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A compact experimental set up for neutron tomography

Ein kompakter Experimentaufbau für Neutronentomographie (englischsprachig)

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Abstract
Tomography with monochromatic neutrons can be performed with rather short flight paths having nonetheless a good medium spatial resolution. It is demonstrated that the appropriate use of a crystal monochromator having a certain mosaic spread improves remarkably the performance of the set up. This is of fundamental importance in the case of energy selective and Bragg edge neutron tomography, phase contrast tomography and tomography with polarized neutrons that all use narrow wave length bands.

keywords: neutron tomography, monochromatic neutrons, spatial resolution, energy selective tomography,

1. Introduction

In the last years neutron tomography became one of the fastest emerging topics in applied neutron physics and it has an increasing number of application in material sciences [1] – [4]. From simple geometrical considerations, the so-called L/D ratio (L = distance source –object, D = diameter of the source) is used to characterize the spatial resolution of an instrument [5]. Conventional neutron tomography instruments consist of a source ("pin hole", diameter D), a collimation path L, the object to be investigated and a detector unit (converter screen CCD camera). Based on this layout and on more sophisticated set ups a number of improvements and new imaging signals have enlarged the possibilities of neutron CT [6] – [8]. Together with this growth the use of monochromatic neutron radiation became more and more a necessity. To select a certain (narrow) wave length the use of a double crystal monochromator system for neutron radiography and tomography has big advantages as published in [10], another method is described in [11], [12], however, monochromatic neutrons are needed especially for energy selective and Bragg edge radiography and tomography and for imaging with polarized neutrons [13]-[15]. At steady state neutron sources a crystal monochromator is superior to chopper devices if a small $\Delta\lambda/\lambda$ is needed. The size D being the source of radiography and tomography instruments determines – together with L the spatial resolution. The usual length L of such instruments is of the order of 8m - 18m (and more), D is of the order of cm so that a L/D ~ 500 – 1200 corresponding to a beam collimation of app 0.12° - 0.05° can be reached. The advantage of large L/D is evident: The spatial resolution depends in the same manner on L/D as on the distance object - detector, which can strongly vary in the case of large (> 200mm) objects. A monochromator crystal acts different to an aperture in a conventional tomography set up and so the conditions for imaging are different. So the role of a mosaic crystal as source in a tomography set up has to be considered more precise in conjunction with spatial resolution. Detailed calculations show that the mosaic structure plays a more complicated role than suggested. So some unique features such as a special L – dependency on spatial resolution will make such set ups very feasible for a number of investigations.

2. Experiments

To prove experimentally this special behavior a short set up was installed at the neutron guide NL3b at the BER II reactor of the Helmholtz Centre for Material and Energy (former Hahn Meitner Institute) Berlin. The neutron beam had to be shared with another instrument (V12b), a high resolution double crystal diffractometer that used only 1% of the beam. So the neutron beam could independently be used from a V12b due to an own shutter (Fig.1). A graphite monochromator (C-monochromator , (002)- reflection) in the neutron guide reflected app. $5*10^5$ $cm^{-2}s^{-1}$ neutrons with a mean wave length λ = 0.524(5)nm to the optical bench (Fig.1).
The total length of the optical bench was app 2m, L < 2m. To calculate the expected L/D for this set up one had to consider the beam divergence φ_{guide} coming from the neutron guide incident on the C- crystal which depends on the coating (m=1,2,..), on the wave length as ~ 0.12 x λ[Å] and on the mosaic spread φ_{mosaic} of the Bragg reflecting C- crystal. In our case φ_{guide} was 0.63° (FWHM) and φ_{mosaic} was 0.4° (FWHM) , the reflected beam divergence was calculated by the convolution integral $\varphi(\theta)$:

$$\varphi(\theta) = \int \varphi_{guide}(\alpha) \cdot \varphi_{mosaic}(\theta - \alpha) \cdot d\alpha \qquad (1)$$

