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Union of Compact Accelerator-Driven Neutron Sources I & II

Novel neutron focusing mirrors for compact neutron sources

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Abstract

We demonstrated neutron beam focusing and neutron imaging using axisymmetric optics, based on pairs of confocal ellipsoid and hyperboloid mirrors. Such systems, known as Wolter mirrors, are commonly used in x-ray telescopes. A system containing four nested Ni mirror pairs was implemented and tested by focusing a polychromatic neutron beam at the MIT Reactor and conducting an imaging experiment at HFIR. The major advantage of the Wolter mirrors is the possibility of nesting for large angular collection. Using nesting, the relatively short optics can be made comparable to focusing guides in flux collection capabilities. We discuss how such optics can be used as polychromatic lenses to improve the performance of small-angle-scattering, imaging, and other instruments at compact neutron sources.

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Keywords: neutron optics; neutron mirrors; neutron focusing; small-angle neutron scattering; neutron imaging;

1. Introduction

Neutron radiation is useful for a wide range of applications, from materials science to medicine to security inspections. Despite recent progress with neutron sources, neutron instruments remain limited, sometimes severely, by available neutron fluxes. (This statement is especially true for compact accelerator-based neutron sources.) Therefore, the progress in neutron optics and instrumentation is as important a path toward more powerful neutron instruments as the development of brighter sources.

Relatively weak interactions of neutrons with most materials give neutron radiation its penetrating power. However, the weakness of interactions results in the refractive index, which is very close to unity for most materials, $1 - n \approx 10^{-6}$. Consequently, neutrons reflect from surfaces only at grazing angles,

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which are normally not larger than a few degrees. The refractive index depends on the square of the neutron wavelength so that refractive optics is strongly chromatic, a considerable disadvantage for instruments operating with polychromatic neutron beams. As a result, it is challenging to build efficient neutron optical components, such as lenses and mirrors, which are normally used in visible-light optics. Currently, several kinds of neutron focusing mirrors exist. Elliptical Kirkpatrick-Baez (KB) mirrors have been recently developed, following their successful use for synchrotron x-rays [1]. KB mirrors can be precisely figured with low roughness, and coated with multilayers having high critical angle. However, for large neutron sources of 5 – 50 mm, such mirrors are not always optimal since they work best for sources of less than 1 mm. Furthermore, elliptical KB mirrors are not ideal as imaging devices, since the magnification of an elliptical mirror depends on an incident angle, leading to distortions in imaging of large objects. Somewhat similar toroidal mirrors are used in small-angle neutron scattering (SANS), but with limited success so far [2].

In 1952, Hans Wolter described the advantages of axisymmetric glancing-angle mirrors for an x-ray microscope, based on the pairing of a con-focal ellipsoid and hyperboloid [3]. A modification of this idea has found applications in x-ray astronomy, where paraboloid-hyperboloid telescope mirrors are used routinely [4]. We demonstrated that such optics can be used for neutron imaging and scattering applications [5,6]. The major benefit of Wolter-type optics is the possibility of nesting cylindrical mirrors with different diameters but the same focal length inside each other to enhance neutron collection efficiency. In contrast, KB or toroidal mirrors cannot be easily nested. Additional benefit is the flexibility of the optics, which can be made removable, in contrast to most neutron guides. The degree of flexibility offered by short removable mirrors could be a great asset for compact neutron sources, which often operate a small number of beam-lines. In this paper, we present the current status of the development of axisymmetric neutron optics, especially for applications such as SANS, imaging and scattering from small samples.

