COMPOUND REFRACTIVE OPTICS IMPROVE RESOLUTION OF 30 m SANS INSTRUMENT

In the most favorable cases, cold neutrons can be deflected through an angle of a degree or two by grazing incidence reflection, but by only an arc second or two by refraction. Hence grazing incidence reflection optics has long been considered the most promising means for focusing neutrons for applications such as small-angle neutron scattering (SANS). Numerous attempts over more than 30 years to produce highly reflective surfaces for neutrons have been vitiated, however, by SANS from the mirror surfaces themselves, which blurs the focus. The best mirrors produced thus far are only marginally better for SANS than pinhole collimation, i.e., circular apertures separated by long distances.

Scientists at Bell Laboratories recently took a fresh look at this problem and proposed that multiple refraction from relatively high index, low absorbing material could be superior to reflection optics or conventional pinhole collimation for SANS. Initial measurements [1] at Risø National Laboratory, Denmark, demonstrated the proposed focusing effect, but did not make quantitative comparisons with reflection optics or pinhole collimation for application in SANS instruments. Measurements made recently at the NCNR in collaboration with the Bell Labs scientists [2] have addressed these issues and have demonstrated and quantified the significant improvement in resolution that can be achieved with compound refractive optics.

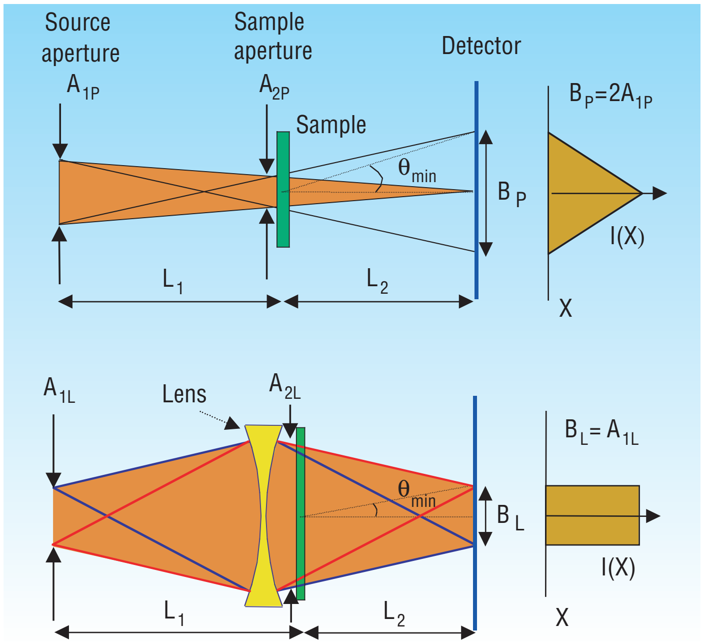

FIGURE 2. Upper panel, conventional SANS pinhole collimation. The source and sample apertures, A_{1p} and A_{2p}, respectively, determine the shape and extent of the beam profile, I(x), at the detector plane. Lower panel, focusing lens geometry. Ideally, the source aperture, A_{1L}, alone determines the beam profile.