We approximated φ_{guide} and φ_{mosaic} by (normalized) by Gaussian functions having the $FWHM_{guide}$ = 0.63° and $FWHM_{mosaic}$ = 0.4° , the resultant FWHM of $\varphi(\theta)$ became 0.76°, corresponding to a L/D ~ 75 . The geometrical $(L/D)_{geom.}$ was given by the maximum size of the reflected neutron beam (30 x 40) mm^2 (width x height) coming from the C-monochromator and L ~ 2m, so that a geometrical $(L/D)_{vertical}$ ~ 50 and $(L/D)_{horizontcal}$ ~ 70 was estimated. That means that a minimum blurring for l = 20mm (due to L/D = l/d ~ 70) of app. d=300µm corresponding to ~ 1.7 lp/mm was expected.

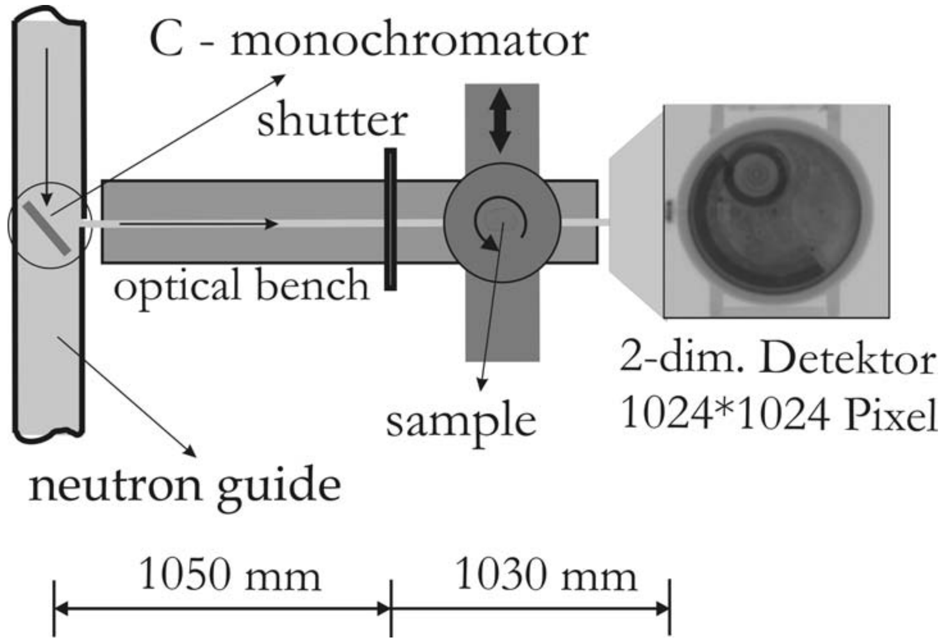

Fig.1 The short set up for neutron tomography at the BER II reactor at the Helmholtz centre Berlin

At first the spatial resolution was measured with a so-called "Siemens star" for different scintillator thicknesses and for different distances l of the Siemens star to the detector (= scintillator screen). Neutrons were detected and converted with different thick ^{6}Li scintillators (thicknesses of 400µm and 100µm), the detecting optics was an Andor camera (1k x1k pixel) equipped with a Nikkon 105 mm f/2.8 optical lens, Fig.2 shows the result with the 100µm thick scintillator screen.

One realizes that in both directions the spatial resolution was surprisingly much better than expected from the geometrical $(L/D)_{geom.}$. The image of the Siemens star showed mean spatial resolution of ~ 180 (40)µm with the 100µm thick scintillator and 240(45)µm with the 400µm thick Li-scintillator. In the Siemens star (Fig.2) the 180µm circle resolution is plotted.