2. Wolter mirrors: geometrical optics and manufacturing

Figure 1(a) shows the geometry of the Wolter type-I mirrors. Incident rays reflect from both mirrors before coming to a focus. Since only double-reflected rays make it to the focal plane, the rays which will not intersect the first mirror are stopped by a beam stop in front of the mirrors. Figure 1(b) shows the geometry of the mirrors close to the intersection point. The conditions for the angles on Figure 1 are as follows, when incident angles θ are equal:

$$\tan \theta_1 = r_i / f_s, \quad \tan \theta_2 = r_i / f_i \quad (1)$$

$$\phi_E = (\theta_2 - 3\theta_1) / 4, \quad \phi_H = (3\theta_2 - \theta_1) / 4, \quad (2)$$

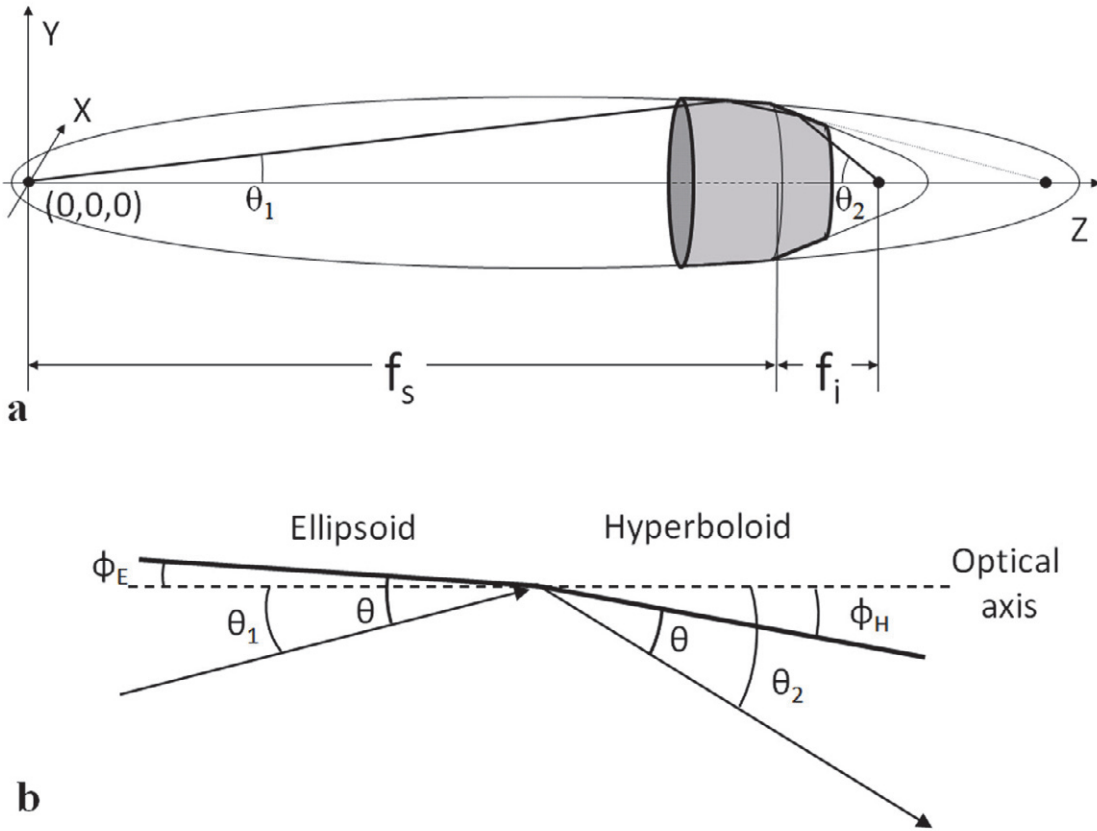


Figure 1 (a) Schematic view of a pair of Wolter focusing mirrors consisting of co-focal ellipsoid and hyperboloid. The small (“point”) source is at the origin, coincident with the left focal point of the ellipsoid. The right focus (image) coincides with the left focal point of the hyperboloid. The right focal points of the ellipsoid and hyperboloid (the right-most dot on OZ axis) are coincident. The beam and optical axes coincide with OZ axis. The distance f_s is between the source and intersection of the mirrors. The radius r_i at intersection and the length of each mirror are input parameters. The distance between the intersection and the image is f_i , while θ_1 and θ_2 are the angles between incident and reflected rays and the optical axis OZ. (b) Schematic drawing of a cross-section of the mirrors (and rays) near intersection. The mirrors are shown in bold, the arrows are the rays and the dashed line is the optical axis. The angles θ_1 and θ_2 are between the rays and the optical axis, θ is between the rays and the mirrors, and ϕ_E and ϕ_H are between the tangent of the mirrors at the intersection point and the optical axis.

