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A New CCD-Camera Neutron Radiography Detector at the Atominstitute of the Austrian Universities

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Abstract – Neutron radiography provides a very efficient tool for non - destructive testing as well as for many applications in fundamental research. A neutron beam penetrating a specimen is attenuated by the sample material and detected by a two dimensional imaging device. The image contains information about materials and structure inside the sample because neutrons are attenuated according to the basic law of radiation attenuation. At the Atominstitute of the Austrian Universities neutron radiographic examinations have been carried out for more than 35 years, mainly with detectors consisting of X-ray films and a Gd - converter enclosed in a vacuum cassette. Presently a neutron tomography set - up is under development. For high quality 3D image reconstruction, about 200 digitized neutron transmission images from different angles of the object are necessary. Therefore the first step was the design of an adequate electronic neutron radiography imaging device. The requirements for a detector suitable for neutron tomography are: exact and reproducible positioning, easy handling, high spatial resolution and dynamic range, high efficiency and a good linearity. The key components of the detector system selected on the basis of this requirements consist of a neutron sensitive scintillator screen, a cooled slow scan CCD-camera and a mirror to reflect the light emitted by the scintillator to the CCD-camera. The whole assembly is placed in a light-tight enclosure. In this paper the strategy of the selection of the individual detector components is described. Comparisons on the influence of the use of different components on the properties of the whole position sensitive imaging device are demonstrated. Finally the new CCD-camera neutron radiography detector of the Atominstitute is presented and first results of test measurements performed at the neutronradiography facility NEUTRA at the continuos spallation source SINQ at Paul Scherrer Institute are shown.

1 Introduction

At the 250 kW TRIGA Mark II reactor at the Atominstitute of the Austrian Universities two neutron radiography (NR) stations are available. The main characteristics of these two facilities are shown in Table 1:

	STATION 1	STATION 2
FLUX DENSITY ($cm^{-2}s^{-1}$)	$3\cdot10^5$	$1{,}3\cdot10^5$
L/D-RATIO	50	125
BEAM DIAMETER (cm)	40	9
Cd - RATIO	3	20

Table 1: main characteristics of the NR-facilities at the Atominstitute

Since 1964 , NR-activities at the Atominstitute encompass both research oriented work as well as non-destructive testing for various users [1]. Presently the point of main emphasis in NR-activities at the Atominstitute is set on the development of an experimental set-up for neutron tomography. For a 3 dimensional reconstruction of the sample interior, 2 - dimensional transmission images taken from different view angles are required [2]. The quality of the tomography depends strongly on the number of images from different view angles [3]. Good results can be obtained by rotating the object in the beam by 180 degrees with 0.9 degree-steps [4]. Hence it follows that for a high quality 3 - dimensional reconstruction of a sample, 200 2 - dimensional transmission images from different view angles of the specimen are required. Therefore the experimental set-up for neutron tomography consists of the neutron source with a collimator, a rotary table for the rotation of the object, a proper detector and a motion control system which coordinates the rotary table with the detector.

The detectors presently mainly used for NR at the Atominstitute consist of X-ray films and a Gd-converter enclosed in a vacuum cassette. After each exposure, the film has to be developed and the image is digitized by a scanner. It is obvious that such a detector is not the best choice if an application requires 200 digitized images per sample. Therefor the first step of the development of an experimental neutron tomography set-up was the selection and optimization of a proper detector. This paper shows the requirements for a detector suitable for neutron tomography. It presents the basic principle of the chosen detector system, the strategy of the selection of the individual detector components, comparisons on the influence of the use of different components on the properties of the whole imaging device and results of first test measurements.

2 Requirements for the Selection of Detector Suitable for Neutron Tomography

Due to the tremendous influence of the number and quality of the transmission images of the object on the result of the 3 dimensional reconstruction, the demands for a proper detector as one of the key components of the neutron tomography set-up are extremely high:

1. Exact and Reproducible Positioning:

It is evident, that for all exposures of one sample (from different view angles), the detector needs to be in exactly the same position. Corrections of different detector positions during the reconstruction calculations would be very time consuming, not precise and for many cases even impossible.

2. Easy Handling:

The enormous number of digitized images needed for each tomography requires a detector that can be controlled according to the rotary table by a computer to automate the whole set of measurements needed for the tomography of each sample. Also the digitization of the image data should be automated and not cause additional work.

3. High Efficiency:

In order to save time it is extremely important to reduce exposure time.

