intensity profile at the nominal focal point (z = 80 mm).

The vertical beam profiles for the collimations 10' and 80' are depicted in **Figure 3** as intensity maps in the (yz)-plane. Again the double peak structure is observed before and after the focal point due to the reflection of the neutrons from the top and bottom sides of the guide. As expected, the focusing is very pronounced for the 10' collimation when compared with the 80' collimation. The broad 5 mm wide hump can be removed by an appropriate beam stop as discussed above.

**Figure 3.** Vertical beam profiles, i.e. (yz)-intensity maps for a vertical collimation of a) 10' and b) 80'. The horizontal collimation was fixed at 10'. The measured intensity is integrated along the horizontal x-direction of the detector.
**Figure 4** summarizes the experimental data for the four different vertical collimations used. The intensity distribution consists of a broad plateau with a width of 5 mm due to the direct beam and the focused beam, which has a FWHM that increases with decreasing collimation. The inset provides the fitted FWHM of the sharp component after the broad plateau is subtracted from the data. The level of the plateau is determined by estimating the intensity at the kink of the beam profile near the $y = \pm 2.5$ mm position as indicated by arrows in **Figure 4**. The width of the beam at the focal spot can be reduced by almost a factor of four when the collimation is decreased from 80’ to 10’. Note that the amplitude of the sharp component is essentially independent of the selected collimation as expected and that the maximum divergence of the beam before the first collimator is only about 60’.

![Figure 4](image)

**Figure 4.** Vertical beam profile at the nominal focal point for various collimations. The measured intensity is integrated along the horizontal $x$-direction of the detector. The arrows at the left indicate the level of intensity of the neutrons, which pass the focusing guide without being reflected from the sides of the guide.

4. Conclusions

We have introduced a focusing system for neutrons that allows the selection of the vertical and horizontal beam size at the sample position over a wide range by means of a combination of two collimation stages and a 500 mm long focusing parabolic neutron guide. Because only neutrons being useful for the experiment enter the neutron optical system, the background is significantly reduced while the flux density at the sample position is improved. Longer guides improve the homogeneity of the focused beam [2]. Similar concepts can be applied to Montel optics using parabolic or elliptic mirrors yielding the additional benefit of a very homogeneous phase space [6] and allowing even more bulky sample environments. The presented focusing system installed on a mechanical support with provision for a highly reproducible positioning using kinematic mounts allows a very efficient, swift, and cost-effective conditioning of neutron beams at beamlines for diffraction, spectroscopy, imaging, and irradiation.

References

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