$$\theta = \theta_1 + \phi_E = \theta_2 - \phi_H \tag{2}$$

The ellipsoid and hyperboloid are defined respectively by the equations:

$$r_E = b_E \sqrt{1 - (z - z_{0E})^2 / a_E^2}, \quad r_H = b_H \sqrt{(z - z_{0H})^2 / a_H^2 - 1} \tag{3}$$

Here z is the coordinate along the optical (beam propagation) axis, x and y are perpendicular to z , and $r^2 = x^2 + y^2$. The parameters a and b denote the semi-major and semi-minor axes of the ellipsoid and

hyperboloid, while z_0 denotes the location of their centers. From the initial parameters and the confocality condition for the hyperboloid and ellipsoid mirrors, it follows for z_{0H} and z_{0E} :

$$z_{0E} = c_E, \quad z_{0H} = 2c_E - c_H = 0.5(f_s + f_i) + z_{0E}, \quad c_H = \frac{f_i \theta}{r_i / f_i - 2\theta}, \quad (4)$$

Parameters a and b are found using the definitions for ellipsoid and hyperboloid: $a_E^2 - b_E^2 = c_E^2$ and $a_H^2 + b_H^2 = c_H^2$.

The technique used to produce axisymmetric mirrors is the electroformed nickel replication process [4]. Pure nickel or nickel-alloy mirrors are electroformed onto a figured and superpolished nickel-plated aluminium cylindrical mandrel from which they are later released by differential thermal contraction. The resulting cylindrical mirror has a monolithic structure that contains two segments in accordance with chosen Walter geometry. The replicated optics technique, developed for hard x-ray telescopes, is a perfect match for neutron applications. Since nickel is the material with one of the highest critical angles for neutrons, the electroform nickel optics can be used to focus neutron beams [5,6]. Multilayer coating to increase the neutron critical angle is under development.

3. Neutron evaluations

3.1 Neutron beam focusing

A system of four nested ellipsoid-hyperboloid Ni mirror pairs was made and tested at the Neutron Optics Test Station at the MIT Reactor. The mandrels for these mirrors were initially made for x-ray imaging applications [7]. Numerical parameters for each of the four mirror pairs are listed in Table 1. Each row in Table 1 corresponds to one of the four nested mirror pairs. The diameter of each mirror is such that it does not project a shadow onto a larger mirror. The optics have a magnification $M = 1/4$; when the angles between rays and the optical axis are small (paraxial approximation in geometrical optics), angular and lateral magnifications are equal to each other, $M = \theta_1/\theta_2 = f_i/f_s$. The origin ($Z = 0, r = 0$) is at one focus of the ellipsoid. The source is at the origin, and the detector is at $Z = 3.2$ m. The focal distances are: $f_i = 640$ mm, $f_s = 2560$ mm. The projected length of the hyperbolic section along the optical axis is L_H , and that of the elliptical section is L_E . The grazing angle for a ray from the origin to the intersection point is also reported in Table 1. Hyperbolic and elliptical shapes are given by equations (1) – (5).

