Neutron tomography using an elliptic focusing guide

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Abstract

A cone beam arrangement was applied to cold neutron imaging by using an elliptic focusing guide. The beam parameters were characterised in the focal point and at the sample position. Improved experimental conditions for tomographic applications were achieved by using the advantage of a point source geometry providing a larger beam and enabling geometric magnification. The experimental data were compared with Monte Carlo simulations. The performed experiments and simulations prove superior spectral and geometrical homogeneity of the cone-beam set-up realised, as compared to the classical pinhole geometry.

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**Introduction**

Neutron tomography (NT) has gained significant importance as a non-destructive method for the investigation of the composition of bulk materials in various fields of science and technology [1,2]. Developments concerning new experimental methods such as phase-contrast, energy-selective, dark-field and polarised neutron imaging have witnessed substantial progress in NT [3,4,5,6,7,8,9,10,11,12,13]. In addition, the utilisation of innovative detector systems enabled to overcome some of the limits of conventional neutron tomography concerning spatial and time resolution [14,15].

The current concept of neutron imaging is based on the simple pinhole geometry [16]. The best achievable spatial resolution is limited by the highest possible $L/D$ ratio, where $L$ is the distance between the first diaphragm with a diameter $D$ and the sample position [17]. In this case, the beam size at the sample position is defined by the available divergence and the distance $L$. Due to the use of long distances $L$ and short distances $l$ between the sample and the detector to achieve high spatial resolution, the beam is essentially parallel and perpendicular with respect to the projection images. If a neutron guide upstream the pinhole is used, the beam divergence is determined by the angle of total reflection of the neutrons from the walls of the neutron guide [16,17]. This angle depends on the neutron wavelength and causes a spectral heterogeneity of the beam downstream the neutron guide. Therefore, the available divergence and beam size at the sample position is also determined by the coating of the neutron guide.

Here we demonstrate how neutron radiography and tomography can benefit from a focusing neutron guide producing a well-defined cone-beam [18]. Due to Liouville's theorem, the phase space volume occupied by the neutron beam is invariant and hence the spatial compression of the beam into a focal point implies an increased beam divergence [19,20,21,22]. The geometry used is similar to the configuration applied in conventional micro-focus X-ray CT scanners where the X-rays emerge from a spot of a few micrometers diameter. The cone beam geometry allows for a variable magnification by altering the position of the sample with respect to the source and the detector.
Simulations

Two focusing neutron guides (convergent and elliptic) were simulated using the Monte Carlo simulation code ‘McStas’ [23]. For matters of comparison, a straight guide was also considered. In the simulation, cold neutrons were supplied by a curved neutron guide (cross section: 30 mm × 120 mm, length: 20 m, radius of curvature 3000 m) with a coating of $^{58}\text{Ni}$, which gives 1.2 times the critical angle $\theta_c$ of natural Ni (m=1.2). The total length of the beam-defining system (straight, convergent and elliptic guide) downstream the curved supplying guide was 3 m for the three models considered. A flight path of 5 m between the end of the guide and the detector plane represents the length of the real instrument, Fig. 1a.

The intensity distribution measured at the sample position (Fig. 1a) shows that the elliptic guide provides a largely homogeneously illuminated area of approximately 20 cm × 20 cm. The observed segments in the image are due to the multiple neutron reflections in the rectangular guide. The intensity gaps between the segments (seen as dark lines with approximately 15 % intensity decrease) can be corrected by an image normalisation used as common procedure in digital radiography. The convergent guide illuminates a similar area but with a less uniform radial intensity distribution, while the standard configuration based on a combination of a straight guide and a pinhole provides a beam that is just 1/9 the area of the beams produced by the focusing guides.

The simulated intensities at the sample position for a defined $L/D$ ratio are depicted in Fig. 1b. In order to simulate different $L/D$ ratios, pinholes with various diameters $D$ were placed at the exit of the guide system for the straight and convergent setups, respectively, and at the focal point of the elliptic guide. The distance between the exit of the guide and the detector plane was kept constant at $L = 5$ m.

The comparison shows that the neutron flux in the central part of the beam depends only on the $L/D$ ratio but not on the neutron guide configuration used (Fig. 1b). A study of the spectral uniformity shows that the spectrum for the elliptic set-up is essentially given by the spectrum as transmitted by the neutron guide and is almost independent of the distance from the beam axis, while the spectrum softens rapidly when a straight guide is used (Fig. 1c).
The simulations provide evidence of a significantly improved performance of the elliptic set-up because of the enlarged beam area with improved spectral and intensity homogeneity.

