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Benchmark experiments on "entry-grooves" in moderator / reflector material

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Abstract. Some influence of the surface structure on the coupling of neutrons with moderating material is well established, e.g. reentrant holes or –grooves are employed at different facilities to enhance the flux of neutrons emanating from moderators. For increasing performance, hitherto emphasis and effort has mainly been focused on amplifying useful neutron flux by optimizing the output-side of moderators. Recent preliminary numerical studies have indicated that similar structuring as established for boosting the flux at the output-side of a moderator might also be beneficial at the input-side by first letting the neutrons better enter the moderator volume. Experiments will be reported on a series of measurements illuminating several cubes of polyethylene with surface structuring in the thermal neutron beam of the NEUTRA facility at PSI, SINQ. With the new dual-detector set-up at NEUTRA, both the transmission through, as well as the reflection from the cube can be measured for different alignments and orientations. Demonstrating good agreement between calculations and measurements while verifying the above predictions for this mock-up geometry can be taken as a starting point for investigating more representative conditions. Whether significant improvements over simple-shaped moderator geometries can be achieved in realistic settings needs to be scrutinized by taking all relevant boundary conditions into consideration.

1. Introduction

Neutrons in spallation sources are set free with energies much higher than suitable for using them as probes in diverse instruments. Their energy has to be reduced, i.e. they are thermalized or cooled to even lower energies by means of moderators. There is a long tradition in optimizing these moderators, because it is of interest for any instrument to obtain a maximum signal-to-noise ratio for any given input power. Thus, it is proven and well established at many sources that certain geometrical structures enhance the neutron output from moderators. Still, the efficiencies of the diverse stages between the spallation reaction and the collection of appropriately moderated neutrons leaving the moderators are disappointingly low.

The simple idea proposed recently was that anything, which enhances the coupling of a neutron field on the output side of a moderator, might also be helpful when employed on its input-side.

Very preliminary simulations indicated some effects of structures like grooves or holes; they can improve the filling of the moderator material to start with and thus subsequently boost the neutron flux out of that material. Details and references are given in reference [1]. This paper further investigates these ideas. Recently, benchmark experiments on toy-geometries have been begun, work is still ongoing. First results of measurements at PSI´s NEUTRA radiography station at the spallation neutron source SINQ have been obtained and are reported here.

2. Experimental set-up

2.1. *The NEUTRA facility*

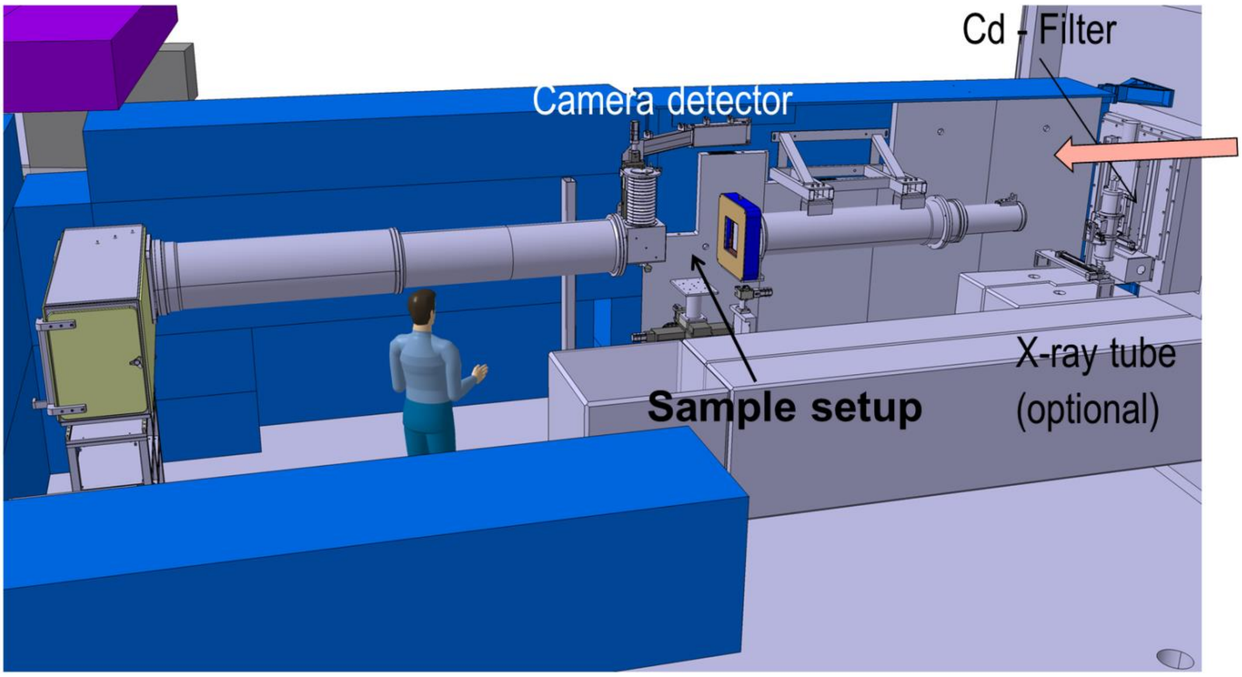


Figure 1. The NEUTRA radiography station at PSI´s SINQ spallation neutron source, http://www.psi.ch/sinq/neutra.

The radiography station NEUTRA (see figure 1) usually works with thermal neutrons (see figure 4). It features a high degree of flexibility concerning possible experimental set-ups [2]. For the measurements on the mock-up moderator specimens the middle position has been used, marked "Sample setup" in figure 1. There, an almost parallel beam of thermal neutrons was available, and detectors for thermal neutrons based on ^{6}Li doped ZnS have been used. Both, image acquisition with CCD cameras and imaging plates have been employed. Exposure times were 5-6 seconds and 60 seconds for experiments with thermal and "fast" input, respectively.

2.2. *Specimens and configurations*

Standard neutron radiographs with the detector behind the samples as well as images perpendicular to the neutron beam, i.e., sideways at 90^o, with the detector area aligned parallel to the incoming neutron beam, have been taken for many different configurations.