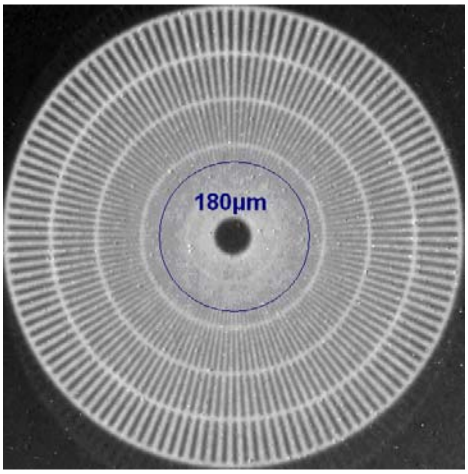

Fig.2 Measured test pattern of the "Siemens Star" with the lens Nikkor 105 mm and 100µm Li - scintillator thickness.

To verify this spatial resolution with a different method the L/D was determined by measuring the edge spread function, using a straight Gd-edge of 500 µm thickness and deriving from the image (radiogram) the resulting modulation transfer function (MTF) and so the corresponding spatial resolution (line pairs/mm) at the 10% MTF. This was done for different distances l of the Gd-edge to the Li-scintillator screen, the results are shown in Fig.3. For both scintillator thicknesses the spatial resolution became of the same order if l > 50mm. This result is important, because the detection efficiency of the 400µm thick scintillator is ~30% larger than of the 100µm Li-screen. For tomographies of objects with a diameter larger than 50mm the geometrical blur is the same for both scintillator thicknesses, so the use the thicker screen may save app. 30% on beam time. For sample-to- screen distances l < 20mm one measures – for the given geometry (L ~ 2060mm, L + l = constant) - a spatial resolution > 2lp/mm which is much better than expected from $(L/D)_{geom.}$ (Fig.3).

This behavior only can be understood if the ratio L/D did not determined the spatial resolution as is assumed in the conventional pin hole technique but must be taken as a divergence which was constant for all L and l in this set up. This divergence was given by φ_{mosaic} and φ (see above) that were both independent of L. Therefore the size of the area of the C-crystal could not be D, i.e. the reflecting monchromator area, if one measured a spatial resolution of ~ 2 – 3 lp/mm corresponding to a spatial resolution d = 200 µm - 170 µm which agreed perfectly with the Siemens star measurement. D must be replaced by a D_{mosaic} which was about 2 -3 times smaller than (30 x 40)mm^2 reflecting C - crystal area . Note, that D_{mosaic} does not determine the mean size of a mosaic block of the C-crystal, due to the beam geometry (distance of the sample from the C crystal and to the detector) of this set up. Based on these results one can show, that for certain L one has mixture between this mosaic – based L/D and geometrical L/D. A major result is that apparently L can remarkably be reduced and due to the $1/r^2$ – law one gains intensity without loss of spatial resolution.

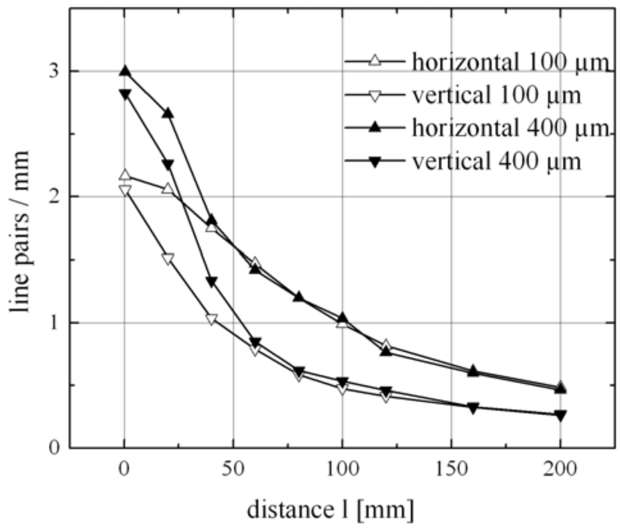

Fig.3 Spatial resolution (Lp/mm) as a function of l = distance Gd edge – screen for different Li-scintillator thicknesses. (2 Lp/mm ~ 250µm spatial resolution).

