Properties of Neutron Pixel Detector based on Medipix-2 Device

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Abstract - Neutron transmission radiography can serve as a complementary diagnostic method to X-ray radiography. It can produce contrast images of materials, which are indistinguishable in X-ray images (typically materials containing Hydrogen). Good performance of a neutron detecting device is essential for the acquisition of high quality neutron images. The properties of the neutron pixel detector based on the single X-ray photon pixel detector device Medipix-1 (64 x 64 square pixels with pitch of 170 µm) were already demonstrated and published. Slow neutrons are captured and converted in a surface layer containing Li-6 to tritons and alpha particles which are subsequently detected by a silicon pixel detector. A Medipix-2 detector (256 x 256 square pixels with pitch of 55 µm) was adapted in a similar way. The detector performance was tested at the NEUTRA station of the Paul Scherrer Institute using a beam of slow neutrons from the spallation source SINQ with an intensity of \(3 \times 10^6\) neutrons/cm\(^2\)s. The spatial resolution, detection efficiency and other detector properties have been determined and are compared with several types of contemporary neutron imaging systems (Medipix-1, CCD camera, imaging plates). The results demonstrate the superiority of the Medipix-2 based neutron imager in terms of spatial resolution, linearity and dynamic range. The system is very promising in applications for micro-neutron tomography, especially when large detector areas will become available.

I. INTRODUCTION

The hybrid silicon pixel device of Medipix type developed at CERN [1] was originally designed for position sensitive single X-ray photon detection. The Medipix device consists of a semiconductor detector chip bonded to a readout chip. The silicon detector chip is equipped with a single common backside electrode and a rectangular front side matrix of electrodes. Each element of the matrix (pixel) is connected to its respective preamplifier, discriminator and digital counter integrated on a readout chip. Each individual pixel counts ionizing particles of adequate energies crossing its area. Basic properties of Medipix devices are summarized in Tab. 1.

![Image](image.png)

Tab. 1. Medipix 1 and 2 devices.

<table>
<thead>
<tr>
<th></th>
<th>Medipix-1</th>
<th>Medipix-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>64 x 64</td>
<td>256 x 256</td>
</tr>
<tr>
<td>Pixel size</td>
<td>170 x 170 µm(^2)</td>
<td>55 x 55 µm(^2)</td>
</tr>
<tr>
<td>Counter</td>
<td>15 bit</td>
<td>13 bit</td>
</tr>
<tr>
<td>Read out</td>
<td>384 µs parallel (at 10 MHz)</td>
<td>266 µs parallel or 9 ms serial (at 100 MHz)</td>
</tr>
<tr>
<td>Technology</td>
<td>1 mm SACMOS</td>
<td>6-metal 0.25mm CMOS</td>
</tr>
</tbody>
</table>

Thermal neutrons can be hardly detected by the silicon detector itself. Therefore we deposited a layer of neutron converter on the Medipix surface [2] as illustrated in Fig. 1. The following nuclear reactions were considered for converter design:

\[
\begin{align*}
^{6}\text{Li} + n & \rightarrow ^{3}\text{H} (2.72 \text{ MeV}) \\
^{11}\text{B} + n & \rightarrow ^{7}\text{Li} (0.84 \text{ MeV}) + ^{7}\text{Li} (1.01 \text{ MeV}) \\
^{11}\text{B} + n & \rightarrow ^{7}\text{Li} (1.47 \text{ MeV}) + ^{7}\text{Li} (0.48 \text{ MeV}) \quad (93.7\%) \\
^{11}\text{B} + n & \rightarrow ^{7}\text{Li} (1.78 \text{ MeV}) + ^{7}\text{Li} (0.09, 0.20, 0.30 \text{ MeV}) \quad (6.3\%) \\
^{13}\text{Cd} + n & \rightarrow ^{13}\text{Cd} + ^{1}\text{H} (0.56 \text{ MeV}) + \text{conv. electrons} \\
^{157}\text{Gd} + n & \rightarrow ^{157}\text{Gd} + ^{1}\text{H} (0.09, 0.20, 0.30 \text{ MeV}) + \text{conv. electrons} \\
^{157}\text{Gd} + n & \rightarrow ^{157}\text{Gd} + ^{1}\text{H} (0.08, 0.18, 0.28 \text{ MeV}) + \text{conv. electrons}
\end{align*}
\]

Thermal neutrons are converted in the layer into secondary radiation (heavy charged particles, electrons) which can be subsequently detected by the pixel detector. The signal created by secondary charged particles is high enough to set the discriminator threshold well above noise and possible gamma background. Count of events in each pixel obeys a Poisson distribution with standard deviation determined only by the number of neutrons reacting in the converter. Therefore, the signal to noise ratio can be improved to any arbitrary level by extending the exposition time.