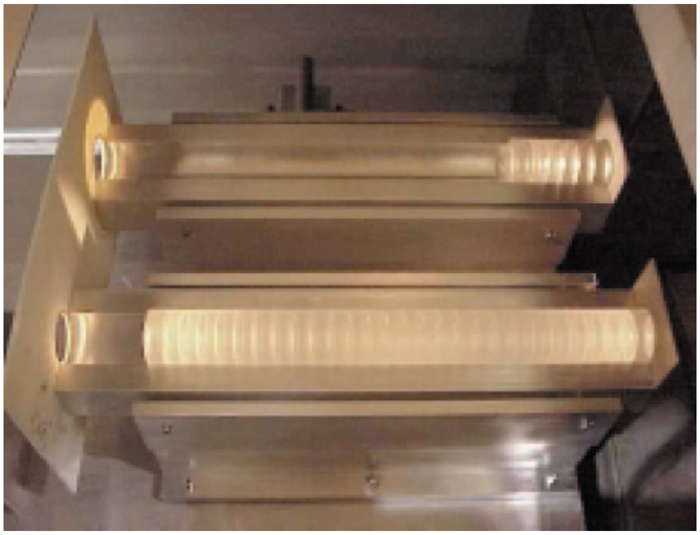

FIGURE 1. Now installed in the pre-sample flight path of the NG-7 30 m SANS instrument are two sets of MgF_2 biconcave lenses that can be inserted into the beam under computer control. The 28-lens array in the foreground focuses 8.44 Å neutrons at a distance of 15 m from the lenses, and the 6-lens set focuses 18 Å neutrons at the same distance. Each lens is 25 mm in diameter, has a radius of curvature of 25 mm, and is 1 mm thick in the center.

Our tests were made with the same set of cylindrical biconcave MgF_2 (magnesium fluoride) lenses used in the Risø study. Up to 30 lenses were placed end-to-end near the sample position of the 30 m SANS instrument to focus neutrons, emanating from a circular source aperture 15 m upstream, onto the plane of instrument's two-dimensional detector. Figure 1 shows an array of 28 lenses for focusing 8.44 Å neutrons at a distance of 15 m from the sample, next to a set of 6 lenses for focusing 18 Å neutrons at the same distance.

For this geometry, as depicted in Fig. 2, the lenses ideally produce a 1:1 image of the source aperture at the detector independent of the size of the sample. Since the scattering signal is proportional to sample size, the lens system can, in principle, be used to improve resolution more efficiently, by reducing the size of the source aperture, than is possible with pinhole collimation where both the source aperture and sample size must be reduced proportionally to improve angular resolution. Aberrations and small-angle scattering by the lenses could, however, blur the image to

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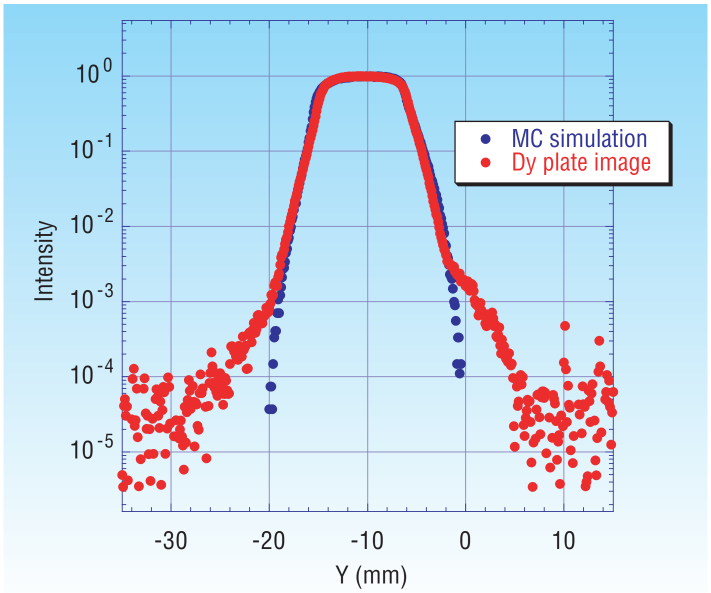

FIGURE 3. Red dots are measured points along the vertical profile of the image formed by the 28 lens array shown in Fig. 1 of a 9.5 mm diameter source of neutrons 15 m upstream from the lenses. The blue dots are a Monte Carlo calculation of the profile that includes the effects of spherical and chromatic aberrations as well as the broadening caused by gravity. The shoulder in the measured profile at Y = 0 is due to a residual fast neutron component in the beam.