Specimens consisted of diversely structured Polyethylene (POLY) cubes with a side-length of 2 cm and distinguished by diverse structures (see figure 2). These (surface) features included six evenly distributed grooves extending over a third of the extension of a cube, 20 drillings of the same depth on a side and a through-hole of 5 mm diameter. For comparison, full cubes were also included in the sample 'towers'. In order to be able to separate them in the images, the different POLY cubes were separated by layers of POLY containing the strong neutron absorber material boron carbide.

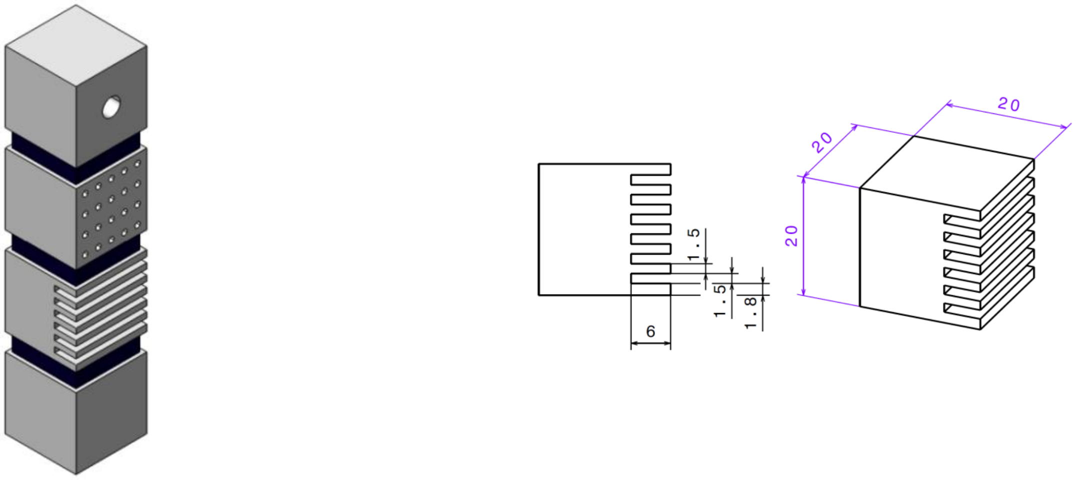


Figure 2. Example of specimen with differently structured POLY cubes of 20 mm side length, separated by neutron absorbing material.

Various specimens were rather uniformly illuminated by the incoming neutron beam as indicated by the arrow on the right hand side in figure 1. Many radiographs have been taken with two towers present at the same time. Side-ways measurements were taken with only one specimen present at a time (see figure 3).

Figure 3. Examples for configurations with two (left) and one (right) specimen. In standard radiography set-ups (left) the detector (scintillator and CCD camera) is behind the samples and the neutrons illuminate the two columns simultaneously. With the detector sideways (right) only one column could be investigated at a time. Some of the measurements with one column included detectors both behind and on the side. The single column (right) is mirrored in the detector behind it and in an imaging plate at the side. From these optical reflections by plane surfaces an assessment concerning the alignment (e.g. tilt) of the columns can be drawn.

2.3. Spectra

Both, thermal and epi-thermal neutrons have been employed. The latter have been obtained by closing a light instrumental shutter containing layers of cadmium and boron carbide to filter out the dominant thermal fraction of the neutron beam. Thus, some “fast” contribution remained. In an attempt to coarsely characterize the achievable fast flux, numerical simulations with MCNPX were performed (see figure 4).

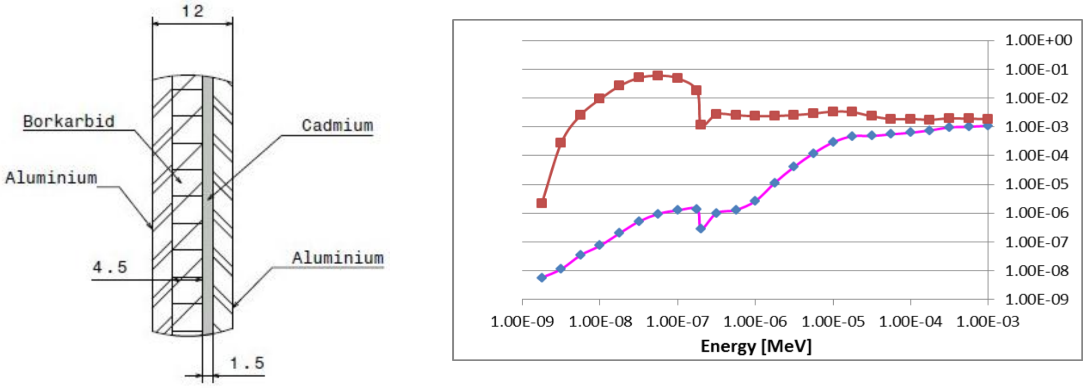


Figure 4. A “fast” neutron beam has been obtained by letting the standard thermal beam arriving from the left hand side pass through a light shutter (left). Extending the measured thermal part of the spectrum by an 1/E contribution, the effect of the shutter has been simulated (right). The thermal fraction in the remaining flux was found to be suppressed by several orders of magnitude.

Whereas a high intensity neutron-flux of about 1.2 10^7 n/cm^2/sec was available for experiments with the original thermal neutron beam, the signal was low for the set-up with “fast” neutrons. With standard thermal input, signal-to-noise was more than satisfactory for exposure times of 5 or 6 seconds. On the other hand, with the “fast” input, 60 seconds of exposure were necessary, and even then contributions of several sources of noise marred the obtained pictures. Dark current in the CCD detectors was suppressed by cooling. Additionally, it was attempted to calibrate the measurements and take care of fixed pattern noise stemming from the granulation of the used scintillator plates during image analysis and evaluation.

3. Results

During several experimental campaigns a large number of measurements have been performed, both, with thermal and with “fast” neutrons′ input, in diverse set-ups. Initial radiographs were recorded with two specimens present at the same time. The underlying assumption, i.e., that they would not “disturb” each other, was proven wrong immediately.

