Beam characterization for neutron imaging after installation of the external collimator at TRR-1/M1

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Abstract. The neutron imaging facility at Thai Research Reactor-1/Modification 1 (TRR-1/M1), located at Thailand Institute of Nuclear Technology (Public Organization) has been improved for non-destructive characterization of internal structure of materials. The aims are to study the beam characteristic after an installation of the external collimator, and to optimize the exposure condition for a new setup. The neutron imaging setup was modified to increase the L/D ratio. As a consequence of the extended distance from the beam port to the sample position, an external collimator was installed to focus the neutron beam since 2018. Moreover, a new sample holder was installed to support sample rotation and translations with increased stability. The experiment was performed at the TRR-1/M1 reactor with 1 MW-reactor power. The neutron beam at the 8-inches south beam port of the TRR-1/M1 was evaluated in terms of beam homogeneity and the relationship between the grayscale value and image quality obtained from a CCD camera. The present performance of the neutron imaging system was tested with an ASTM standard sample, called sensitivity indicator. The results are shown in terms of image contrast and sharpness.

1. Introduction
Neutron imaging is an alternative technique for non-destructive characterization of materials, in particular, for investigation of internal structure [1,2]. This imaging technique as well as X-ray imaging can be mutually used for strengthen imaging information extracted from a sample [3]. Specifically, it is seen that neutron imaging has a sensitivity of detection on light elemental composition different from X-ray technique. Nuclear Research and Development group at Thailand Institute of Nuclear Technology (TINT) has been developing the neutron imaging facility to improve the image quality, and also to establish neutron tomography setup. In the process of the development, the neutron imaging room was renovated to increase the L/D ratio, while the divergence of neutron beam due to the increase of the beamline distance is compromised by an installation of extended collimator. The collimator is, thus, needed to be designed so that the neutron beam becomes parallel beam. In addition, the verification of beam quality is needed to observe characteristics of neutron beams. The aims of this work are to
determine the beam characterization for neutron imaging after installation of the external collimator at the TRR-1/M1, and to evaluate an appropriate exposure condition for neutron imaging.

2. Experimental setup

The 1 MW TRR-1/M1 research reactor at TINT was employed to generate neutrons for the imaging facility. Neutrons generated from the reactor core were fast neutron, which were needed to be slow down in order to decrease their kinetic energies down to meV range, called thermal neutrons. The moderator used for the deceleration is a cylinder made from a graphite chunk. A tangential beamline together with a conical collimator was installed inside the reactor wall to guide the thermal neutron beam to the experiment room. At the exit of neutron beam port, the beam aperture is set about 15×15 cm². An external collimator with an aperture size of 18×18 cm² [4] was installed outside the reactor wall in a movable beam-shutter, which is also a shielding made from 375 mm-thick borated polyethylene (BPE) together with 125 mm-thick lead sheets. Another external collimator was also installed right-after the beam-shutter to further collimate the neutron beam to the sample position. This collimator is a square hollow, composed of the 5 cm-thick BPE and 1 cm-thick of lead. The aperture (hollow) size is 18×18 cm² with a length of 50 cm.

A neutron imaging system consists of a neutron-to-photon conversion plate made from ⁴LiF/ZnS, 45-degree mirror, a Nikkor 50-mm/f1.2 lens and a 2048×2048-pixel CCD camera. The CCD camera is located away from the beamline to avoid the direct exposure of neutron beam, potentially damage the CCD. All equipment is contained in an L-shape aluminium box in order to prevent the visible light from environment. During the measurement, the CCD camera was kept cooled at -5°C to reduce the dark counts. Figure 1 shows (a) the neutron imaging facility at TINT, including the beam shutter, the extended collimator, the sample stage and the detection system, and (b) the appearance of the sensitivity indicator (SI) sample. The neutron flux at the beam exit of an extended collimator and the conversion plate position were \(2.5\times10^5\) n/cm²/s and \(1.5\times10^5\) n/cm²/s, respectively. It is found that the neutron flux is decreased by one order of magnitude compared to \(10^6\) n/cm²/s neutron flux obtained from the previous setup before the installation of external collimators [4]. However, the neutron beam should have become more parallel.

![Figure 1](image1.png)

Figure 1. (a) The schematic of neutron imaging facility at the Thai Research Reactor TRR-1/M1. (b) The sensitivity indicator (SI), containing plastic strips on Al body labelled by Row I-IX Column A-E.

2.1. Data acquisition

Two sample positions for neutron imaging were performed in order to carry out 2D-imaging, and to test a tomography setup. For a conventional neutron imaging, all samples were located close to the conversion plate in order to reduce the distance between the sample and the conversion plate. The sample were attached to a substrate, used for covering the conversion plate, by aluminium tape to reduce the neutron scattering. For neutron tomography (3D imaging), the samples were needed to be mounted on the rotation stage located at 8 cm in front of the conversion plate. This limitation, thus, reduces the image quality compared to the former setup. However, the 3D imaging allows us to investigate the internal structure in all directions, which cannot be seen in the former setup.
2.2. Standard sample
An ASTM standard sample in accordance with E2023 [5], called sensitivity indicator (SI), was used to determine the quality of imaging system (see figure 1(b)). The sample body is U-shape aluminium covered by 9 strips (Row I–IX) with 5 steps (Column A–E). The strips are made from methyl-methacrylate (i.e. plastic) fixed to the aluminium body. Aluminium strips are also inserted between the plastic strips. The thicknesses for Column A to D decrease from 5.08 to 0.64 mm. For the colored rows, there are thickness-varied plastic shims under the strips, containing single holes in each step (Column A–D). The shims are used to distinguish each strip for imaging.