4. High Spatial Resolution, Large Dynamic Range, Good Linearity:

These items are always very important for the quality of images gained by NR. But the influence on the quality of neutron tomography is even higher.

3 Selection of the Detector

A comparison of the above requirements with the performance of x-ray film combined with a converter immediately shows that another detector has to be developed. Exact positioning is quite difficult as after each exposure the enclosure of film and the converter has to be removed and opened to change the film. Additionally this is quite a time consuming procedure, especially as all 200 films have to be developed and scanned. Also the exposure time by using film is quite high. Dynamic range and linearity are poor. Only the spatial resolution is satisfying. Other detectors extensively used for NR are neutron sensitive imaging plates (IP) [5]. They are made of a storage layer (sensitive crystals) doped with Gd. After the exposure a special scanner is used to read out the information stored in the IP. The advantages of IPs compared to film are a higher dynamic range, better linearity and a higher sensitivity. The spatial resolution is not quite as good as for images taken by film, but it is still reasonable. But regarding the requirements of exact and reproducible positioning as well as the handling, almost the same difficulties occur as with the use of the film technique.

Another neutron sensitive imaging device is a CCD-camera combined with a scintillator screen. It fulfills all the requirements for a detector suitable for neutron tomography investigations. As the detector has not to be removed between the exposures the demand of exact positioning during one set of images is fulfilled. The detector is controlled by a computer and can easily be connected with a computerized motion control system of the rotary table. Image data are digitized and can immediately be used for the 3 dimensional reconstruction. Compared to film the efficiency is much higher, the dynamic range is larger and the linearity is better. The spatial resolution depends strongly on the lens, the size on the chip and the distance between scintillator and camera. The resolution limit is set by the scintillator screen in the range of 200μm.

4 Design of a CCD-Neutron Radiography Detector

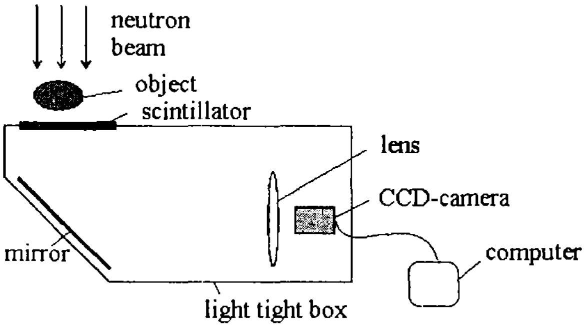

Figure 1: set-up of a CCD-camera neutron radiography detector

The neutron beam reaches the neutron sensitive scintillator screen after penetrating the sample. The light emitted from the screen is reflected to the camera by a mirror and focused on the CCD-Chip by a lens. These components are located in a light shielded tube together with shielding components to protect the CCD-camera from neutron and γ-radiation. The CCD-camera is connected to a computer to read out the information stored by the CCD-Chip and to reconstruct and process the digitized image data obtained with the imaging device of figure 1 [6].

5 Selection of the Key Components for the CCD-Camera Neutron Radiography Detector

Because the CCD-camera is the most sophisticated and expensive key-component of this imaging device , it has been selected first and the rest of the components have been selected or manufactured according to the boundary conditions following from the choice of the camera and from their interactions with each other.

5.1 CCD-Camera

To fulfill the demands of high sensitivity, a large dynamic range and a good signal to noise ratio, a nitrogen cooled slow scan CCD-camera with a thinned SITe SI502A chip has been chosen. The pixel array format of this chip is 512 x 512 pixels with a pixel size of (24 x24) μm. The Quantum Efficiency of the CCD-camera is in the range of 80 - 90 % for wavelengths from (350 - 800) nm, as shown in Figure 3. The high precision CCD driver electronics provides 16-bit digitization (65535 gray levels). Figure 2 shows the correlation of the temperature of the CCD-chip with the dark-current. To obtain this curve, images without neutrons and with closed camera shutter have been made at different CCD-temperatures. For the ideal case for each image a gray-level close to zero in each pixel is expected (due to statistics, dark current, read out noise and the influence of background radiation, which causes white spots in the image, the mean gray-level within a dark picture can never get zero). Figure 2 shows that for „high" CCD-temperatures this value is far away from zero, but for lower CCD-temperatures the value of dark-current decreases rapidly.