3.1. Measurements in standard radiography mode

Comparing images obtained in standard radiography alignment for thermal versus “fast” input neutrons, general similarities and some differences can be noted. All results reported here have been obtained in the “NEAR” condition, i.e., with a distance between columns and detectors of about 5 mm. More results recorded for larger distances up to 6 cm (“FAR”) have been taken but not yet analyzed.

As a general remark, the here presented images were enhanced for best visibility, numerical values and profiles are as measured and normalized making use of the full depth (16 bit) resolution of the measured data. All plots are with arbitrary, relative units.

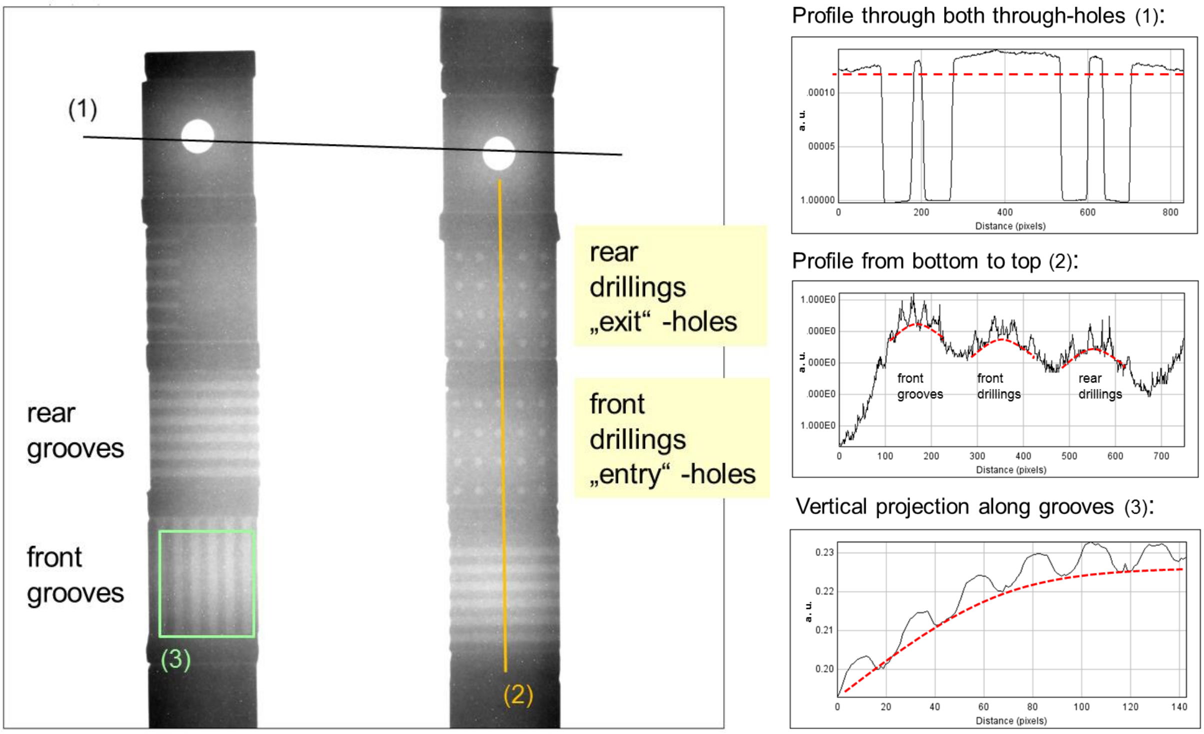


Figure 5. Radiography with thermal neutron beam (left); profiles along the specified lines and over an area, respectively, are given (right). Red dotted lines do not indicate any modelling, they are just meant to guide the eye. Most prominent, large amounts of scattering are visible: in the center between the two columns higher levels are detected than towards the rims at the sides (profiles 1 and 3). The modulation in the image thus is not just produced by "simple" attenuation. Comparing full cubes with grooved ones, it is found that the reduction of scattering material due to the grooves by 15 % results in an observed enhancement of the throughput by more than 50 %. Features at the front yield rather similar effects for the through-going neutrons as the same features at the rear side. For each individual cube, more neutrons come from the center than from the periphery (profile 2).

It seems important to note that a strong background is observed with one or two POLY-towers in the beam. This diffuse background leads to a global "curvature" of the measured overall neutron distribution and is especially visible in the case of two specimens. This unstructured background adds to all detected more local features; the "empty" field between two specimens actually shows the highest measured neutron intensity. Here, it is only hypothesised that the diffuse component stems from the overlay of neutrons scattered from the individual cubes with the distribution of the re-emitted neutrons from the sides of the cubes following a Lambert law. This can nicely explain the local curvature seen for single cubes with a prominent peaking of the scattered intensity in the center of the surface facing the detector.

From this it becomes clear that the obtained images cannot simply be interpreted as attenuation-based radiographs. There is strong scattering and a Lambert-Beer law is not applicable in this conditions.

