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The Focusing Mirror at the ILL Spin-Echo Spectrometer IN15: Experimental Results

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A high-quality toroidal mirror has been installed on the IN15 spin-echo spectrometer at the ILL Grenoble. The 4 m-long mirror consists of eight identical elements. The mirror surfaces are highly polished zerodur substrates coated with a ^{65}Cu layer and protected by a thin layer of aluminium. The imaging properties of the mirror were measured with a two-dimensional position-sensitive detector with a spatial resolution of 1.5 mm. For a 2 mm-diameter entrance source aperture, a noise-to-peak intensity ratio of 5×10^{-5} was achieved for $q > 10^{-3}$ Å^{-1}. The full-width at half-maximum of the focused neutron beam is of the order of $2 - 4 \times 10^{-4}$ Å^{-1}. Experimental results are compared with the results of Monte-Carlo ray-tracing simulations.

KEYWORDS: neutron focusing, toroidal mirror.

§1. Introduction

The spin-echo spectrometer IN15, under construction at the ILL, has been designed to provide higher energy resolution, and smaller values of the wave vector transfer q, than those of existing spin-echo instruments (such as the IN11 spectrometer at the ILL). In order to attain the low q-range (10^{-3} Å^{-1}) typical of small-angle scattering spectrometers, with a reasonable instrument length and flux, it has been constructed with a focusing option. In this configuration, neutrons are totally reflected by a large toroidal mirror which produces an image of the source aperture in the plane of an area detector.

Focusing small-angle scattering (SANS) instruments were first proposed more than thirty years ago.[1)] A number of detailed discussions of the advantages of a neutron focusing spectrometer, compared with a conventional pinhole collimation spectrometer, are given in references 2 and 3. The construction of such instruments was not undertaken until recently because mirrors of sufficient quality were not available for neutrons. Focusing mirrors rely on total reflection; therefore small slope errors as well as small surface roughness over large surface areas are required for good imaging. In addition, the reflecting surface must have the highest possible critical angle. These parameters must be combined for successful implementation of curved mirrors on neutron beam lines. An analysis of different reflecting surfaces for neutron beam focusing is given in ref. 4. The best image quality was obtained with a ^{65}Cu-coated surface rather than with a Ni-coated surface (commonly used for neutrons).

The present paper includes a brief description of the toroidal mirror recently installed on IN15. The imaging properties of the mirror were tested without the spin-echo option. The aim of these preliminary tests was to measure the contrast ratio, the q-resolution, and the size and quality of the image for different source apertures and neutron wavelengths. The experimental results are compared with Monte-Carlo ray-tracing simulations.

§2. Toroidal focusing mirror on IN15

A schematic diagram of the geometry of the test configuration installed on the IN15 spectrometer accommodating a toroidal focusing mirror is shown in Fig. 1. The source aperture and the detector are placed at the foci of the mirror. The glancing angle at the centre of the mirror is 1.5°. For the preliminary tests of the mirror a small (80 mm-diameter) position-sensitive detector was used with a spatial resolution of 1.5 mm.

The mirror (Zeiss, Oberkochen, Germany) consists of eight identical elements (500 mm x 170 mm), giving it a total length of 4 m. The in-plane radius of curvature is 408.75 m and the sagittal radius is 280 mm. The slope error is less than 2.5×10^{-5} rad (rms.) along the longitudinal axis and less than 5×10^{-5} rad (rms.) along the perpendicular axis of the mirror. Mirror surfaces are highly polished zerodur (a low thermal expansion glass

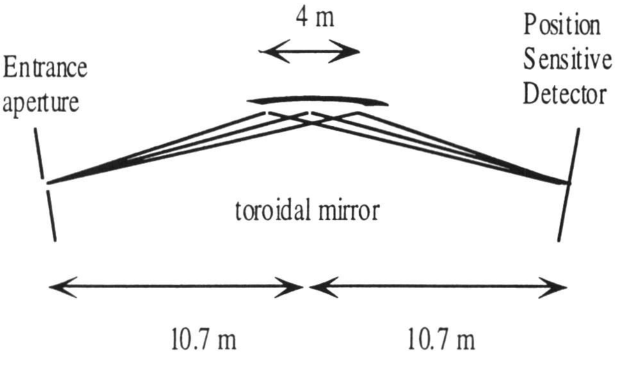

Fig. 1. Test configuration with toroidal mirror halfway between the entrance aperture and the detector.