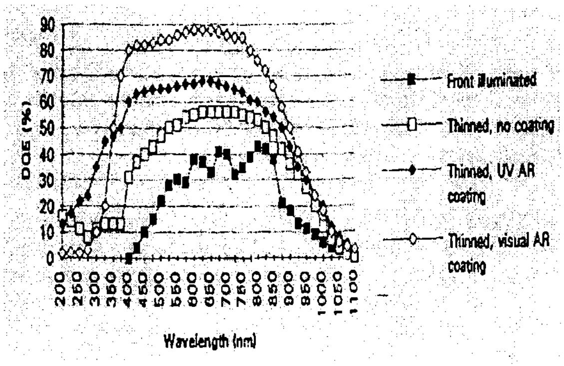

Figure 3: spectral sensitivity function of SITe chips

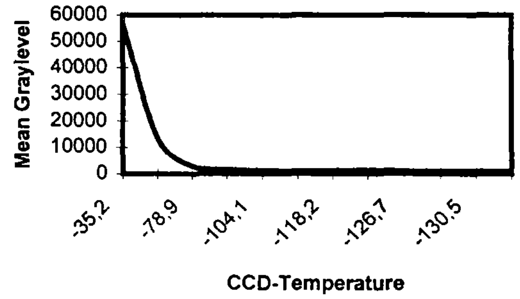

Figure 2: dark-current depending on the temperature of the CCD-chip

5.2 Lens

As the light transmission should be maximized and picture distortion has to be avoided, the high quality of the lens is extremely important. The desired image size is about (20-25) cm^2. The available space beside the facility is less than 1.3 m. Based on this boundary conditions a Nikon NOKT 58 mm F 1,2 lens has been chosen. Figure 4 shows that the light intensity decreases for smaller apertures. From one aperture to the next one (i. e. from 1.2 to 2) it is about a factor of two. This means that the sensitivity of the detector increases tremendously if an open aperture (1.2) is used. But for this case the distance has to be adjusted very carefully, because with a completely open aperture the image is blurred more easily.

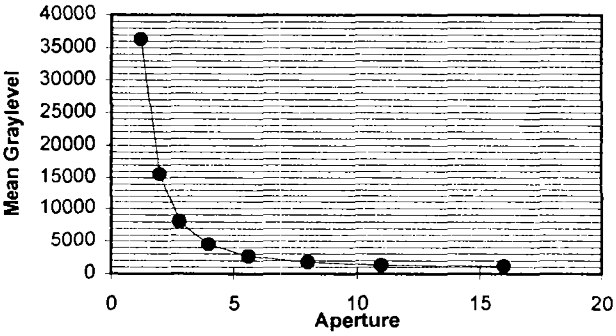

Figure 4: detected light quantity vs. aperture

5.3 Mirror

The demands for this detector component are a high reflectivity (95 %) of the light emitted by the scintillator, generation of as few γ-rays as possible and no lasting activation of the materials of the mirror. According to that a 2 mm thick glass plate coated with Al and with TiO$_2$ as protecting layer was manufactured at the Paul Scherrer Institute (PSI) in Switzerland.

5.4 Box

A light shielded tube which also serves as a positioning device for the detector components has been designed according to the boundary conditions given by the size and appearance of the individual detector components, the desired image size and the space available at the facility. The material for the whole box is Al to avoid lasting activation. It has been manufactured at PSI. Light tightness of the box has been successfully tested. The image size is (21 x 21) cm.

5.5 Neutron Sensitive Scintillator Screen

According to the spectral sensitivity function of the selected chip, a neutron sensitive scintillator screen with a suitable emission spectrum had to be found. Four adequate neutron sensitive scintillators have been compared:

1. Bicron 705: ZnS(Ag)-^{6}LiF
2. Kasei Optonics
3. Levy Hill: ZnS(Ag)-^{6}LiF
4. NE 427: ZnS(Cu)-^{6}LiF

The detection mechanism is: $^6_3\text{Li} + n \rightarrow {}^3_1\text{H} + {}^4_2\text{He} + 4{,}78\ \text{MeV}$
All test - measurements have been performed at the neutronradiography facility NEUTRA at the continuos neutron spallation source SINQ at Paul Scherrer Institute in Switzerland [7].

neutron flux	~3x10^{6}cm^{-2}s^{-1}
mean neutron energy	25 meV
Cd - ratio	16
L / D	550
beam diameter	35 cm
γ - background	1,5 mSv / h

Table 2: main characteristics of the neutronradiography facility NEUTRA at PSI

The following issues have been investigated separately for each of the four neutron sensitive scintillator screens:

5.5.1 Efficiency and Linearity

To compare the efficiency and linearity of the whole CCD-camera NR detector depending on the choice of the scintillator, series of open beam measurements with different exposure times for each scintillator were made. From each of these images, the mean gray-level was determined (the gray-level is higher for a brighter image, respectively for longer exposure times, and vice versa).