Table 1. Geometrical parameters of the test mirrors used in these experiments.

a_H [mm]	b_H [mm]	a_E [mm]	b_E [mm]	L_H [mm]	L_E [mm]	r_i [mm]	θ [deg]
533.2821	7.296319	2133.382	14.59266	30.000	31.097	14.298	0.40000
533.2827	7.665439	2133.393	15.33097	30.000	31.097	15.021	0.42022
533.2824	8.053217	2133.404	16.10662	30.000	31.097	15.781	0.44148
533.2811	8.460593	2133.415	16.92151	30.000	31.096	16.579	0.46381

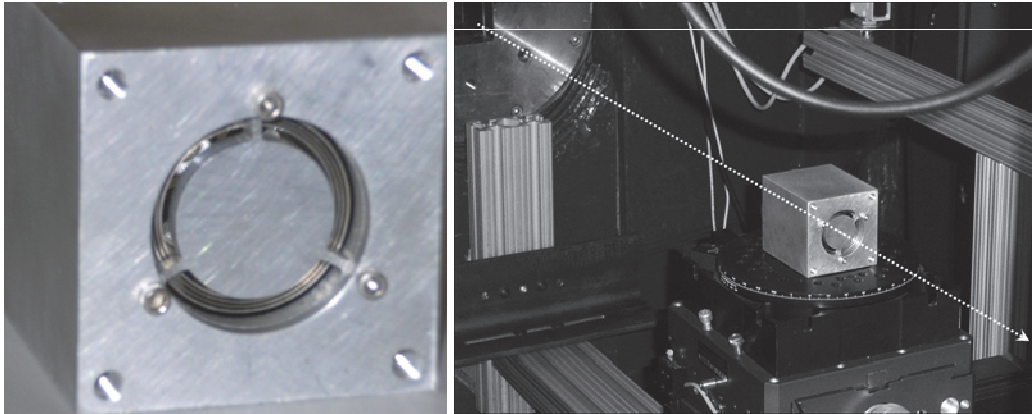


Figure 2. (a) System of four nested Ni mirrors inside an Al housing, front view. (b) Optics at the neutron beamline at the MIT Nuclear Reactor Laboratory. The mirrors are positioned on top of a goniometer. The beam follows the dashed arrow.

The mirrors were placed in the polychromatic thermal neutron beam. Figure 2 shows the photograph of the mirrors installed at the beam-line. The source (a 2-mm diameter cadmium aperture) and a detector were positioned in two focal planes. The detector is based on a standard neutron-sensitive scintillator screen. The light output from the screen is detected by a CCD (Andor Luca EMCCD). The spatial resolution of the detector was calibrated by imaging a 1.2 mm pinhole in a Gd foil. By fitting the image with a Gaussian, we found that the pixel size was $(92 \pm 4) \mu\text{m}$, FWHM. The image of the neutron source demagnified by the mirrors is shown on Fig. 3. Half-power diameter (HPD) of the spot is 0.62 mm.

The mirrors described above were optimized for the ease of testing and manufacturing. Since they are relatively short and made of Ni, these mirrors are not optimized for flux collection. For example, ray-tracing calculations predicted that only neutrons of up to about 5 meV are focused. These cold neutrons constitute a small fraction, about 5%, of the thermal neutron flux at the MIT Reactor. Supermirror multilayer coating will increase the upper cut-off energy, and therefore the collection efficiency of the mirrors. Also, longer mirrors will collect higher portion of the neutron flux.

