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Neutron Beam Control Using Polycapillary Optics

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Small capillaries (~ 10 μm) can efficiently bend thermal and cold neutron beams by means of multiple reflections. Capillary neutron optics, assembled from an array of capillary fibers, have many functions in beam control including focusing, collimating, bending, and splitting. The design of such optics is flexible enough to achieve different functions in a single unit. For example, a neutron bender/focuser, which we are currently constructing, bends a cold neutron beam out of the line-of-sight from the source to reduce the background, and then focuses the beam to a submillimeter spot with greatly increased neutron current density. In this paper, we report the technical specifications of the neutron bender/focuser. Other optic configurations for various applications are discussed.

KEYWORDS: neutron optics, polycapillary optics, capillary optics, neutron focusing, neutron bender, neutron splitter, neutron bender/focuser.

1. Introduction

Like the neutron guides commonly used at research reactor facilities, capillary neutron optics are reflective optics that transport thermal and cold neutrons by means of multiple total external reflections.[1-8] However, capillary optic transport the neutrons using small (~ 10 μm) diameter capillary channels. A neutron beam can be effectively deflected with a curved neutron guide if the diameter of the guide d, is much smaller than its radius of curvature R ($R > 2d/\theta_c^2$ where θ_c is the critical angle of total external reflection). The advantage of the small channel diameters in capillary optics is that the neutron beam can be efficiently guide through a much smaller radius of curvature (~ 1 m) compared to that (~ 5 km) for the wide (~ 50 mm) conventional neutron guides. Multifiber neutron optics, which consist of large arrays of curved polycapillary fibers, have many functions in beam control including focusing, collimating, bending, and splitting.

Previously, a multifiber capillary focusing optic[8] was designed and assembled by X-Ray Optical Systems, Inc. for use with the Prompt-Gamma Activation Analysis (PGAA) instrument at the U.S. National Institute of Science and Technology (NIST). This optic collects a cold neutron beam from a ^{58}Ni coated guide (50 × 45 mm^2), and focuses it onto a 0.53 mm FWHM spot. The average gain in neutron current density within the area defined by the FWHM is 80. The significant gain in neutron current density and small spot size achieved using the multifiber optic clearly demonstrates the considerable potential benefit to neutron absorption techniques. However, improvements beyond the existing design of neutron focusing optics are possible.

One problem associated with existing optics is that the focus of the lens lies along the same axis as the neutron guide. Hence, both the focus and the surrounding area are illuminated by any unguided neutron field streaming directly through the optic. The background near the focus can be significant, but may be avoided by directing the fibers of the focusing optic so that the focus is well outside the direct path of the beam. We are constructing such a neutron bender/focuser for the cold neutron PGAA station at NIST. In this paper, we report the technical specifications of the neutron bender/focuser and discuss optic designs for additional applications.

2. Expected performance of the neutron bender/focuser

The NIST neutron bender/focuser is designed to collect a 50 × 45 mm^2 cold neutron beam exiting from a ^{58}Ni coated guide. The wavelength distribution of the incident neutron beam is approximated using a Maxwellian distribution that exhibits a 0.49 nm characteristic wavelength. There is a short-wavelength cutoff in the spectrum at 0.4 nm due to a beryllium-bismuth filter cooled to 77 K placed upstream. The lens design is optimized by computer simulations to maximize the neutron flux within an area 1 mm in diameter (FWHM) at the focus. The most important feature of the optic is that the focus occurs 22 mm outside the path of the direct beam.

The simulations use a *Monte Carlo* method to trace a large number of neutron trajectories, so that the distribution of initial conditions can closely represent the actual experimental conditions. The neutron wavelengths are randomly selected according to the wavelength distribution of the incident beam. During the passage of a neutron through a capillary, each incident angle of reflection is calculated. Thereby, the probability that the neutron is actually transmitted can be obtained from the product of reflection probabilities for each reflection. Individual reflection probabilities are calculated according to the Fresnel equation for the reflection coefficient, using the complex index of refraction for the glass. The simulations agree well with the experiments both in the transmission efficiency and exit divergence for neutrons through straight or curved capillaries[5].

Figure 1 shows the schematic drawing of the neutron bender/focuser. The optic consists of 3997 polycapillary fibers, each 190 mm in length. Each fiber has a hexagonal cross section, measuring 0.59 mm between opposite corners, and contains 1657 capillary channels that are 9.5 μm in diameter. The polycapillary fibers are manufactured from boron-free lead-silicate glass (density 3.26 g/cm^3).