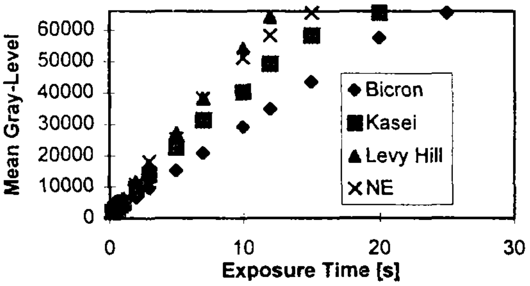

Figure 5: linearity and efficiency: dependency of the mean gray-level on the exposure time

Figure 5 demonstrates the good linearity of this imaging device independing on the choice of the scintillator. Small deviations from the linear increase of the mean gray-level with the exposure time are most likely caused by small neutron flux fluctuations at the facility. Besides, Figure 5 shows that the detector has the best efficiency with the Levy Hill or the NE scintillator screen.

5.5.2 Spatial Resolution:

Due to the size of the CCD-chip , (512x24) μm x (512x24) μm, and the size of the sensitive area of the detector, (26.3 x 26.3) cm^2, the area seen by one pixel is (513 x 513) μm^2. As the inherent resolution of neutron sensitive scintillator screens are usually in the range of 200 μm, the choice of the scintillator should not affect the spatial resolution of the whole imaging device. With each of the four scintillators a knife edge-object (edge of a Gd foil) has been measured. From these images the modulation transfer functions (MTF) were determined and compared (Figure 6) [8].

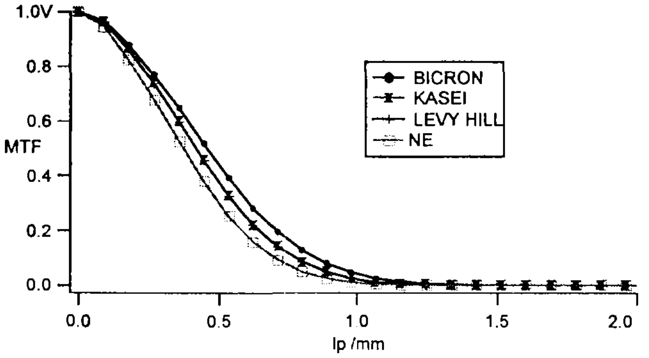

Figure 6: modulation transfer functions (MTF) of the detector obtained with different scintillator screens

5.5.3 Inhomogeneities of the Scintillator Screens

The four neutron sensitive scintillator screens have been compared regarding the homogeneity of their light-emission. For each scintillator an open beam image has been investigated the following way: The image has been subdivided in small areas of interest (AOI). In each of this area the mean gray-level had been derived. Figure 7 shows that only the BICRON scintillator is quite inhomogeneous. The fluctuations of the mean gray-level in the AOIs of the other scintillators appear periodically and on the same position for each scintillator and therefor seem to come from the beamprofile.

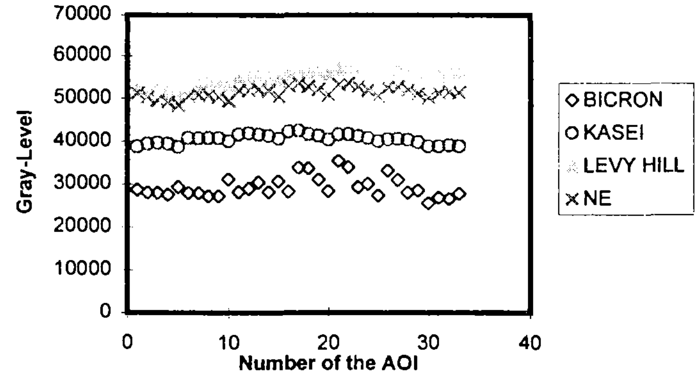

Figure 7: homogeneity of the scintillator screens

5.5.4 After Glow of the Scintillator Screens:

To determine the after glow of the neutron sensitive scintillators, the screens have been exposed to the neutron beam for one hour. After closing the neutron shutter several images have been taken with the CCD-detector to observe how long the scintillator emits light after exposure. Figure 8 shows that the after glow of the scintillators depending on the time after exposure is quite fast, especially for the Kasei Optonics and the Levy Hill scintillator screens, and the effect of the after glow as an disturbing effect for the following neutron radiographic image can be neglected for most applications, as this effect is very small compared to the range of 65535 gray levels of a neutron radiographic image taken with this detector system.