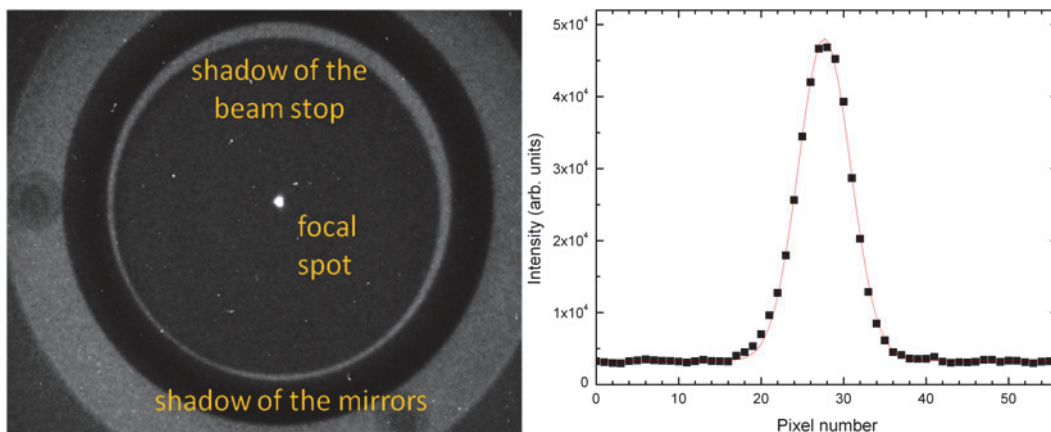


Figure 3. (a) Image of the source when the detector is at the focal plane, taken with the thermal beam at the MIT Reactor. The focal spot is an intense cold-neutron source ($E < 5$ meV) of sub-mm diameter. (b) Cross-section of the focal spot, fitted to a Gaussian to determine FWHM and HPD.

3.2 Neutron imaging

The imaging properties of the same mirror system have been tested at the instrument development beamline at HFIR (CG1-D) at Oak Ridge National Laboratory [8]. The schematic illustration of the neutron microscope tested in this experiment is shown on Fig. 4. The mirrors play the role of an image-forming lens. A neutron scatterer was placed in the neutron beam to produce a source with the divergence large enough to illuminate the mirrors. (The divergence of the beam at CG1-D is limited by the significant distance between the end of the guide and the beam aperture. If the source were located at the end of the guide, the beam divergence would be sufficient and no diffuser would be needed.) A Gd test object [9] was placed after the scatterer in the focal plane of the optics. The schematic drawing of the object is shown in Fig. 5(a). The grid-lines band seen at the bottom of the figure has 30 line groups each with 4 periods ranging from 4 mm down to 0.04 mm. The mirrors were placed as shown on Fig. 4, such that the magnified image of a portion of the grid can be recorded. The test object was translated by 3 mm and then 20 images were collected to cover the whole length of the pattern. An example of the single recorded image is shown in Fig. 5(b). The analysis of the images has shown the microscope is capable to resolve the period of 0.290 mm or single lines of 145 micron wide. This resolution is limited by the (binned) pixel size of the detector, rather than by the mirrors. The resolution can be improved significantly if the source beam had the divergence large enough to illuminate the mirrors without the use of the beam diffuser, which only diffuses a very small fraction of the intensity in the beam. Again, the mirrors were not designed for the use at CG1-D, but to demonstrate and test the feasibility of mirror-based imaging. To the best of our knowledge, this is the first experimental demonstration of neutron imaging using an axisymmetric grazing incidence microscope.

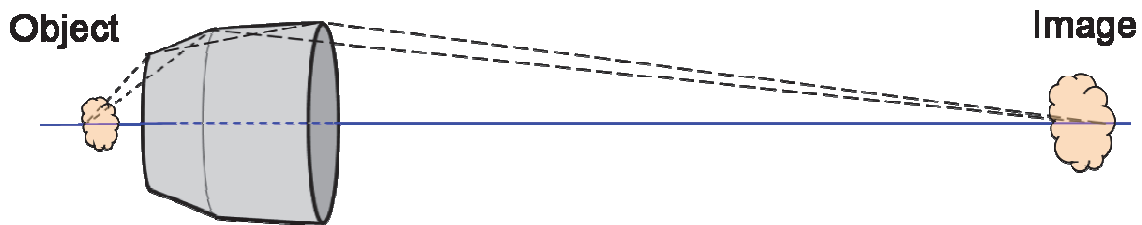


Figure 4. Schematic illustration of a single pair of Wolter mirrors acting as an image-forming lens. In the microscope-like configuration shown here, the neutron beam travels from left to right. The object is in the upstream focal plane of the optics. The magnified image is formed at the downstream focal plane. The source of the neutron beam is located upstream from the object. Only one axisymmetric mirror is shown for clarity, but several co-axial mirrors could be used to increase the neutron flux reaching the detector.