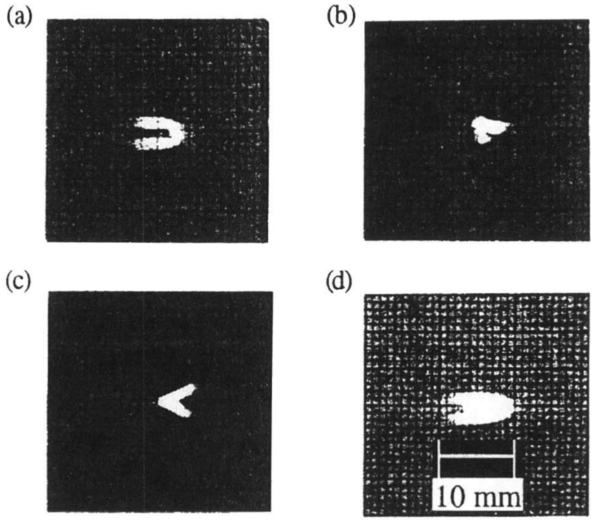

Fig. 2. Photographs of the focused images of a 1 mm diameter light source: (a) extreme left mirror, closest to the source aperture, (b) a central mirror, (c) extreme right mirror, and (d) all eight mirrors.

ceramic) coated with a ^{65}Cu layer protected by a thin layer of aluminium. The surface roughness after coating (Wyko TOPO 2D measurements) is less than 3 Å rms. The height of the useful reflecting surface is 150 mm. The mirror is designed to reflect neutrons with wavelengths greater than 15 Å. Each mirror is placed on an individual support and the latter are fixed on a single Al support. The entire mirror ensemble is in an evacuated tube. The exit and entrance of the tube are 10 mm thick glass windows with a diameter of 150 mm.

The mirrors were aligned using a 1 mm diameter halogen (diverging) light source placed at a focus and the image was observed on a screen placed at the other focus. Each mirror was individually aligned, starting with the central mirrors, and adjusted so that the images superposed. The individual images from three mirrors (the extreme left mirror, closest to the source, a central mirror and the extreme right mirror), and the image obtained with all eight mirrors, are shown below in Fig. 2. The images are viewed looking towards the mirror. The size of the image obtained with all eight mirrors is approximately 4 mm high, 8 mm wide.

§3. Results and Discussion

Figs.3a and 3c show the focused images of a neutron beam for $\lambda = 17.5$ and 22 Å respectively. All measurements were made with a neutron wavelength distribution of 15 % (full-width at half-maximum). The 2 mm diameter circular source aperture is placed at the focal point of the toroidal mirror (10.7 m from the centre of the mirror). The images are viewed looking towards the mirror. The shape of the image is asymmetric at both wavelengths. Such a distortion is attributed mainly to the gravitational fall of the neutrons and to the large distribution of wavelengths. Coma due to the great length of the mirror and alignment errors also contribute to imperfect imaging with a toroidal mirror. Athough the toroidal mirror geometry closely approximates an equivalent ellipsoidal mirror, ray-tracing simulations have shown that the former produces poorer images for long mirror lengths (> 2 m) and small source diaphragms.[5)]

The quality of the image degrades significantly with increasing wavelength due to the gravitational fall of the longer wavelength neutrons. The gravitational fall, Δ, depends on the neutron wavelength and the flight distance. A 22 Å neutron, for example, falls a vertical distance of about 18 mm in a distance of 10.7 m. After hitting the mirror, the neutron beam will fall the same average distance by the time it reaches the focal plane at the detector. In order to compensate for the substantial image deterioration due to the gravitational fall of the neutrons, it has been suggested that this effect may be reduced by lowering the source aperture a distance Δ below the focal point.[4)] Figures 3b and 3d show the images obtained for $\lambda = 17.5$ and 22 Å respectively with the source diaphragm lowered 11 mm for $\lambda = 17.5$ Å and 18 mm for $\lambda = 22$ Å. We see an important improvement in the image quality for both wavelengths. The improvement, which is especially significant in the horizontal plane, occurs because lowering the source, as described above, causes neutrons to strike the mirror at angles such that they appear to have come from points much closer to its focus. The remaining distortion in the vertical direction is due to the neutron wavelength distribution.