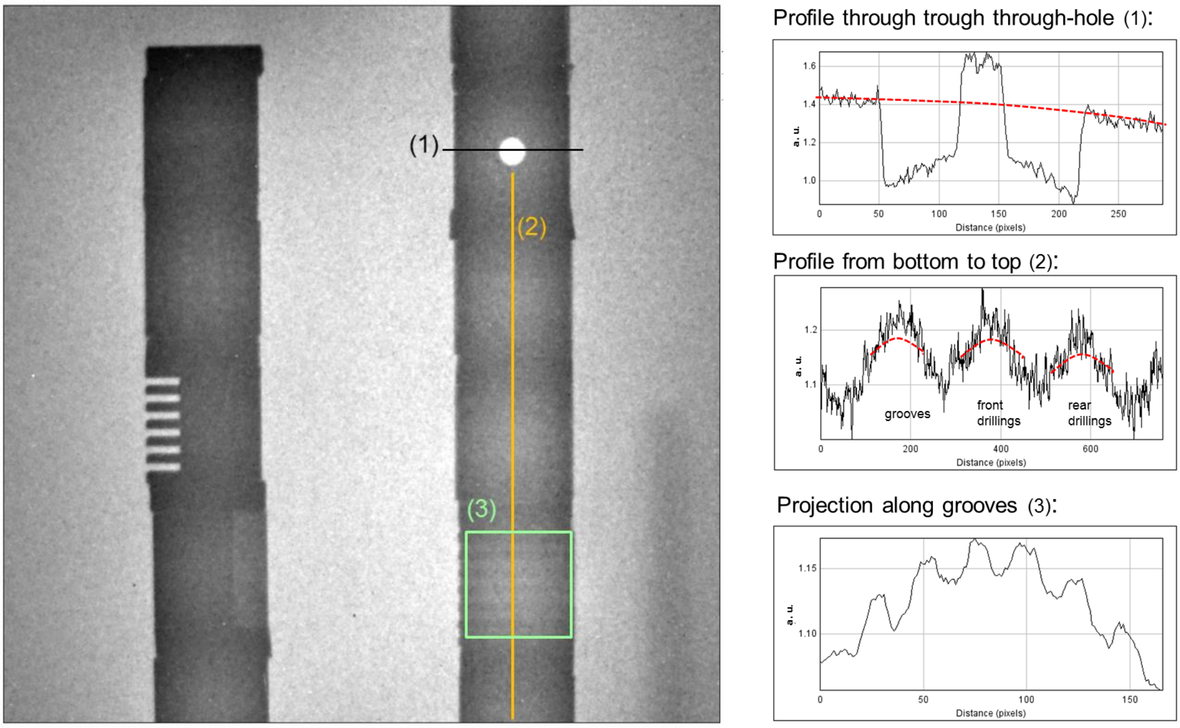


Figure 6. Radiography with "fast" neutron beam (left); profiles along the specified lines and over an area, respectively, are given (right). Compared to the configuration of figure 5, the left hand column had been turned by 90^{o}. Although the signal-to-noise is worse, the findings are similar to the ones obtained with the thermal neutron beam (figure 5). Scattering is clearly observed; the image is brighter between the specimens than along the sides (the shadow on the far right has been produced by a thin strip of gadolinium for tests). A peculiar observation is resulting from the through-hole close to the top of the right column (profile 1): this hole obviously works as an "entry-hole" and also as an "exit-hole" with the total effect of boosting the thermal flux behind it to a higher value than in the empty field in the center of the image.

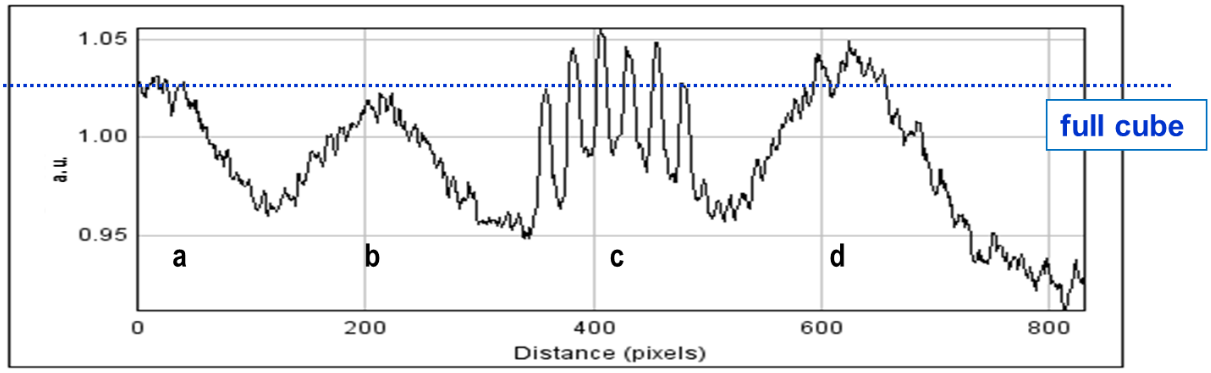


Figure 7. Radiography with "fast" neutrons; further analysis of the image presented in figure 6. Analysis of a profile over an area extending along the center of the left hand column hints at effects attributable to the structuring; from left to right (bottom to top in figure 6): full cube's reference response (a) indicated also by the dotted line; vertical grooves facing to the other column and "depleted" thermal flux passing through (b); horizontal grooves facing to the side and "depleted" thermal flux passing through (c); drillings facing the "fast" incoming neutron beam (i.e., "entry holes") leading to an enhancement of thermalized neutrons leaving from the rear side of that cube (d).

3.2. Sideways measurements

In an incremental stepwise approach, given first hints concerning the effectiveness of the implemented structures obtained in standard radiography alignment, more measurements have been performed looking especially for neutrons scattered 90° to the side with respect to the incoming neutron beam.