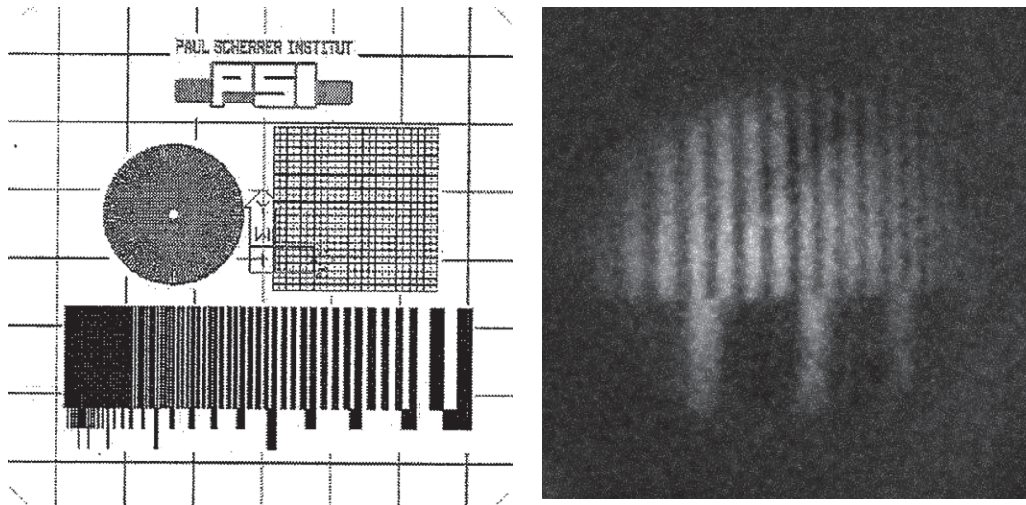


Figure 5. (a) Neutron absorbing test mask (made of Gd). The bottom line pattern (of known variable line width) was used for the neutron imaging experiment. (b) Image of line groups with periods of 0.83, 0.71, 0.59 and 0.5 mm (from left to right).

4. Discussion: possible applications of Wolter-type mirrors at compact neutron sources

There are several neutron techniques, which may benefit from axisymmetric mirrors, especially at compact neutron sources. We discuss the use of such optics for SANS, imaging, and for collecting maximum possible flux on small samples for diffraction or inelastic scattering.

4.1 SANS

SANS has a long history of utilizing focusing optics, such as refracting lenses or collimators, in order to increase the flux on the sample, improve the resolution and extend the range of accessible scattering angles [10]. Usually the focal planes of the optics are at the source aperture and the detector. The sample is placed directly downstream of the optics [11]. Even a small amount of focusing improves the resolution of SANS instruments [10-13]. However, existing focusing devices for SANS have strong limitations in terms of their performance, especially at accelerator-based neutron sources, which rely on time-of-flight SANS. The biggest problem with refractive lenses is strong chromatic aberration: the focal distance of biconcave neutron lens changes as the second power of the neutron wavelength, $f = \pi r / (\rho b_c \lambda^2)$. Consequently, the lenses are not suited for time-of-flight SANS instruments, which use polychromatic neutron beam. In fact, chromatic aberrations reduce the resolution even on reactor-based SANS instruments since the beam is not perfectly monochromatic. Recent developments of magnetic lenses have shown a promise to reduce chromatic aberrations by modulating the magnetic field. However, magnetic lenses are complicated devices, which require constant support while in operation. The need for polarized neutrons further reduces the count rate [14,15].