A ray-tracing program has been developed to estimate the imaging properties of the toroidal mirror as a neutron focusing device and to evaluate effects due to mean wavelength, wavelength distribution, and geometrical factors, such as mirror length. Details of the simulation program are presented in reference 5. It is instructive to compare the simulated images in Figs. 4a - d with the experimental results in Figs. 3a - d. The shapes of the experimentally measured images and the simulated images are not exactly identical for both wavelengths with the source aperture at the focus. This is because the mirrors were optically adjusted so as to achieve a better than toroidal geometry. However, it is gratifying to recover similar images narrower in the horizontal direction than in the vertical direction when the source is lowered below the focus to compensate for the effect of gravity.

Neutron intensity profiles of the focused beam in the horizontal direction are shown in Figs. 5a and 5b for $\lambda = 17.5$ Å and $\lambda = 22$ Å, respectively. For a given wavelength, the intensity profiles with and without a vertical shift of the source diaphragm are compared. The average count rate is 4000 neutrons per second ($\lambda = 17.5$ Å) and 1000 neutrons per second ($\lambda = 22$ Å). The values of the full-width at half-maximum (FWHM, $\Gamma_{1/2}$) of the focused neutron beam, the noise-to-peak ratio (contrast ratio), and the q resolution in the horizontal and vertical directions are given in Table I for both wavelengths and for both positions of the source diaphragm. The noise-to-peak ratio is measured at a distance $2\Gamma 1/2$ from the peak maximum and the q resolution is given by $\delta q = (2\pi/\lambda) \times (\Gamma_{1/2}/L_d)$ where L_d is the distance from the mirror to the detector. Also included in the table are the values of the contrast ratio at $q \approx 10^{-3}$ Å^{-1}. These values are independent of the direction.

The FWHM of the focused beam in the horizontal

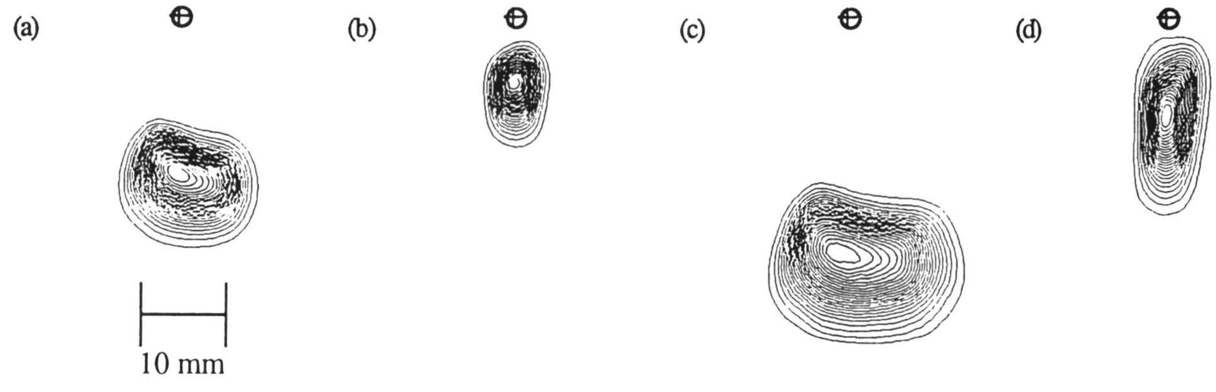

Fig. 3. Contour plots (linear scale) of the focused neutron beam for a source diaphragm diameter of 2 mm: (a) λ = 17.5 Å, source diaphragm at the focus of the mirror; (b) λ = 17.5 Å, source diaphragm 11 mm below the focus; (c) λ = 22 Å, source diaphragm at the focus of the mirror; (d) λ = 22 Å, source diaphragm 18 mm below the focus. The same scale applies to all plots. The crosshairs indicate the position of the focus.