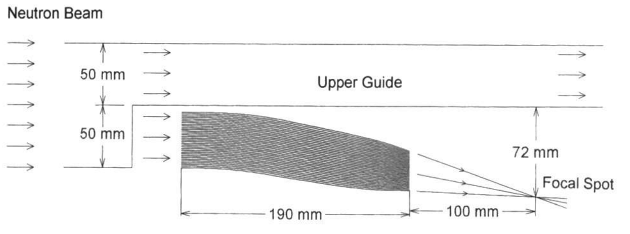

Figure 1. A schematic of the neutron bender/focuser being constructed for PGAA application.

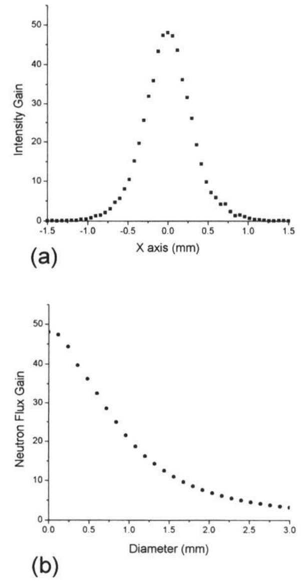

Figure 2. Simulated intensity distribution (a) normalized to the incident beam, and (b) the gains in neutron flux summed from areas of different diameters at the focus.

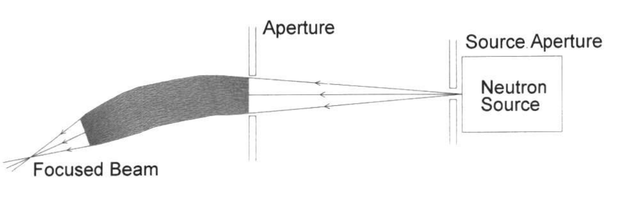

Figure 3. A schematic of a capillary optic used to focus neutrons directly from a source using a small source aperture.

The polycapillary fibers are accurately guided by the six positioning meshes. The geometry of each fiber in the optic is determined by a spline function defined by the placement of the fiber in the six meshes. The optic is designed such that all the fibers lay parallel to each other at the entrance of the lens. At exit, the fibers are close packed and each is directed toward the focus, 100 mm away. The central axis of the optic is curved to a deflection angle of 9.9°, which results in the displacement of the focal spot 22 mm below the field of the direct beam. The lens has a rectangular cross section with dimensions of 50 × 45 mm^2 at entrance and 33.3 × 30 mm^2 at exit. The output beam has a full convergence angle of 19° in the horizontal direction, and 17° in the vertical direction.

For the neutron bender/focuser described above, we have simulated the expected distribution of the neutron current density on the focal plane. The results are presented in Figure 2. The gain in Figure 2 is defined as the ratio of the neutron current density at the focal plane of the optic compared to that of the direct beam at the entrance plane. Figure 2a shows that the intensity profile on the focal plane has a Gaussian shape with FWHM of 0.65 mm. Figure 2b shows the simulated intensity gain averaged over areas of different diameters. The expected intensity gain over the 0.65 mm diameter area is 30.

The greatest advantage of the neutron bender/focuser over the existing focusing optic is that the focal spot is shifted away from the direct beam. This will significantly reduce the background near the focal spot, resulting in better contrast for elemental mapping and improved signal to noise response for PGAA determinations. Furthermore, the displacement of the focal spot away from the upper guide allows larger samples to be measured and reduces the background originating from the material in the upper guide. The longer focal distance also makes for easier shielding of background signals generated from neutrons scattered or absorbed within the optic.

3. Other optic configurations

Capillaries provide an unique and effective way of controlling thermal and cold neutron beams. The design of capillary optics is flexible enough to allow customized output beam configurations for applications other than PGAA. Following are some examples.

• Focusing neutrons directly from a source. The neutron focusing optics described above are designed with parallel capillaries at the input for the most effective capture of neutrons from the neutron guide. However, to capture neutrons directly from the source, the orientations of the capillaries at the input can be modified slightly to point at a common area of maximum brightness in the source. This configuration, illustrated in Figure 3, allows the use of small source apertures (a few millimeters in diameters) without reducing the total output flux from the optic. This will significantly reduce background around the instrument. Furthermore, such an optic would deliver a focused thermal or cold neutron beam, substantially filtered of gamma rays and fast neutrons originating from the neutron source.