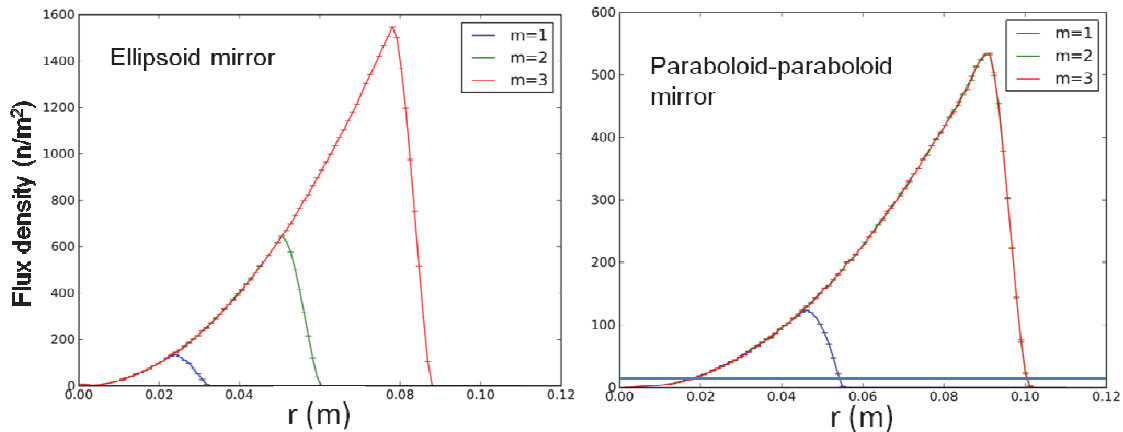


Figure 6. Ray-tracing calculations of an 8-m-long SANS instrument equipped with Wolter mirrors. The graphs show flux densities at the focus of ellipsoid (a) and paraboloid-paraboloid (b) mirrors as a function of the mirror's radius. Different supermirror coatings, $m = 1, 2$ and 3 are shown by different colors. In this particular case, there is no difference in performance of the paraboloid mirrors with $m = 2$ and 3 . Magnification $M=1$, total mirror length = 0.4 m, source-to-focus distance = 8 m, wavelength of 4 \AA . The blue horizontal line on the right figure shows the flux density without the mirrors (of 16 n/m^2). The source divergence corresponds to that of an $m=3.5$ guide.

In contrary to refractive optics, mirrors are free of chromatic aberrations. A mirror-based SANS instrument is installed at FRM-II in Munich. However, the instrument, which uses a single Cu-coated toroidal mirror, requires large samples to collect enough signal [2]. Wolter-type optics discussed here has significant advantages over such toroidal mirrors: (i) nested mirrors of full figure of revolution can collect larger neutron flux on the sample, and (ii) the flexibility in the optical design (see Fig. 6) allows to make the mirrors suitable for various goals, such as to enhance the flux or to shorten the length of a SANS instrument.

Fig. 6 shows ray-tracing simulations of a model SANS instrument with and without various mirrors. The flux density at the focal spot is equal to that of the source. Without mirrors, the flux density at the detector is shown by the blue line on the right figure (corresponding to 16 n/m^2). The simulations show that even a single short ellipsoid mirror made of Ni can improve the signal by an order of magnitude. It is possible to achieve very significant gains in the signal by nesting mirrors of different geometries and supermirror coatings. In addition to achieving higher flux at the detector, the mirrors can help decreasing the minimum q-vector or the length of the SANS instrument. The design of the optics for a real SANS instrument will have to take into account the achievable divergence of the beam, and the wavelength spectrum of the real source. It is clear that using axisymmetric optics at SANS instruments on compact sources may result in significant improvements of the instrumental capabilities.