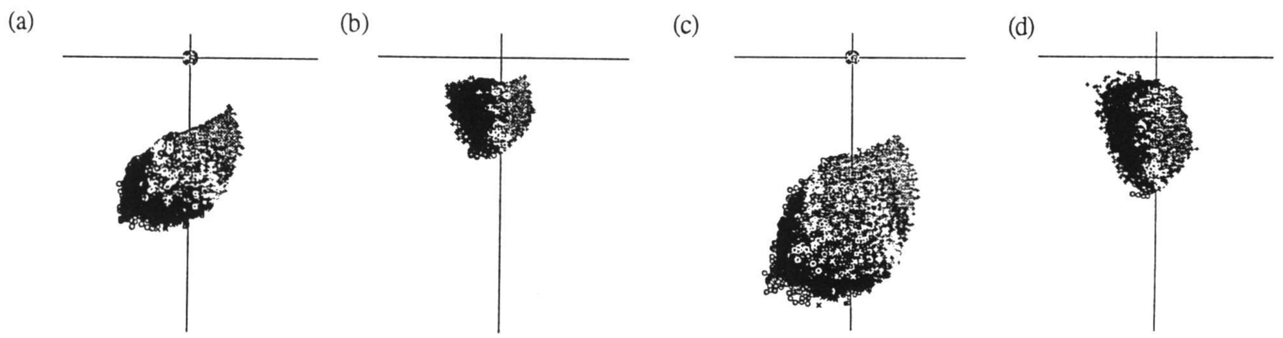

Fig. 4. Simulated images of a focused neutron beam with a 2 mm-diameter source aperture: (a) λ = 17.5 Å, source diaphragm at the focus of the mirror; (b) λ = 17.5 Å, source diaphragm 11 mm below the focus; (c) λ = 22 Å, source diaphragm at the focus of the mirror; (d) λ = 22 Å, source diaphragm 18 mm below the focus. The position of the source at the focus is indicated in (a) and (c).

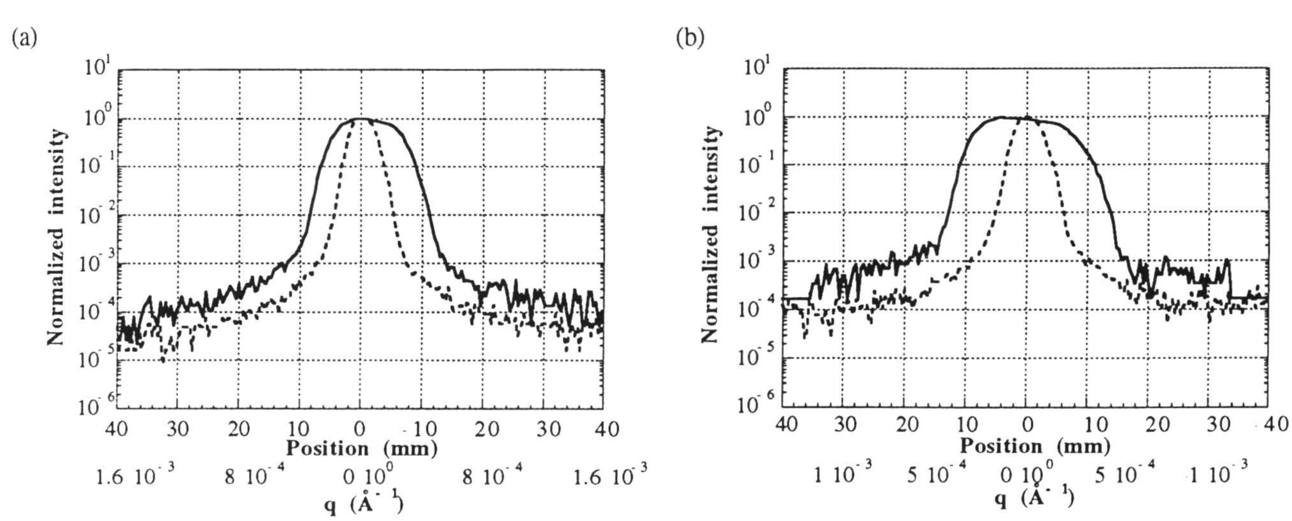

Fig. 5. Neutron intensity profiles in the horizontal direction for (a) λ = 17.5 Å and (b) λ = 22 Å. The full lines correspond to Figs. 3a and 3c and the dotted lines correspond to Figs. 3b and 3d.

Table I. Values of the FWHM, the q resolution (δq), and the contrast ratio, for λ = 17.5 Å and λ = 22 Å with a 2 mm-diameter source aperture positioned at the focus (z = 0) and a distance z = Δ below the focus.