![Image](image.png)

Fig. 1. Medipix device with 300µm thick Silicon sensor chip covered by a LiF converter with illustration of a neutron conversion in the converter layer.
II. NEUTRON CONVERTERS

The Medipix-2 device was tested as a neutron detector with different types of converters using a beam of thermal neutrons\(^1\). Converter materials were examined with the aim at reaching maximal spatial resolution at reasonable detection efficiency.

A. \(^6\)Li in form of \(^6\)LiF powder

The \(^6\)Li based converter material (\(^6\)LiF) in the form of fine powder dispersed in highly diluted glue was sprayed on the detector surface. Glue concentration in the mixture was kept very low. When dried only 5\% of glue is present in the resulting converter layer. Measured thermal neutron detection efficiency is about 3\%.

The spatial resolution of the imager is affected by range of heavy charged particles (in LiF: \(R_{\text{Triton}}=52\mu m, R_\alpha=10\mu m\); in Silicon: \(R_{\text{Triton}}=44.1\mu m, R_\alpha=8.6\mu m\)) and possible charge sharing effect in the pixelated sensor.

Fig. 2. Alpha and triton particles deposit their energy near detector surface producing massive ionisation. The charge sharing effect causes signal in several adjacent pixel cells.

Measuring with a beam of slow neutrons and very short exposition time (1ms) allows to observe signals created by single events and to see the effect of charge sharing.

Each charged particle creates a signal within a cluster of adjacent pixels. The cluster size is dependent on particle energy and detection threshold level.

The spatial resolution has been tested measuring the projection of a straight edge of a 1 mm thick cadmium plate. The detector spatial resolution can be described by the FWHM (Full Width at Half Maximum) of the line spread function (LSF)\(^5\). Since the LSF is equal to the first derivative of the straight edge projection (ERF - Edge Response Function) the FWHM can be easily evaluated (see Fig. 5).

Fig. 4. Cluster size distribution. Analyzed 10 000 clusters.

The dependence of spatial resolution on the detection threshold level (which affects cluster size) was also measured as shown in Fig. 6.

Fig. 6. Dependence of spatial resolution on detection threshold.

The best measured spatial resolution of the Medipix-2 device coated by a \(^6\)LiF converter of 107 \(\mu\)m corresponds to the maximal threshold value.

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\(^1\) The measurements were carried out using neutron beams at the Nuclear Physics Institute of the Czech Academy of Sciences at Rez near Prague (NPI) and at the NEUTRA facility in Paul Scherrer Institute at Villigen in Switzerland (PSI). Measurements in NPI were done on a parallel beam of thermal neutrons from a horizontal channel of the LVR-15 nuclear research reactor [3] a neutron beam intensity of about 10\(^7\) neutrons/cm\(^2\)s, cross section 4 mm (height) x 60 mm (width) and divergence less than 0.5\(^\circ\). The NEUTRA facility [4] is based on a spallation neutron source beam intensity of about 3\(\times\)10\(^5\) neutrons/cm\(^2\)s at proton accelerator current of 1mA and proton energy of 590 MeV and neutron beam cross section of 40 cm.

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\(^5\) Each charged particle creates a signal within a cluster of adjacent pixels. The cluster size is dependent on particle energy and detection threshold level.
B. Amorphous $^{10}$B

The conversion mechanism in $^{10}$B is similar to $^6$Li but energies and ranges of generated secondary particles are lower. All tests done for $^6$LiF were repeated also for a $^{10}$B converter.

Patterns of single events show electron tracks (from gamma interactions). Tracks can be suppressed using a higher threshold level in which case the average cluster consists of a single pixel and the spatial resolution is determined by the pixel dimensions. The observed spatial resolution using edge response measurement is 45µm.

The higher threshold and lower energies of charged particles produced by $^{10}$B imply unfortunately a decrease of detection efficiency which is approximately 2 times lower than that in the case of a $^6$LiF converter.

C. Cadmium foil

$^{113}$Cd emits 0.56MeV gamma rays and conversion electrons after neutron capture. Medipix can detect only the conversion electrons. Electrons produce long tracks in the detector (see Fig. 8).

The electron motion in the Silicon has been simulated in MCNP [5]. Spatial resolution was estimated at 1.6 mm.

