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Detection efficiency, spatial and timing resolution of thermal and cold neutron counting MCP detectors

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ABSTRACT

Neutron counting detectors with boron or gadolinium doped microchannel plates (MCPs) have very high detection efficiency, spatial and temporal resolution, and have a very low readout noise. In this paper we present the results of both theoretical predictions and experimental evaluations of detection efficiency and spatial resolution measured at cold and thermal neutron beamlines. The quantum detection efficiency of a detector (not fully optimized) was measured to be 43% and 16% for the cold and thermal beamlines, respectively. The experiments also demonstrate that the spatial resolution can be better than 15 μm—highest achievable with the particular MCP pore dimension used in the experiment, although more electronics development is required in order to increase the counting rate capabilities of those <15 μm resolution devices. The timing accuracy of neutron detection is on the scale of few μs and is limited by the neutron absorption depth in the detector. The good agreement between the predicted and measured performance allows the optimization of the detector parameters in order to achieve the highest spatial resolution and detection efficiency in future devices.

1. Introduction

Recently there has been a rapid progress in neutron sources and neutron instrumentation, enabling novel high resolution non-destructive testing techniques for material sciences, investigation of hydrogen content and storage, magnetic properties, imaging of archeological objects, to name the few. The increased brightness of modern neutron sources as well as pulsed nature of some of them, allows high resolution neutron tomography, energy resolved neutron radiography, as well as texture and residual strain analysis by measuring the shifts in Bragg diffraction edges. The performance of detection devices has to meet the challenges posed by those new techniques in order to achieve the desired resolution, reduce the data acquisition times and fully utilize the capabilities of modern neutron sources [1,2]. Detection efficiency, spatial and timing resolutions are among the key detector parameters determining the accuracy of mentioned techniques.

Neutron counting detectors with microchannel plates suggested by Fraser [3] provide some unique capabilities for high resolution applications. Our detailed theoretical study of the detection process [4,5] indicate that the MCP detectors can reach efficiencies as high as 50% for thermal neutrons. The preliminary experiments with out optimal microchannel plates [6] agree with the results of our predictions for the particular MCP geometry used in the measurements. In addition, detectors with neutron-sensitive MCPs can count thermal and cold neutrons with spatial resolution comparable to the pore dimensions of 10 μm [7].

2. Experimental results

In this paper we present the results of detailed experimental evaluation of MCP-based neutron counting detector, which consisted of one ^{10}B-doped microchannel plate (8 μm pores on 11 μm centers, 100:1 L/D, 33 mm diameter) followed by a stack of two standard glass MCPs (10 μm pores on 12 μm centers, 40:1 L/D, 33 mm diameter) and a Medipix2 readout [8] positioned 0.7 mm behind the MCP stack. Muros2 [9] back-end electronics allowing externally triggered acquisition frames was used for signal processing. The experiments were performed at two neutron beamlines at the Paul Scherrer Institute (PSI): NEUTRA with thermal spectrum and ICON with cold spectrum.

2.1. Neutron detection efficiency

The high accuracy of the Medipix2 shutter and fast event detection by the MCPs allow counting of individually detected neutron events in acquisition frames controlled to ~1 μs accuracy.

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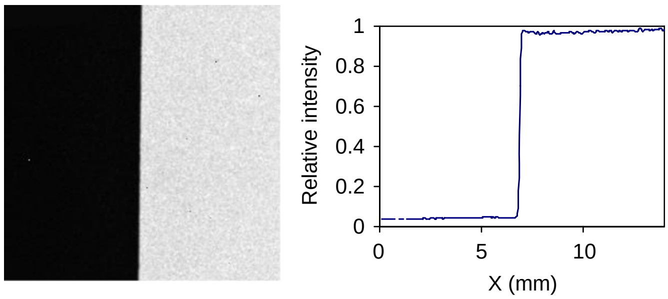

Fig. 1. Detector response to thermal neutron beamline with half covered by a Gd foil (installed on the input window a few cm away from the detector active area). Gamma photons produced by neutron capture in Gd are not detected effectively by the MCP detector, enabling high-contrast imaging.

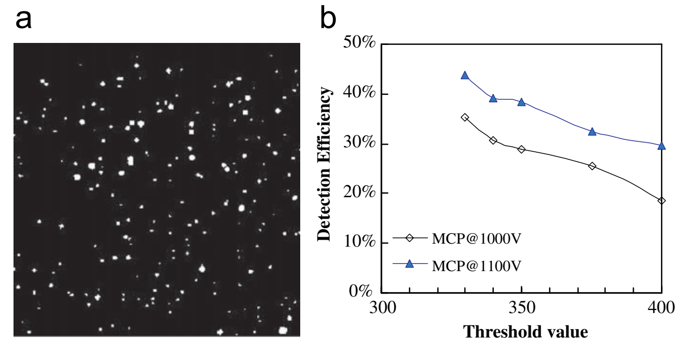

Fig. 2. (a) Single 30 μs acquisition frame with 202 individual neutron detection events. $14\times14\,mm^2$ active area. Medipix2 threshold = 330 (arbitrary digital units, false zero) and (b) neutron detection efficiency measured as a function of Medipix2 threshold. No readout noise present at values above 325, allowing effective neutron counting with QDE ~43%. Measurement performed on the cold neutron beamline at ICON facility.