3. Results and discussion

3.1. Beam quality
Figure 2 shows the distribution of neutron beams at the conversion plate characterized from open-beam response image, measured for different exposure times. The grayscale 16-bit images are shown as a percentage of grayscale value, compared to the center area. The percentage numbers labelled in the areas are separated by 5×5 grids on the images. It is seen that the photon intensity increases as a function of time, while the deviation of photon intensity near edges is up to 28% for the 30-second image. It is noted that the small variation for long exposure images is due to the fact that the photon intensity at the center area is over the maximum of 16-bit grayscale value, in particular, for an exposure time of 150 seconds (not shown).

![Image](image1.png)

**Figure 2.** The distribution of neutron beam interpreted from the photon intensity of open-beam images for different exposure times.

3.2. Image quality
The SI sample was used to investigate the quality of images for both 2D-imaging and tomography setups. The 2D-image was recorded from the sample located close to the conversion plate. Figure 3 shows 2D-image of the SI sample recorded at different exposure times, i.e., 30, 60, 90, 120 and 150 seconds. All images were processed by subtracting the background, which is the dark image (without neutron beam). It is clearly seen that the brightness increases as a function of exposure time. One can note that the image area in column D of the SI sample, recorded for 150 s, shows saturated brightness since there are too many photons detected by the CCD camera. However, we cannot clearly observe all gaps beneath plastic sheets due to the limitation of dynamic range for our detection system.

![Image](image2.png)

**Figure 3.** Images of the sensitivity indicator for exposure times of 30, 60, 90, 120 and 150 s.
Figure 4 shows (a) a plot of grayscale versus the image position on the screen of SI sample, and (b) a plot of mean grayscale value as a function of exposure time for individual column of the SI sample. It is seen that the step-like brightness profiles, representing grayscale in each column of the SI sample, can be observed for all exposure times. This result confirms that our neutron imaging facility can distinguish the different column stacks in the standard sample. The different grayscale value for each step is caused by the different thickness of plastic strip in each column, which decreases from column A to column D. In figure 4(b), the mean grayscale values of each column (step) are fitted by individual linear equations. All fitted linear lines tend to converge to zero grayscale for zero exposure time. This scenario proves that our facility as well as the subtracting background process is sufficient to scale the measurement for this range of exposure time. It can be seen that the image contrast is constant for the same area.

![Figure 4](image)

**Figure 4.** (a) Grayscale profiles for each strips (columns), and (b) average grayscale values for each strips (columns) of the SI were plotted as a function of image positions for different exposure times.

Figure 5 shows the sharpness of the edge between the strips (column A and B) for different exposure times. Linear lines are individually fitted to each slope in the area between 10% and 90% of the difference in grayscale value between column A and B. The sharpness value is in an arbitrary unit, where the value was obtained from the slope around the dashed line separating A and B in figure 4 (a). It is found that the sharpness increases as a function of exposure time between 30 and 150 s. This scenario is resulted from the fact that the statistic of detected neutrons at the conversion plate is improved for longer exposure time.

![Figure 5](image)

**Figure 5.** Sharpness of image as a function of exposure time obtained from edges between the strips of SI sample.

### 3.3. Establishment of tomography

The same image of SI sample located at the conversion plate is compared to the image captured for the SI sample located on the sample stage, which is about 8 cm from the conversion plate. Figure 6
shows (a) the comparison of the images taken from the same SI sample located at the conversion plate and on the sample stage, and (b) the line profile of the grayscale image for these sample positions. It is clearly seen that the image of sample located at the conversion plate is sharper than the one on the sample stage. One can also observe holes (bright dots) in Row II for the former position. The smallest hole size observed for the image in figure 6(a) is 0.5 mm.

Figure 6. (a) Images of the SI exposed to neutron beam for 90 s, located at the conversion plate and on the sample stage. (b) Line profiles of grayscale images taken from these positions.

The image profiles for each column are guided by dashed lines. The grayscale value for the sample placed at the sample stage is lower than the one at the conversion plate. The difference in the grayscale value of these images is found to be up to 20%. This scenario is possibly resulted from the attenuation and scattering of thick plastic strip, where higher scattering yield is expected for distant imaging. The neutron scattering in the sample leads to the variation of the detected position of neutrons, where the image become blurred (see figure 6(a)). The spread of neutron beams due to scattering, thus, reduces the neutron flux detected at the conversion plate.

4. Conclusion
After the installation of external collimators, the current information obtained from this study, allows us to determine the quality of neutron beam. As the open-beam image response features a collimated profile at the center, it is noted that imaging setup should be carried out in such a way that the sample is placed along the axial beamline. Image contrast obtained from the line profile of images for a variation of exposure times is still unchanged, due to high-resolution optical imaging system. However, the neutron scattering at the sample plays a role in the quality of neutron imaging, resulting in low quality of image, e.g. blurred image. It is seen that the sharpness of the image is linearly increased as a function of exposure time, where longer exposure time for the SI leads to a saturation of 16-bit imaging. The optimization of appropriate imaging condition is needed to be further studied, before the neutron imaging facility is ready for establishment of neutron tomography setup.

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