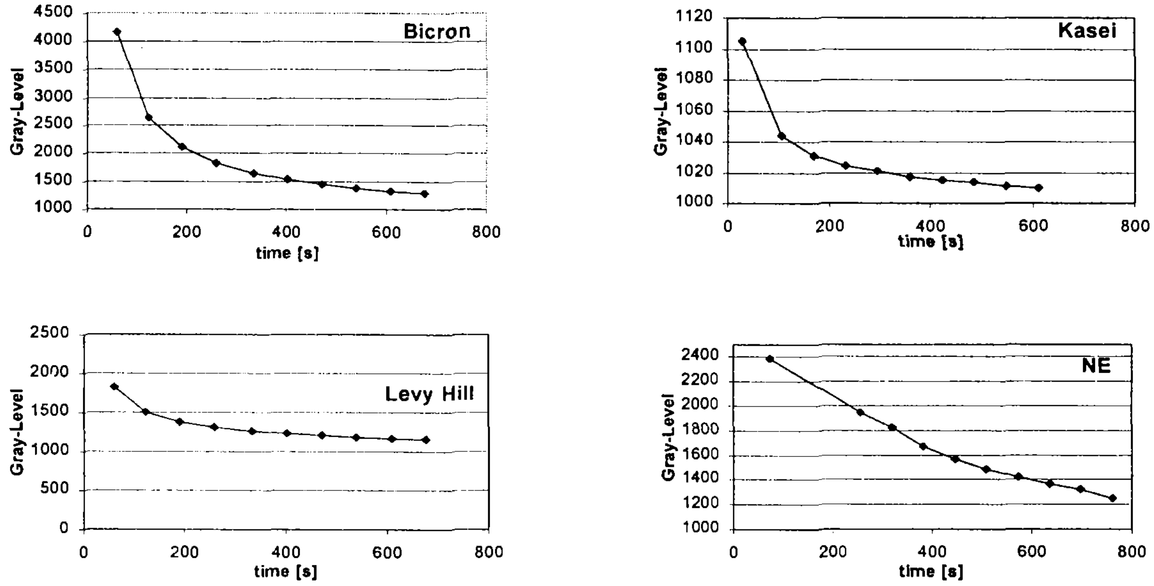

Figure 8: behavior of the emission of light of the scintillators after the exposure to neutrons

After this large series of test measurements and comparisons of different scintillator screens, a neutron sensitive scintillator by Levy Hill (ZnS(Ag)-6LiF) has been selected for the new CCD-camera NR detector at the Atominstitute.

6 Conclusions and Outlook

A new CCD-camera NR detector has been designed, optimized and tested with the aim of providing a tool for scientific and industrial radiography applications requiring high quantitative precision as well as for neutron tomography investigations. The detector consists of the following key components: The selected camera is an Astrocam nitrogen cooled slowscan CCD-camera with a thinned SITe SI502A/T chip of the format (512 x 512) pixels and a pixel size of (24 x 24) μm^2 and with a Nikon NOKT 58 mm F 1.2 lens. The high precision CCD driver electronics provides 16-bit digitization (65535 gray levels). A mirror made of a 2 mm thick glass plate coated with Al reflects the light emitted by a (ZnS(Ag)-6LiF) Levy Hill scintillator screen to the camera. These components are placed in a light-tight box, made of Al. The image size is (21 x 21) cm^2. One camera pixel faces 410 μm^2. The detector has an excellent linearity and sensitivity. Based on the test measurements performed at PSI, exposure times of 1-1.5 minutes are expected at the NR facilities of the Atominstitute. This means that all measurements needed for one tomography can be made during one working day.

If a zoom lens would be used, the resolution could be improved on the cost of light-intensity and image size. For next year the purchase of a Nikon 180mm F 2,8 lens is planned. With this lens we expect to see an area of about (7 x 7) cm^2 (if the distance between scintillator and camera is not changed). The loss of light intensity compared to the 58mm F 1.2 lens is expected to be around a factor of 7. The resolution limit given by the lens / scintillator would be in the range of 140 µm, but for this case the resolution limit would properly be set by the scintillator screen in the range of 200 µm, or even below.

Due to the results of the first test measurements performed at the NR facility NEUTRA at Paul Scherrer Institute, we are confident of having developed a powerful instrument suitable for neutron tomography investigations. The imaging device will be transferred to the Atominstitute this autumn.

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8 References

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