This improvement of spatial resolution of ~ 3 - 2.5 lp/mm should be seen in reconstructed images of objects that had details smaller than app. 300µm corresponding to 1.7 lp/mm. So neutron tomographies of samples were performed having tiny details that would not be resolved with a spatial resolution of < 1.5 lp/mm. Fig.4 shows the reconstruction of an old watch measured with this set up. The tomography was performed with 301 projections each with an exposure time of 17 min. That is equivalent for a step size of 0.6° for an angular range of 180°. Additionally, ten dark field and ten flat field images with identical exposure time were registered. The dimensions of the object was $(35 \times 40 \times 12)mm^3$. The reconstruction of the slices was carried out with the programme Octopus and the 3D reconstruction with the software VG Studio Max. Due to the good spatial resolution of >2 lp/mm for l ~ 20mm details smaller than 300µm could be visualized.

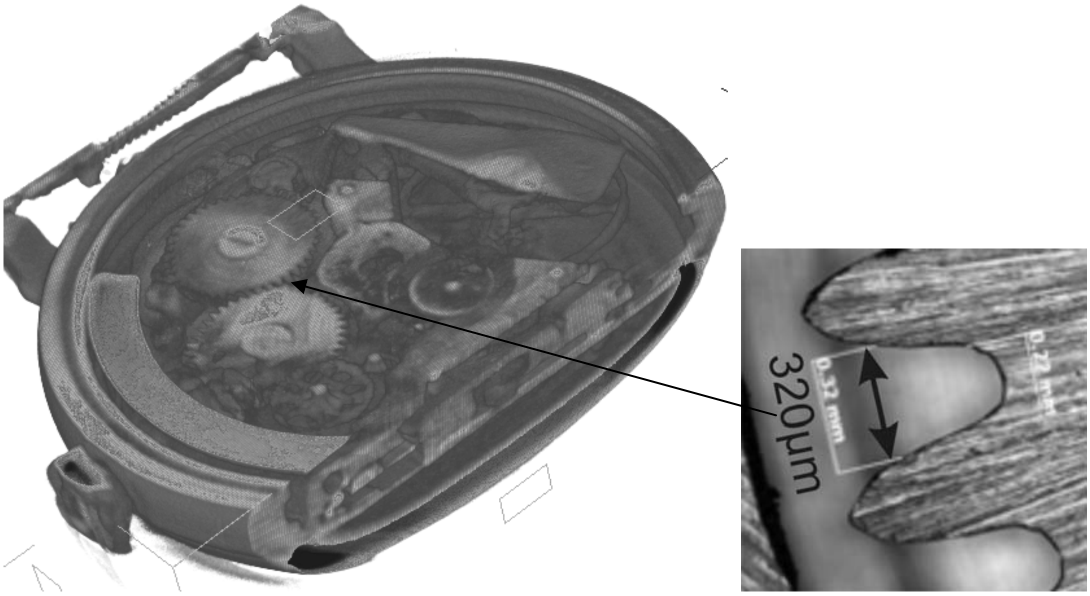

Fig.4 Left: 3D reconstruction of a watch, displaying inner details that would not appear with L/D ~ 70, right: photograph of the original gearwheel with length scale.

3. Conclusions

This paper demonstrates that the proper use of mosaic crystals as sources for neutron tomography instruments reduces their length and exposure times and improves their spatial resolution. Detailed investigations with a 2m long CT - system yielded an app. 2 – 3 times better L/D than expected from the geometrical $(L/D)_{geom.}$. This is explained by the special functionality of the C-monochromator which consist of small mosaic blocks that serve as small individual sources. Due to the conversion of the geometrical L/D – ratio into a L-independent beam divergence the distance of the mosaic crystal to the sample can be reduced so that one yields an intensity gain without loss of spatial resolution. Within another instrument at the BER II reactor (PONTO) using the same C monochromator (mosaic spread and size) it could be demonstrated that the neutron flux increased by a factor three if L is decreased from 300cm down to 150cm. This remarkable intensity gain is lost if conventional pin hole technique is applied to the instrument, i.e. placing the sample at largest available L hoping to improve the spatial resolution.

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