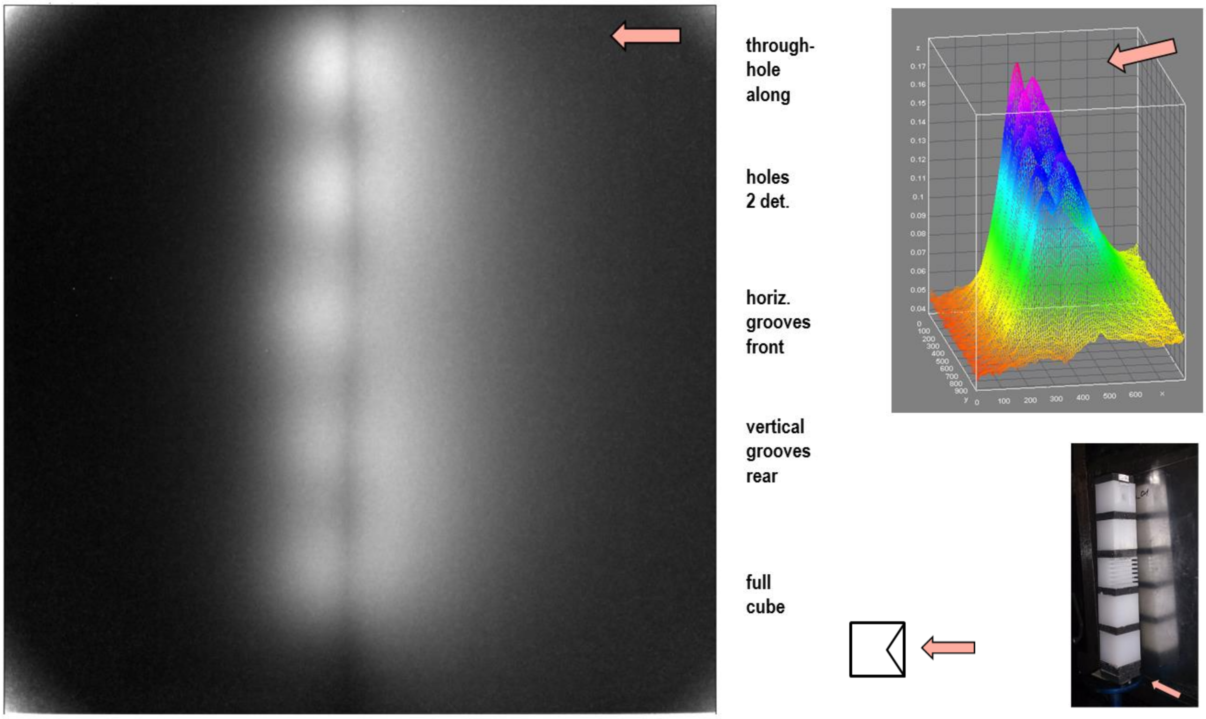


Figure 8. Sideways image for thermal neutrons' input (left); 3-D visualisation and set-up (right). The red arrows indicate the direction of the incident neutron beam. Some inadvertent "leaning" of the sample-column is documented in the photograph. The bright corners of the image are an artefact caused by the normalization procedure. The dominant fraction of the neutrons impinging on the sample is "diffusely scattered back" (especially visible in the 3-D plot). A well-distinct line of low intensity is observed between backscattered flux and neutrons emanating at 90° from the individual cubes. More sideways' intensity is measured at the position of the cube with input-grooves (middle) than for the full cube (bottom).

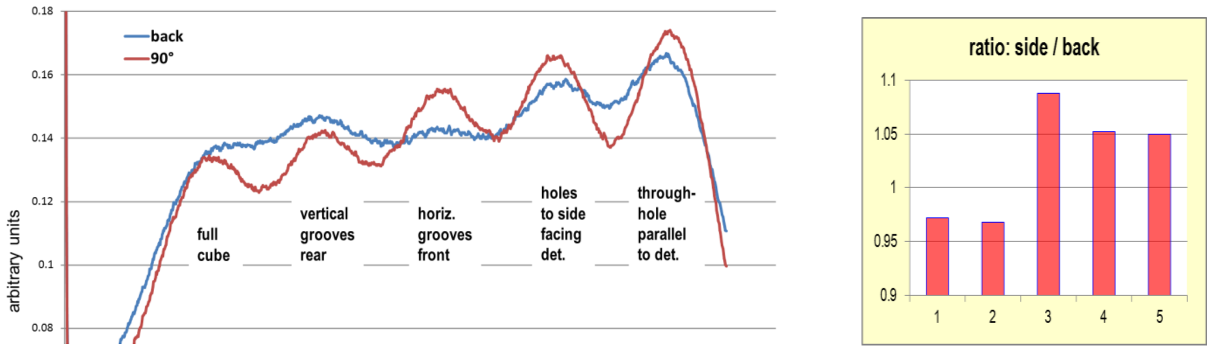


Figure 9. Sideways scattering for thermal neutrons' input; further analysis of the image in figure 8. Profiles along the column show significant differences between "reflected" neutrons and flux leaving the cubes at 90° sideways; the structuring of the cubes does have an impact (left). In order to compensate for the "leaning" of the

sample, ratios between "reflected" and "scattered" fractions are plotted for the individual cubes (right). Most noticeable is that the maximum effect is found for grooves on the front facing towards the incoming beam (middle position "3" in this orientation of the specimen). Grooves on the opposite rear side reduce the fraction scattered at 90^{o} to the side (2), whereas drillings on the side facing the detector (4) and a through-hole running along the incoming beam (5) augment it. Scattering from the full cubes (1) here looks very similar to the neighbouring sample with rear grooves (2).

For direct comparison, more results obtained with the same specimen as in figures 8 and 9 are reported next; figures 10 and 11 show images obtained in almost identical conditions, but with the specimen turned by 180^{o} and with better alignment of the tower, i.e. straight and not "leaning".