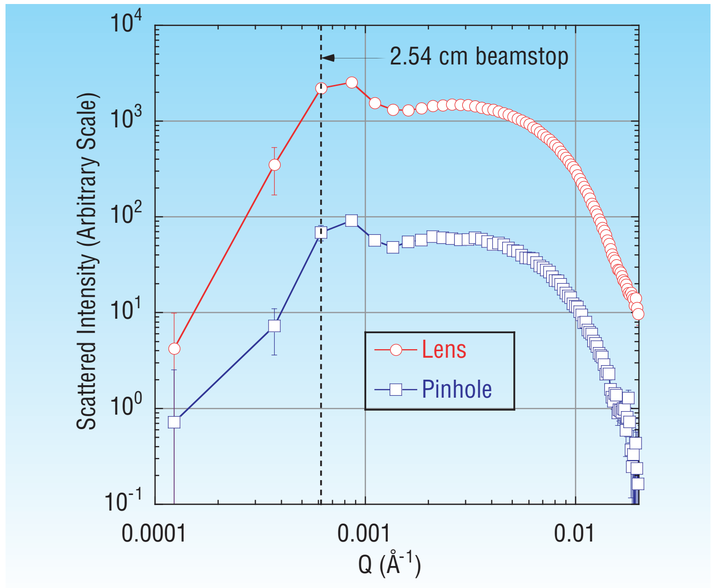

FIGURE 4. Small-angle scattering from voids in a single crystal (2.5 cm in diameter and 1 cm thick) of fast-neutron-irradiated aluminum. The measurements were made under equivalent resolution conditions (i.e. nearly identical beam spot size at the detector) using both simple pinhole collimation and the 28 biconcave lens array shown in Fig. 1. The integrated gain in intensity due to the lenses is approximately 26.

such a degree that any advantage over pinhole collimation, which does produce a sharply defined beam spot at the detector, would be lost.

To accurately measure the intensity profile produced by the lenses, a dysprosium foil was positioned at the focal plane and exposed to the focused beam for approximately 2 h. The activated foil was then placed in contact with a high resolution image plate which stored the image produced by the emitted gamma rays with a spatial resolution of better than 0.1 mm. A typical profile obtained from reading out the image plate is shown in Fig. 3. Also plotted in the figure is a Monte Carlo calculation of the profile that includes the effects of spherical and chromatic aberrations as well as the broadening caused by gravity. The measured profile agrees with the simulation down to intensity levels of 10^{-3} of the peak intensity and has an overall signal-to-background ratio in the wings approaching 10^5, which is highly satisfactory for most SANS measurements.

The practical benefit provided by the lenses is demonstrated by the SANS data from voids in a single crystal (2.5 cm in diameter and 1 cm thick) of fast-neutron-irradiated aluminum shown in Fig. 4. The measurements were made under equivalent resolution conditions (i.e., nearly identical beam spot size at the detector) using both simple pinhole collimation and the 28 biconcave lens array shown in Fig. 1. The first data point unaffected by the beam stop in both data sets occurs at $Q \approx 0.001$ Å^{-1}, but the scattered intensity at the detector (counts/cm^2/s) is more than 10 times higher by using the lenses to illuminate a much larger area of the sample.

The focusing lenses shown in Fig. 1 are now installed for routine use in the NCNR's 30 m SANS instrument on guide NG-7. Further testing is planned to understand, and hopefully eliminate, the sources of parasitic scattering that contribute to the tails of the beam profile seen in Fig. 3, prior to installing a lens system in the NIST/NSF 30 m SANS instrument on guide NG-3.

REFERENCES

[1] M. R. Eskildsen, P. L. Gammel, E. D. Isaacs, C. Detlefs, K. Mortensen, D. J. Bishop, Nature **391**, 563-566 (1998).

[2] S. -M. Choi, J. G. Baker, C. J. Glinka, P. L. Gammel, Proceedings of the XIth International Conference on Small-Angle Scattering, 1999, J. Appl. Cryst. (in press)