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Wolter mirrors for neutron imaging

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Abstract

Conventional radiography based on attenuation of a well-collimated beam remains the mainstay of neutron imaging. The spatial resolution attained with this pinhole-camera method depends on the beam collimation; therefore, achieving the spatial resolution of a few microns is practically difficult, since collimating the neutron beam results in a low flux. The use of focusing devices allows maintaining sufficient spatial resolution without collimating the beam. Therefore, axisymmetric grazing-incidence focusing mirrors (Wolter mirrors) have begun to be introduced to neutron imaging. In this paper, a design of a neutron microscope for NIST Center for Neutron Research (NCNR) is presented. We evaluate the spatial resolution and study field curvature aberrations of Wolter mirrors through ray-tracing simulations. A general formula is found describing the field curvature, and ways to counter these aberrations are discussed.

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Keywords: neutron imaging; focusing mirrors; field curvature

1. Introduction

Conventional radiography uses the pinhole-camera method, which trades resolution for signal. High resolution requires maintaining large L/D ratio, where L is the aperture-to-sample distance and D is the diameter of the source aperture, and small sample-to-detector distance. Increasing the L/D ratio results in decreasing the neutron flux reaching the sample, therefore available resolution is limited by the signal-to-noise ratio. In contrast to neutrons, modern light and x-ray imaging methods often use sophisticated optical devices, which allow for increased spatial resolution and high signal-to-noise ratios. Therefore, axisymmetric focusing mirrors (Wolter mirrors) have been introduced to neutron imaging as image-forming lenses. We call an imaging instrument based on Wolter mirrors a neutron microscope, because its optical design reminds that of a conventional optical microscope. The demonstration of the prototype neutron microscope was presented previously [D. Liu et al. (2012)]. Here we present the details of an optimized microscope, which is currently under construction at NIST.

The resolution of neutron imaging utilizing image-forming optics is determined by the optics, not the L/D ratio. Furthermore, the spatial resolution can be improved by using magnifying optics. A divergent beam is required to

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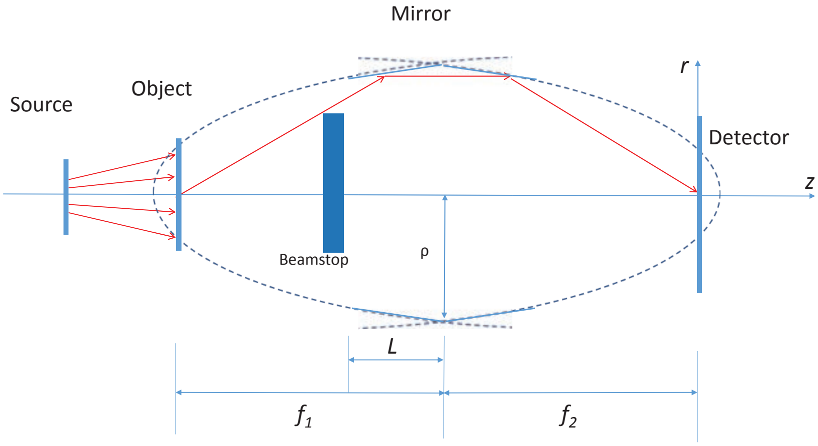

Fig. 1. Schematic layout of neutron microscope using a Paraboloid-Paraboloid (P-P) mirror. Here f_1 and f_2 denote the object-optic-distance and optic-detector-distance respectively, the magnification is defined as $M = f_2/f_1$. A beamstop is located at the upstream of optic to absorb direct rays, which do not intersect the mirrors.

illuminate the optics thus a larger source size can be used to increase the neutron flux. Also, optics is placed between a sample and a detector, creating a separation of several meters between them. This separation is very beneficial for measurements requiring bulky sample environment, or for polarized neutron imaging, or imaging of spent nuclear fuel, whose radiation may damage a CCD-based detector. A design of Paraboloid-Paraboloid (P-P) mirror with magnification 1 has been made for NCNR and the production of mirrors has recently started. Fig.1 shows a schematic illustration of this device. A sample is placed at the focus of one parabola, and the image is formed in the focus of the second parabola.

Similar to the optics for visible light, grazing-incidence neutron mirrors also have optical aberrations. Aberrations fall into two classes: monochromatic and chromatic. Wolter optics are free of chromatic aberrations, if gravity is ignored [D. Liu et al. (2013)], because neutrons of different wavelengths reflect the same way when the incident angles are smaller than the critical angle. But monochromatic aberrations, such as spherical aberration, coma, astigmatism, distortion and Petzval field curvature, still occur. The field curvature is the dominating aberration in the case of glancing-incidence focusing mirrors. It means that the focal surface is not a plane, but a curved surface, a parabola facing upstream, where off-axis rays come to focus. In this paper, we study the field curvature of Wolter optics by ray-tracing simulations and a general formula describing the field curvature is found.

2. Design of Paraboloid-Paraboloid (P-P) Mirrors for NIST Center for Neutron Research

A detailed design has been done of the mirrors with magnification $M = 1$ for the new Cold Neutron Imaging Facility (NG-6) at NCNR and the mirrors are being fabricated. As shown in Fig. 1, the object and detector are placed at the two focal plane of two Paraboloids respectively. A set of coaxial P-P mirrors will be nested together to increase the neutron intensity. The following constraints were used based on the imaging facility geometry and location: total length (between the sample and detector) is of 7.0 m. Performance calculations were done for the neutron wavelength of 0.6 nm. Mirrors coating is Ni or Ni-58, and the surface is ideal without imperfections. The source size is chosen to be 20 mm in diameter when the focusing mirrors are used. P-P mirror geometry was chosen for $M = 1$ because of the symmetry, which improves the optical performance and eases the manufacturing [Feurmann and Gordon (2008)]. Ray-tracing simulations were conducted to optimize the optics using the software package McStas [Lefmann and Nielson (1999), Willendrup etal. (2004)] which is routinely used for simulating neutron-scattering instruments and conducting virtual experiments, aiming at optimizing two parameters: (i) to select appropriate radii for nested