**Experiment**

A set-up using an elliptic guide was tested experimentally and was compared with the set-up using a straight guide. For this purpose, a focusing elliptic 500 mm long neutron guide with a rectangular cross sections of $10.6 \times 21.2$ mm$^2$ and $4 \times 8$ mm$^2$ at the guide entrance and exit, respectively, was used. The focal points were specified to be at a distance of $F_1=1580$ mm and $F_2=80$ mm from the ends of the guide. The walls had a supermirror coating $m=3$. The experiments were performed at the beam line CONRAD for neutron tomography at the Hahn-Meitner-Reactor of the HZB [24].

The beam was characterised at the focal point, 80 mm downstream of the focusing guide using a cold neutron spectrum (maximum at 3 Å). To allow for a comparison with the conventional geometry, gain factor images with and without the focusing guide were recorded.

The size of the focal point in the central area of the spot was found to be 0.36 mm in horizontal and 0.55 mm in vertical direction (Fig. 2). This small size of the focal point is a good precondition for the realisation of a point source geometry with a high $L/D$ value. The focused white neutron beam shows a maximal intensity gain of 80 in the focal point. With increasing distance from the focal point, a desired beam size can be selected and by placing an aperture with a diameter $D$ in the focal point, the $L/D$ ratio can be adjusted. This configuration was used for further imaging experiments.

**Applications**

The cone beam geometry enables large beam cross sections at relative short distances from the focal point. Use of the above described and characterised elliptic guide with the focal length $F_2=80$ mm allowed for enlargement by a factor of 3 the horizontal and vertical beam size at a given distance of 5 m from the end of the guide to the detector at CONRAD. The larger beam size enables tomographic investigations of large samples. Additionally, the small focal point provides a good $L/D$ ratio, which is important especially when the sample dimensions hinder positioning of the
sample close to the detector plane. We have investigated a particle filter for a diesel engine (15 cm in diameter) using the elliptic set-up. The distance between the focal point (80 mm from the guide end) and the detector plane was 4.2 m. 600 projections of the sample were recorded within a rotation range of 360° in equidistant angular steps. The filter was reconstructed using an algorithm for cone-beam geometry (Fig. 3a left). For comparison, a further measurement using the set-up with the straight guide only and a pinhole with D = 2 cm was performed. The sample was moved through the beam in order to illuminate it completely. In this case the tomographic data set was reconstructed using a filtered backprojection algorithm assuming parallel beam geometry (Fig. 3a right). The number of projections and the angular increment were the same as for the elliptic set-up. The comparison shows that the quality of the reconstruction is rather markedly improved by the cone-beam set-up.

The possibility for magnification provided by the cone-beam set-up was studied by visualizing a periodical grid (Gd mask deposited on Si wafer) with a periodicity of 1 mm. The measurement at 1.2 m distance from the detector shows a magnification of 20 % (right hand side of Fig. 3b).

**Conclusion**

We have shown that the installation of an elliptic guide allows for the realization of a beam-line for tomography with neutrons in cone-beam geometry. The advantages are a larger beam cross section at the sample position, a better spatial and spectral homogeneity of the beam, as well as a shorter beam line. In addition, by decreasing the pinhole at the focal position of the elliptic guide, the L/D ratio can be increased thus allowing high resolution. In addition, due to the magnification of the sample by the cone-beam, highly efficient detectors providing only limited spatial resolution can be used. It is forseen that by increasing the critical angles of the supermirror coatings to above m = 6 and by using modified guide geometries, the beam size in the focal position can be decreased to below 20 μm, thus providing very high spatial resolution.
References

1 J. Banhart, Advanced Tomographic Methods In Materials Research And Engineering, Oxford University Press, New York (2008),


Figure captions

Fig. 1 Monte Carlo simulations of different neutron guide configurations. (a) Intensity distribution 5 m behind the guide in a detector plane of 30 cm × 30 cm for a straight guide with a pinhole of 1 cm; convergent guide (coating m=3.0, length: 3 m, input: 3 cm × 3 cm, output: 1 cm × 1 cm); elliptical guide (coating m=3.0, length: 3 m, input section: 3 cm × 3 cm, output section: 0.89 cm × 0.89 cm, F1=7.5 m, F2=0.2 m). (b) Neutron flux as integrated over the central area of the detector (1 cm × 1 cm) as a function of $L/D$. (c) Spectra calculated at different distances from the beam axis integrated over an area of 1 cm × 1 cm.

Fig. 2 Characterization of the beam at the focal point of the elliptic guide. (a) intensity distribution. (b) horizontal (○) and vertical (Δ) intensity profiles were fitted by Gaussian functions.

Fig. 3 Imaging experiments. (a) tomographic slice of the central part of a particle filter measured in the cone-beam geometry (left) and parallel beam scanning geometry (right). (b) Magnification of a grid with 1 mm periodicity measured at different distances from the detector (0.5 cm, 60 cm and 120 cm) in the cone-beam arrangement.