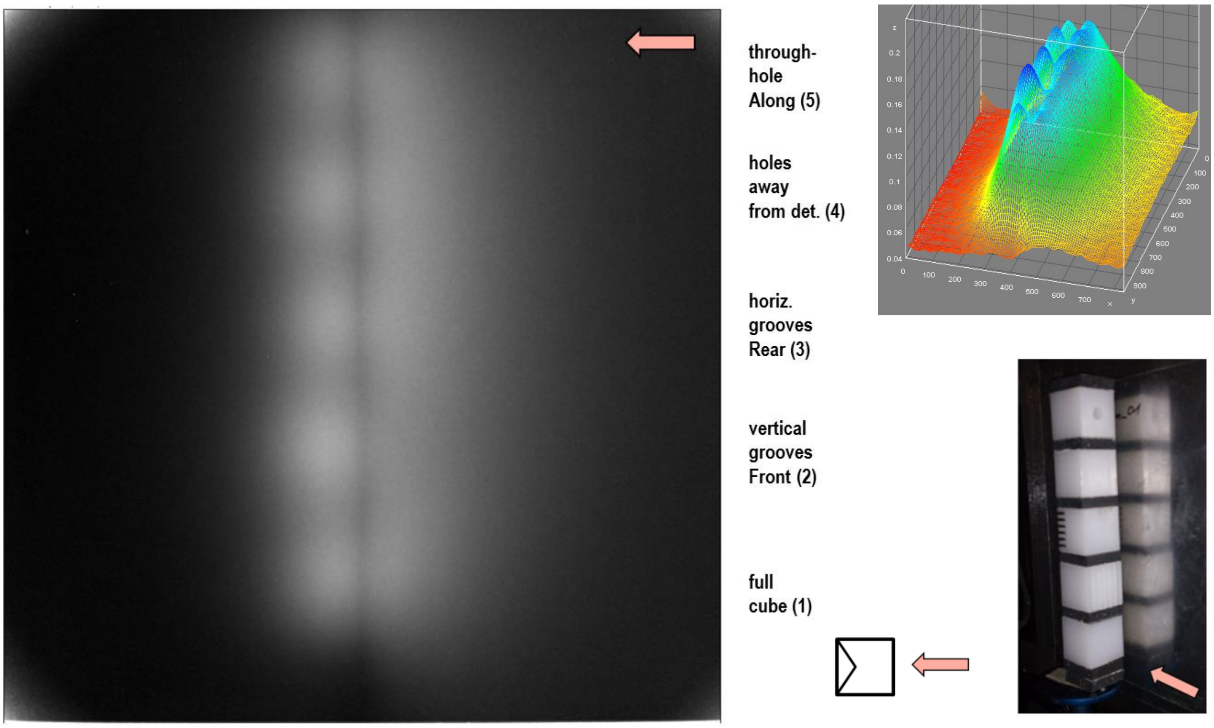


Figure 10. Sideways image for thermal neutrons' input (left); 3-D visualisation and set-up (right). The principal findings are the same as in figure 8 above with the same sample turned 180^{o}, i.e., front and rear sides were exchanged and here, the drillings pointed away from the detector; straight alignment of the column with respect to the detector plane. The most important difference is that by turning the column the positions of cubes with grooves facing the incoming beam or the opposite rear side have been swapped and the ratios of the scattered fractions changed accordingly as seen in figure 11. Scattering to the side at 90^{o} from the cube featuring entry grooves (2) is stronger than from the full cube below (1).

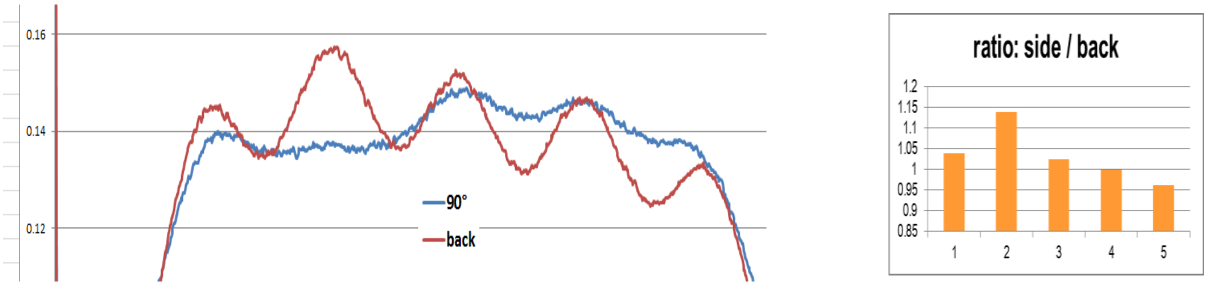
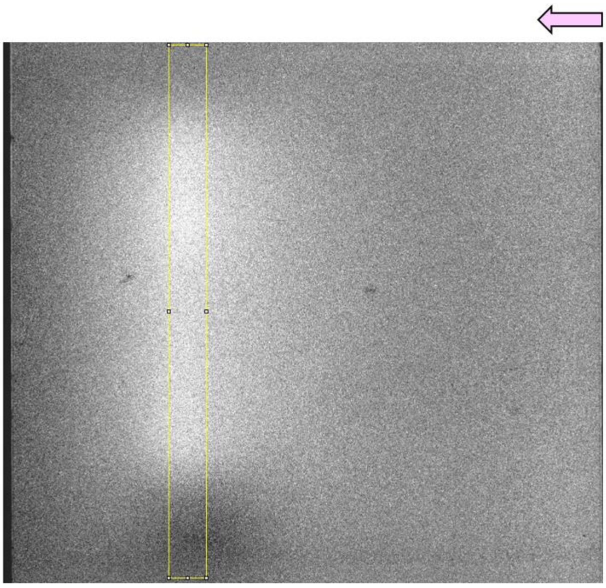
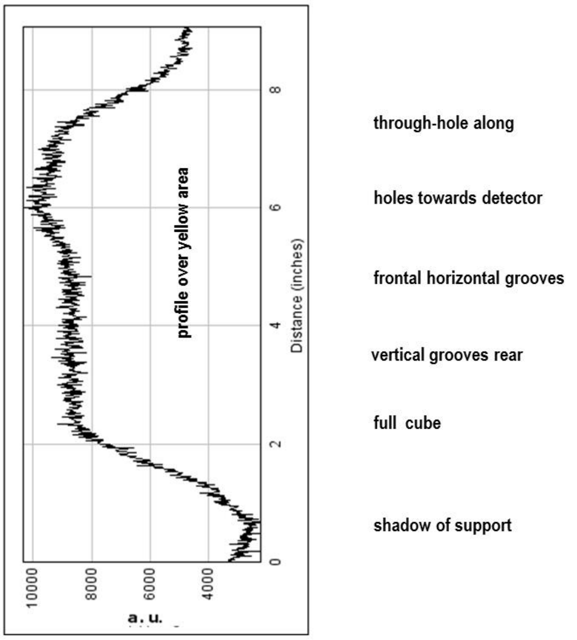


Figure 11. Sideways scattering for thermal neutrons' input; further analysis of the image in figure 10. Most neutrons are scattered 90^{o} to the side from the cube now pointing with grooves towards the incoming neutron beam, i.e., with entry-holes, and the "directly reflected flux" there is reduced correspondingly (2).

With strongly reduced flux to start with and resulting difficulties with respect to the achievable signal-to-noise ratio, measurements with a “fast” neutrons’ input proved more difficult than with thermal input. Nevertheless, sideways images could be taken with imaging plates and also with the CCD camera set-up pivoted 90° to the side. For the configurations with identical input and sample-conditions but different detectors, the obtained results were qualitatively identical. For their “nicer” appearance, here, two experiments employing an imaging plate are presented in figures 12 and 13.