• Neutron collimation and anti-scattering devices for neutron radiography[9]. The spatial resolution of neutron radiography depends on the collimation of the primary beam. A capillary bundle can collimate a neutron beam within $\pm\theta_c$ over a short distance. For glass, $\theta_c = \gamma_c\lambda$, where γ_c= 10 mrad/nm. A parallel capillary bundle, made of borosilicate glass for high neutron absorption cross section is placed between the sample and imaging device. The optic can be used as an anti-scattering device with a high selectivity ratio defined as the ratio of the transmission efficiency of primary neutrons to that of scattered neutrons. This is accomplished because the capillary optic will only transmit scattered neutrons within a very small solid angle of $\pi\theta_c^2$. Figure 4 illustrates the use of capillary optics in neutron radiography for ^{10}B imaging. Likewise, it can be used to image hydrogenous regions, such as corrosion, in a material or organic inclusions.

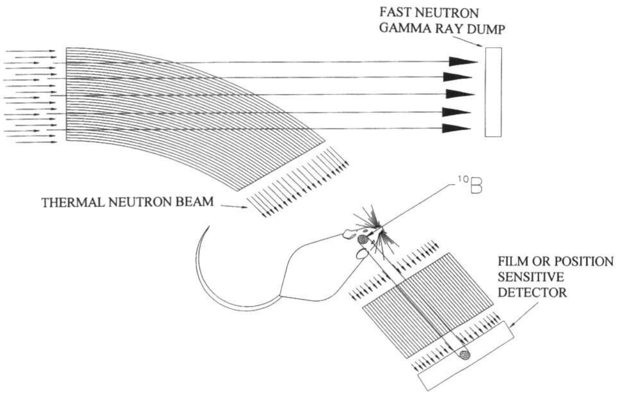

Figure 4. A schematic showing the use of a capillary optics for neutron radiography of ^{10}B imaging.

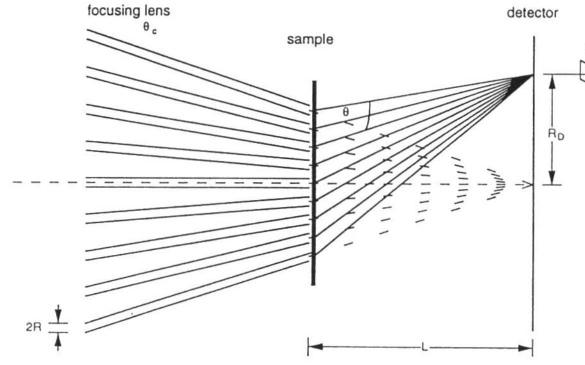

Figure 5. A schematic showing the experimental arrangement of a focusing guide small-angle neutron scattering experiment.

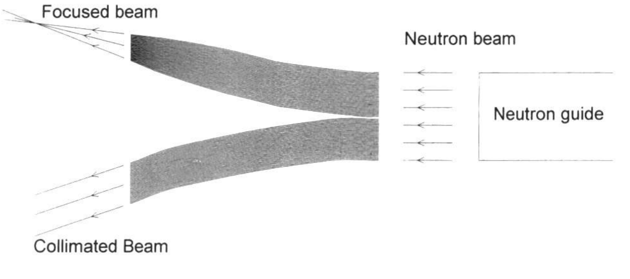

Figure 6. A schematic for a neutron beam splitter which creates both a focusing beam and a collimated beam from a single input.

• Small-angle neutron scattering (SANS). It has been suggested that a capillary focusing optic would be useful when coupled with a high resolution position-sensitive detector for SANS[10]. Such a system, shown in Figure 5, will drastically reduce both the cost and size of a SANS instrument. The minimum Q-value detectable with the system may be about 6×10^{-3} nm^{-1}.

• Beam splitting. With a single multifiber optic, capillary fibers can be arranged in such a way that multiple groups of fibers are bent into different directions to create multiple neutron beam stations. The properties of each output beam can be optimized for its application. Figure 6 shows a neutron beam splitter which creates a focusing beam and a collimated beam. Such a lens needs not occur at the end of a neutron guide, but could be implemented along the guide as well. This would create pseudo end stations. Or, a reactor beam port could be bifurcated.

4. Summary

Although a relatively recent innovation, capillary neutron optic offer much potential for improving the utilization of neutron sources. Applications of neutron focusing using multifiber and monolithic capillary optics are appearing in the scientific literature. We have presented the description of a new lens developed to improve the signal-to-noise ratio in PGAA measurements and to enable larger samples to be interrogated. Furthermore, additional applications for multifiber capillary optics are suggested toward the greater utilization of limited neutron resources.

Acknowledgments

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