D. Gadolinium

Gadolinium emits a lot of gamma rays and conversion electrons after neutron capture. Medipix can detect only conversion electrons and some fraction of weak gamma rays. Gadolinium was not available for us and thus only simulations were done (see Fig. 11).

The most probable emission is of 80keV electrons (~23%). Spatial resolution in terms of LSF FWHM is estimated at ~100
µm. MTF is degraded at low frequencies by more energetic electrons. Further image degradation is expected due to high gamma background (see Fig. 12).

Fig. 12. Detection sensitivity of the 300µm Si sensor for 80 keV gamma rays is not negligible as their path can be very long.

III. COMPARISON OF DETECTOR SPATIAL RESOLUTION

A CCD camera with scintillator filled by ⁶Li (pixel size 139µm) and an imaging plate (scanner pixel size 50µm) [4] were compared to the Medipix-1 and Medipix-2 devices coated by a ⁶LiF conversion layer. Imagers were compared for spatial resolution and image quality. The spatial resolution has been tested on all detectors measuring the projection of a straight edge of a 1 mm thick cadmium plate and evaluating the FWHM of the Line Spread Function. Results are summarized in Tab. 2.

Tab. 2. Spatial resolution of tested imagers.

<table>
<thead>
<tr>
<th>Imager</th>
<th>Resolution (FWHM of LSF) [µm]</th>
<th>Resolution [lp/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medipix-1</td>
<td>370</td>
<td>2.5</td>
</tr>
<tr>
<td>Medipix-2</td>
<td>107</td>
<td>8.5</td>
</tr>
<tr>
<td>CCD camera</td>
<td>824</td>
<td>1.1</td>
</tr>
<tr>
<td>Imaging plate</td>
<td>124</td>
<td>7.3</td>
</tr>
</tbody>
</table>

The performance of tested imagers is demonstrated by the measurement of two sample objects: A blank cartridge and a fishing thread.

IV. SAMPLE IMAGES AND NEUTRON MICRO-TOMOGRAPHY

In order to demonstrate the quality and capabilities of the adapted Medipix-2 device we took several transmission images of some representative objects. Photographs and neutronograms of a watch, grasshopper and valve are given in figures 14, 15 and 16 respectively.

Fig. 13. Photographic and neutron radiographic images of a blank cartridge (upper row) and of a fishing thread with 100µm in diameter (lower row) taken by different imagers. The best performance of the Medipix-2 device is apparent.

Fig. 14. Photograph and neutronogram of a wrist watch. Tiny plastic toothed wheels are observable through the massive metallic casing.

Fig. 15. Photograph and neutronogram of a grasshopper.

Fig. 16. Photograph and neutronogram of a valve (4mm in diameter).

The Medipix-2 detector coated by ⁶LiF converter layer was also used for a demonstrational tomographic measurement of a blank cartridge, a lemo connector and a tooth. All measurements have been done for 100 projections each with exposition time of 150 seconds. The standard Filtered Back Projection algorithm was used for 3D reconstruction. Results are shown in figures 17, 18 and 19.
Fig. 17. Photograph and tomographic 3D reconstructions of the blank cartridge. Explosive filing of the cartridge (marked by red) is clearly visible.

Fig. 18. Photograph and tomographic 3D reconstructions of a LEMO connector. Golden contacts are visible and marked by red colour.

Fig. 19. Photograph and tomographic 3D reconstructions of a fresh tooth.

V. CONCLUSIONS

The position sensitive thermal neutron detector based on the Medipix-2 device covered by several types of neutron converter layer was successfully simulated, realized and tested. The best spatial resolution was 45 $\mu$m (in terms of line spread function FWHM) achieved with a $^{10}$B converter at detection efficiency of 1.5%. A better detection efficiency is shown by Medipix-2 with a $^{6}$LiF converter (3%) but the spatial resolution is not so good (100 $\mu$m). Other types of tested converters generating conversion electrons (Cadmium and Gadolinium) in combination with silicon pixel detector are little suitable choice for position sensitive detection of slow neutrons due to distorted MTF and high gamma background.

The spatial resolution, detection efficiency and other detector properties were compared among several types of neutron imaging systems (Medipix-1, CCD camera, imaging plates). The results demonstrate the superiority of the Medipix-2 based neutron imager in terms of the spatial resolution, linearity and dynamic range. The system is very promising in applications for micro-neutron tomography, especially when larger detector areas become available.

VI. REFERENCES