The striking difference between images obtained with thermal and “fast” input, respectively, is the lack of a detected fraction, which is “directly reflected back” from the entry surface of the cubes. Given the almost exclusive sensitivity of the detectors for thermal neutrons, this matches perfectly with expectations, as only multiple scattered and thus moderated neutrons give a signal.





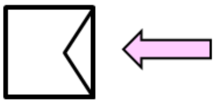
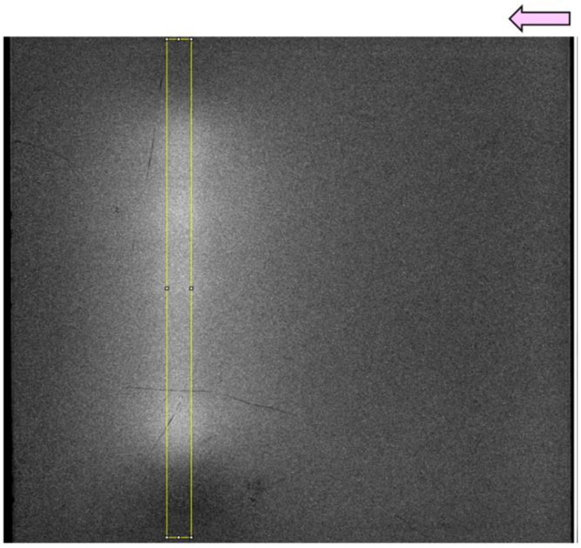
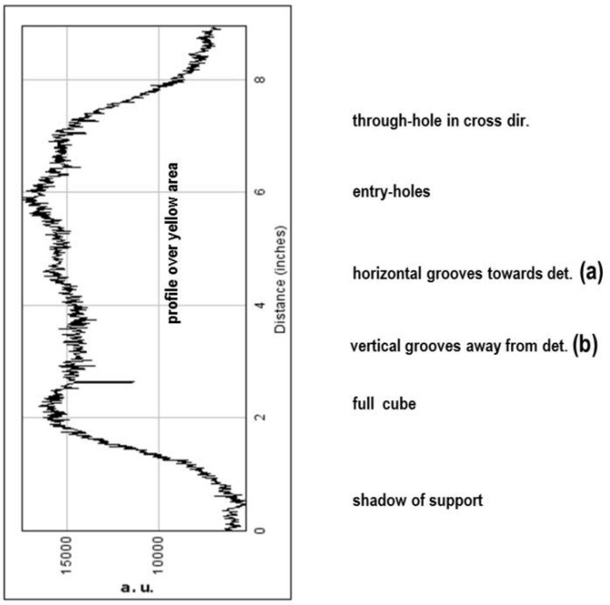
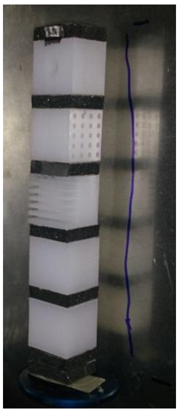


Figure 12. Thermalized neutrons deflected at 90° to the side for “fast” neutrons′ input (top left); intensity distribution in marked area (top right); alignment of the specimen in front of the sideways detector, i.e., image plate, (left). The enhanced signal for the cube pointing exit-drillings towards the detector confirms the well-known effectiveness of structures for enhancing the output flux out of a moderator. Enhancement is also seen with the through-hole in nice correspondence to the observation that it proved effective as an entry-hole (and exit-hole) for “fast” input (figure 6).

Rotating the specimen of figure 12 by 90° in clockwise direction turned the exit-drillings into entry-drillings; results are shown in figure 13. Noticeably, the peak in the detected flux 90° to the side stayed at the same position on the detector. Some more effects of the diversely structured cubes are discussed below in the caption of figure 13.







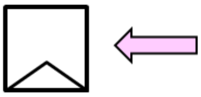


Figure 13. Thermalized neutrons deflected 90^o to the side for "fast" neutrons´ input (top left); intensity distribution in marked area (top right); alignment of the specimen in front of the sideways detector, i.e., image plate, (left). The same specimen as in figure 12, just rotated by 90^o. Entry-holes enhance the flux to the side. Comparing entry-grooves (a) to exit-grooves (b), the former boost the scattered / moderated fraction to the side whereas the latter reduces it, i.e. grooves are directing the emanating neutrons according to expectations, which means "draining" away from the detector when facing in the opposite direction. In this setting, the through-hole shows a small effect as exit-hole.

3.3. Preliminary Simulations

In parallel to the measurements, simulations were carried out with MCNPX in an attempt to reproduce the experimental findings. To start with, a full cube and one with grooves facing the incident neutron flux has been investigated. Both, radiography and sideways detectors have been simulated, and the responses to thermal as well as "fast" neutron beams were calculated.

Just the same as with the experiments, work is still in progress, and the results of the simulations as available right now have to be considered preliminary. Nevertheless, similarities and differences have already been found between the simulations and measurements and are reported in figures 14 and 15 below.

Results so far are only available for local features; in particular, no global effects like the measured extended diffuse background in the "empty" field have been investigated.