Characteristics of the focused neutron beam	λ = 17.5 Å z = 0	λ = 17.5 Å z = -11 mm	λ = 22 Å z = 0	λ = 22 Å z = -18 mm
FWHM ($\Gamma_{1/2}$) (mm) Horizontal direction	10.5	4.5	15.5	4.5
Vertical direction	7.5	6.0	10.0	10.0
δq (Å^{-1}) Horizontal direction	3.5 x 10^{-4}	1.5 x 10^{-4}	4.1 x 10^{-4}	1.2 x 10^{-4}
Vertical direction	2.5 x 10^{-4}	2.0 x 10^{-4}	2.7 x 10^{-4}	2.7 x 10^{-4}
Contrast ratio (at $2\Gamma_{1/2}$) Horizontal direction	2.5 x 10^{-4} (at ± 21 mm)	6.0 x 10^{-4} (at ± 9 mm)	5.0 x 10^{-4} (at ± 31 mm)	1.0 x 10^{-3} (at ± 9 m m)
Vertical direction	6.0 x 10^{-4} (at ± 15 mm)	5.5 x 10^{-4} (at ± 12 mm)	2.0 x 10^{-4} (at ± 20 mm)	5.0 x 10^{-4} (at ± 20 mm)
Contrast ratio at $q \approx 10^{-3}$ Å^{-1}	1 x 10^{-4}	5 x 10^{-5}	4 x 10^{-4}	1 x 10^{-4}

direction is substantially smaller when the source diaphragm is positioned below the focus (Figs. 5a and b, Table I). However, with the source in this position and depending on the wavelength, it can be up to two times larger in the vertical direction. This may be attributed to the neutron wavelength resolution.

The contrast ratio at $2\Gamma_{1/2}$ depends on the direction for both source positions. At higher q values ($q > 5 \times 10^{-4}$ Å^{-1}), the contrast ratio is a factor of four or five times better when the source diaphragm is lowered a distance Δ below the focus. In fact, in this position, for λ = 17.5 Å, the contrast ratio is of the order of 5×10^{-5} in both the horizontal and vertical directions for $q \approx 1.6 \times 10^{-3}$ Å^{-1}. The intensity profile shown in Fig.5a suggests that the contrast ratio may be better at even higher q values. For λ =22 Å, it seems that the best contrast ratio is already achieved at $q \approx 10^{-3}$ Å^{-1}. This is again due to the poorer image quality with 15% wavelength resolution. The values given in Table I are of the same order of magnitude as those obtained in recent investigations of flat sample focusing mirrors[4)] and are much better than those obtained in previous tests of curved mirrors which were hampered by a Ni coating.[2-3)]

Fig.6 shows the intensity profiles (horizontal direction) for a 2 mm and a 10 mm diameter source aperture positioned 11 mm below the focus with λ = 17.5 Å. The FWHM of the focused neutron beam is two times larger for the 10mm diaphragm compared with the 2 mm diaphragm. While the contrast ratio is slightly poorer with the 10mm source diaphragm, the gain in intensity compared with the 2mm source diaphragm is approximately proportional to the diaphragm area.

§4. Conclusions

A 4 m-long toroidal focusing mirror was installed and successfully aligned on the IN15 spectrometer at the ILL. We have shown that SANS optical focusing is feasible, and that with a high quality mirror surface, with less than 3Å rms micro-roughness, contrast ratios as low as 5 x 10^{-5} may be achieved for $q \approx 10^{-3}$ Å^{-1}. We still have to perform a detailed analysis of the effect of the wavelength resolution and of the intensity gain that is achieved with the toroidal focusing mirror. We hope to couple the focusing option with the spin-echo technique in the near future.

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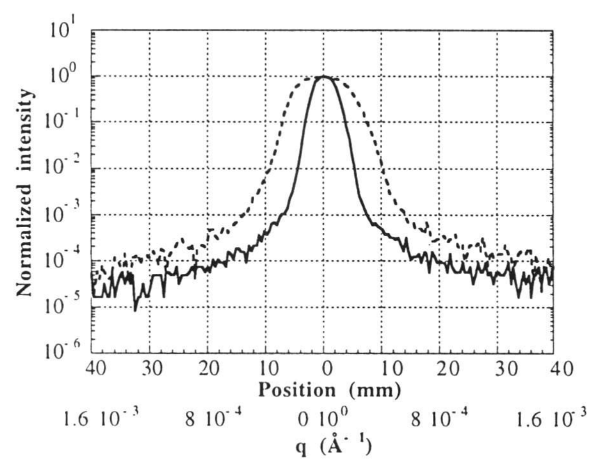

Fig. 6. Intensity profiles (horizontal direction) for a 10 mm-diameter (- -) and a 2 mm-diameter (—) source aperture positioned 11 mm below the focus; λ = 17.5 Å.