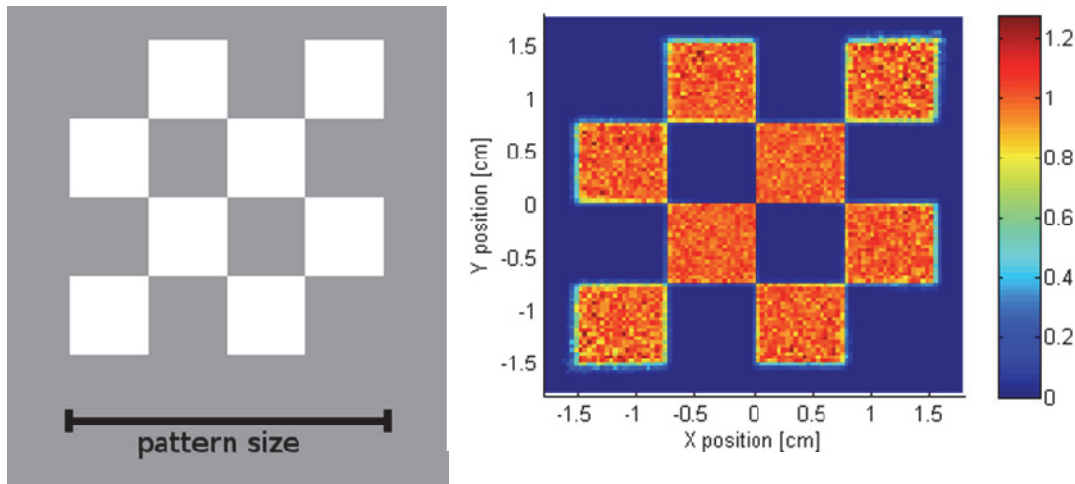


Figure 7. Ray-tracing results of a neutron microscope shown schematically on Figure 4. (a) Test pattern made of an absorbing (grey) and transparent (white) materials. Each white square is $0.75 \times 0.75 \text{ cm}^2$. (b) Simulated image. The source is 4 cm diameter, located 35 cm in front of the sample. The source-to-image distance is 10 m. The optics consists of four nested mirrors with magnification $M = 1$ and radii of 15 - 19 cm, $m = 3$ supermirror coating.

4.2 Neutron imaging

Neutron imaging is one of the fastest-developing neutron methods. The two key challenges for neutron imaging are weak source brilliance and poor detector spatial resolution. These challenges can be addressed by using lenses, as in optical microscopes, see Fig 4. We demonstrated this approach experimentally, as described above. The use of axisymmetric focusing mirrors could lead to dramatic improvements in the spatial resolution of neutron imaging instruments. Currently, the resolution is limited by the collimation of the beam (L/D ratio) and the detector pixel size. The angular resolution of Wolter mirrors can reach 0.1 mrad, corresponding to $L/D = 10^4$. By using the mirrors, the neutron source size could be made much larger than that in the pin-hole geometry, thus increasing the signal without negatively affecting the spatial resolution. In addition, if the images are magnified, the detector-pixel-size limitation is relaxed. We did ray-tracing simulations of a neutron microscope equipped with Wolter-type optics. An example of such simulations is shown on Fig. 7. Practically, the magnification of such optics can vary between 1 and 10. Depending on the available flux and required spatial resolution, one should be able to design the mirrors, which could improve the performance of existing and future imaging instruments. It is feasible to equip an instrument with several sets of mirrors with different magnifications for experiments, which require different spatial resolution or field of view.

4.3 Neutron flux collection for studies of small samples

Often, neutron instruments require collecting as many neutrons as possible on a sample or some optical element. We believe that short efficient collectors made from nested axisymmetric mirrors could prove effective for compact neutron sources because they can efficiently condense neutron beams such that the source brilliance is preserved while trading off beam size and angle. Preliminary calculations are reported in Ref. [6], where it is shown that Wolter mirrors can collect neutron flux density on the sample as much as 10 times that of the source. The exact design and performance of such optics depends on the properties of the source, source-to-sample distance and requirements to the beam divergence on the sample.

5. Conclusions

The performance of axisymmetric nested neutron focusing mirrors has been reported. The mirrors are made with a mature technology and are commonly used in x-ray astronomy and imaging. We demonstrated the adaptation of these optics for neutron techniques and showed that utilizing such mirrors in SANS and imaging instruments should result in significant gains in performance. The mirrors might be especially suitable for compact neutron sources, where the performance and flexibility of the instruments are paramount for successful research programs.

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