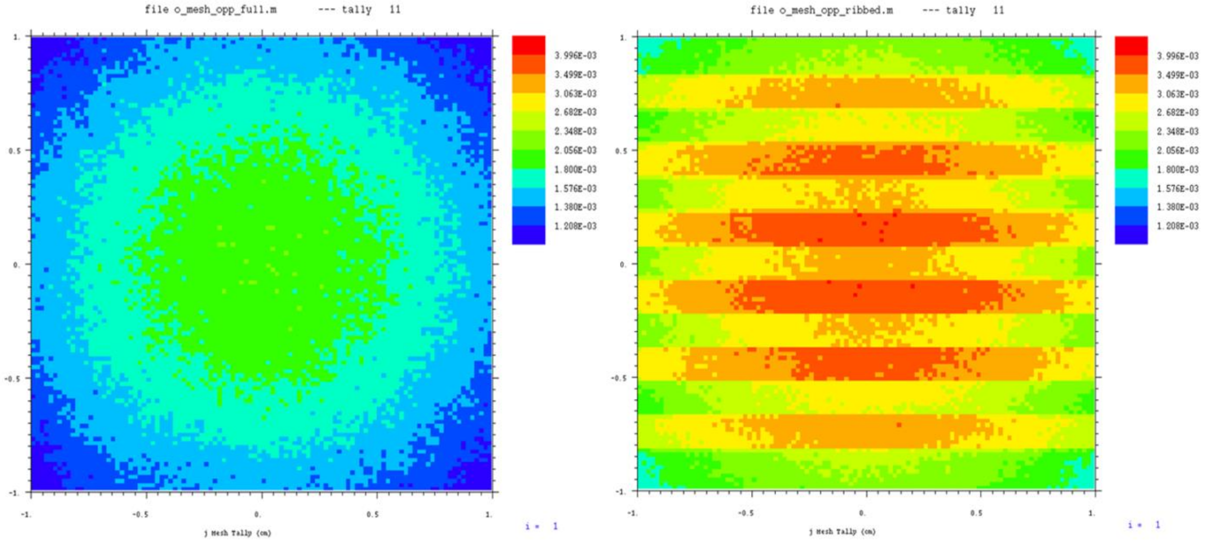


Figure 14. Radiography with thermal neutron beam, simulation results for a full cube (left) and for a cube whose grooves are facing the incoming beam, i.e. entry-grooves (right). The plots are on the same color-coded scale. An enhancement of the output flux is clearly visible for a cube with entry grooves (15% less material) compared to a full cube; the obtained ratio of 1.54 for the integrated values matches perfectly with the experimental results, compare figure 5.

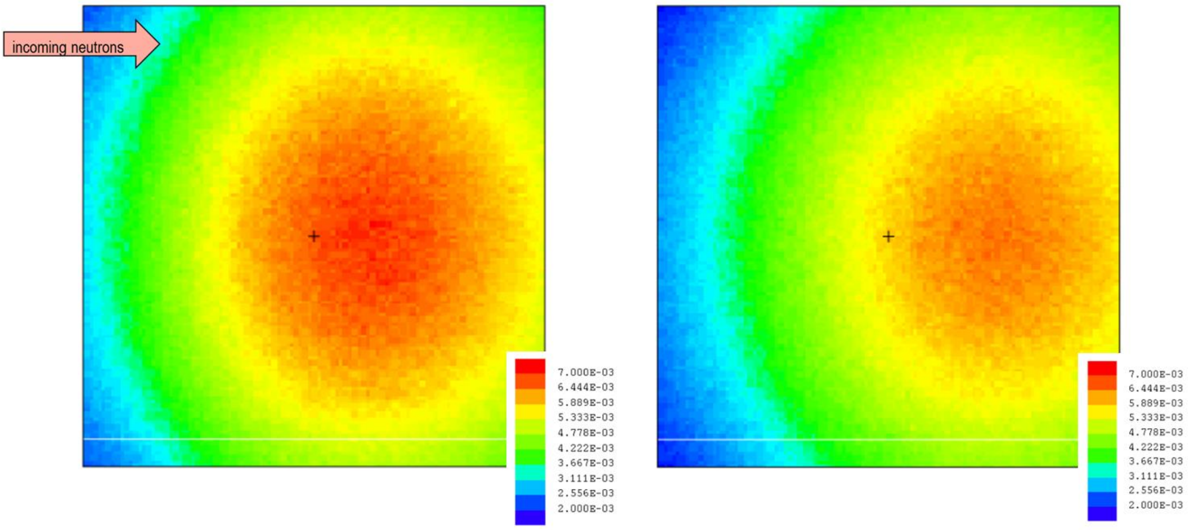


Figure 15. Simulation results with a sideways detector employing thermal neutrons' input, for a full cube (left) and for a cube with entry-grooves (right); plots are on the same scale. A clear shift of the detected flux in forward direction is found for both samples; this could explain the dark line described in figures 8 and 10; additional, more detailed simulations are required.
Simulations indicate a higher total flux 90° to the side for a full cube (left) compared to the one with entry grooves (right); this doesn't match with the measured data which indicate the opposite (see figures 10 and 11).

One hypothesis currently is that differences in the observed scatterd distributions for different input neutron beams might be linked to the conditions employing thermal neutrons, which actually always contained some contamination by "fast" neutrons.

4. Discussion and Preliminary Conclusions

This is work in progress. Not all the measured data have been analyzed yet, and more are to come. The same holds true for the simulations. Nevertheless, it seems safe to claim that evidence for an enhanced coupling of a neutron field to moderator material due to structuring has been found, both, for the input *into* as for the output *out of* the moderator. Quite generally, effects for „entry-“ and „exit-“ holes appear to be rather similar. Some differences for thermal compared to “fast” neutrons seem to exist.

When analyzing different measurements, which involved similar set-ups and, in particular, when contrasting images recorded with the CCD cameras with data obtained by imaging plates, it can be concluded that error bars were sufficiently low not to demolish the principal findings reported here. For these first mock-up experiments the aim was to obtain some qualitative results and understanding, - enough to continue the effort with refined methods in order to complete the picture and derive quantitative results.

It goes without saying that more work is still needed before it is clear how the here presented results can efficiently be used in the design of real moderators; this does not appear to be trivial [3]. One principled obstacle in realistic geometries might result from the observed similarity in the effects of input- and output- structures; what works as an entry-hole, also works as an exit-hole. With neutrons arriving from a target, an entry-hole might not only enhance the filling but at the same time also boost the draining of neutrons in this same direction, i.e., the effects observable at the intended output surfaces of a moderator might largely cancel.

4.1. Next Steps

As of the writing of this paper (September 2014), in addition to continued work on already recorded data, more measurements and simulations are planned. It might, for example, be interesting to measure “reflected” / moderated neutrons for “fast” input with a detector, which is dedicated sensitive to epithermal neutrons. Conversely and somehow complimentary to the investigations with thermal and “fast” input spectra, the scattering from diversely structured specimens for cold input neutrons could give interesting data points.

Collaborations with partners for some further scrutiny of the reported effects would be most welcome, and opportunities for discussion are used as they arise at ICANS XXI and during a specialized conference on neutron radiography immediately thereafter [4].

Acknowledgments

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[3] M. Magán and F. Sordo, private communication, 2013.

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