That allowed the accurate measurement of the neutron detection efficiency determined from the ratio of measured counts in a single frame to the number of incoming neutrons. The frame length was optimized in order to avoid event overlaps. First we verified that these were indeed neutrons counted rather than gamma photons or dark events. The threshold of the Medipix2 readout was increased to the level corresponding to zero counts detected with beam shutter closed. Then images were acquired with half of the detector covered with a 250-μm-thick Gd foil, blocking neutrons and passing gamma ray flux, Fig. 1. The high contrast ratio seen in Fig. 1 indicates that most of the detected events were indeed neutrons interacting with MCP.

We did not observe considerable gamma background on both beamlines at PSI. Although we could not quantitatively measure the gamma rejection ratio of our detector in these experiments, the ratio was found to be sufficient for accurate efficiency measurements as well as high contrast neutron radiography.

Fig. 2 shows the measured neutron detection efficiency together with a typical single frame from which the neutron counts were calculated. The difference in the footprint size of individual neutron events seen in that figure is due to the exponential distribution of electron pulse sizes at low gain operation of the MCP stack.

The noise of the Medipix input pulse amplifier is <100e rms, enabling efficient noise discrimination at MCP gains as low as $(1–5)\times10^4$. The latter allows low gain MCP operation substantially increasing the dynamic range of MCP—Medipix detectors and extending their lifetime, making these detectors capable of operation at counting rates exceeding 10^8 counts/cm^2/s. We also compared the measured results with the predicted detection efficiency calculated for the given MCP geometry and ^{10}B doping level, Figs. 3 and 4. The detailed description of our theoretical prediction of MCP detection efficiency can be found in Ref. [4]. In our model we calculate the probability of neutron absorption inside MCP glass and combine it with the probability of the reaction products' escape into an adjacent pore initiating an electron avalanche. The predicted detection efficiency of 43% for cold neutrons agrees very well with experimental data. The measured sensitivity to thermal neutrons was lower than predicted. That can be explained by larger depth of neutron absorption and the non-optimal bias setting of the MCP stack, which will be thoroughly tested and optimized in the future.

2.2. Spatial resolution of neutron detection

The position of neutron capture in MCPs can be determined very accurately because of the unique capability of MCP to amplify signal within a single pore. That capability of event localization is the main difference between MCP—Medipix neutron counting and neutron detection by the sensors utilizing solid state converters deposited on a Medipix readout. The latter sensors developed by our colleagues at Czech Technical University were very successfully tested in neutron radiographic applications providing spatial resolution better than 100 μm [10,11]. The MCP technology should enable improvement of spatial resolution down to a single pore level (~10 μm), providing the readout can encode the MCP signal with that accuracy.

The localized event detection in MCP is determined by the range of the capture reaction products in the MCP glass. For boron-doped MCPs these ranges are 3.5 and 2.5 μm for alpha particle and ^{7}Li, respectively [5], matching the dimensions of the MCP glass walls (typically 1.2–3 μm). The spatial resolution of our detector was first tested with a Gd imaging mask, containing a set of laser drilled 25 μm holes, Fig. 5. The spatial resolution of the image shown in Fig. 5b is limited by the 55 μm pixel size of the Medipix2 readout. However, in that mode the detector can operate at very high counting rates exceeding 10^8 n/cm^2/s. We also have tested the high resolution capability of the MCP neutron detection with the help of event centroiding, although the latter can be performed only at a very limited counting rate of few kHz due to the serial implementation of back-end electronics [7]. The parallel readout electronics developed by our Czech colleagues [12] should enable high resolution imaging at much higher counting rates. Fig. 6 shows the neutron transmission image of a PSI test pattern acquired in event centroiding mode enabled by a Timepix readout providing information on charge values collected in each 55 μm pixel.

Our proof-of-principle high resolution imaging demonstrate that the predicted single pore detection is indeed possible. That means most of the detected events produced an electron avalanche in a single pore, i.e. most of the time only one of the reaction products particles escapes from the MCP glass and produces secondary electrons in the adjacent pore. Thus the detector spatial resolution can indeed be as high as the dimension of MCP pore spacing, 11 μm in our case.

2.3. Timing resolution of MCP/Medipix2 neutron detection

The intrinsic timing resolution of MCP detectors for UV photons can be as high as <100 ps FWHM [13]. However, in case of neutron detection the variation of the depth of neutron absorption and its relatively slow speed of propagation limit the timing resolution to a ~μs level. That is comparable to the