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Neutron radiography with sub-15 μm resolution through event centroiding

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ABSTRACT

Conversion of thermal and cold neutrons into a strong ~1 ns electron pulse with an absolute neutron detection efficiency as high as 50–70% makes detectors with ^{10}B-doped Microchannel Plates (MCPs) very attractive for neutron radiography and microtomography applications. The subsequent signal amplification preserves the location of the event within the MCP pore (typically 6–10 μm in diameter), providing the possibility to perform neutron counting with high spatial resolution. Different event centroiding techniques of the charge landing on a patterned anode enable accurate reconstruction of the neutron position, provided the charge footprints do not overlap within the time required for event processing. The new fast 2×2 Timepix readout with >1.2 kHz frame rates provides the unique possibility to detect neutrons with sub-15 μm resolution at several MHz/cm^2 counting rates. The results of high resolution neutron radiography experiments presented in this paper, demonstrate the sub-15 μm resolution capability of our detection system. The high degree of collimation and cold spectrum of ICON and BOA beamlines combined with the high spatial resolution and detection efficiency of MCP-Timepix detectors are crucial for high contrast neutron radiography and microtomography with high spatial resolution. The next generation of Timepix electronics with sparsified readout should enable counting rates in excess of 10^7 n/cm^2/s taking full advantage of high beam intensity of present brightest neutron imaging facilities.

1. Introduction

While X-ray radiography can be performed with sub-μm spatial resolution, at the present time the resolution of neutron radiography is yet to be improved to sub 10-μm levels, required for some applications such as fuel cell imaging [1–5], lithium ion battery research [6–10] and many others. The high degree of collimation and brightness now increasingly available from thermal and cold neutron beamlines [11–14] provides the opportunity to perform neutron radiography and microtomography with high spatial resolution—but only if the neutron detection systems can register images with the appropriate accuracy and sufficient detection efficiency. A number of different neutron detection devices have been developed and tested for high resolution imaging. Visible light-sensitive devices (e.g. CCDs and CMOS sensors) combined with various neutron sensitive scintillators, are widely used at various facilities [15–20] and can indeed achieve spatial resolution as high as 10 μm [20] by optical image magnification. Semiconductor devices coated with neutron converter layers (e.g. boron, lithium, gadolinium), have also been tested and high spatial resolution was achieved through the event centroiding [21,22]. A compromise between the scintillator/neutron converter thickness and detection efficiency has to be found in order to avoid self- absorption or light/charge spreading in the scintillator/converter layer.

It has been reported that detectors with neutron-sensitive Microchannel Plates (MCPs) can detect neutrons with sub-15 μm spatial [23,24] and ~1 μs timing resolution [25]. Among advantages of MCP detectors are their high detection efficiency (up to ~70% for cold [26] and ~50% for thermal neutrons [27]), very low background rates (<0.1 c/cm^2/s), the absence of readout noise and high timing resolution. The geometry of Microchannel Plates provides relatively long neutron absorption path (~1 mm—typical MCP thickness) and short escape distances for the products of the absorption reaction (~2–3 μm—thickness of the MCP walls). The secondary electrons produced by the reaction products are amplified within a single MCP pore (typically 6–10 μm in diameter) thus providing the opportunity for detection with high spatial resolution. Doping microchannel plates with ^{10}B, as had been suggested earlier [28,29] and which is now becoming commercially available from Nova Scientific, provides conversion of thermal/cold neutrons into alpha and ^{7}Li particles with the ranges of ~3.5 and ~2 μm,

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respectively, for the typical MCP glass composition, matching the dimensions of present neutron sensitive MCPs produced by Nova Scientific. The amplified signal (typically $>10^3$ electrons per detected neutron) has to be encoded by readout electronics. Various MCP readout technologies have been developed, mostly for photon/electron/ion counting, [30–35] and can be used just as well for encoding the signal produced by neutrons. The input flux rates typically ranging from 10^6 to 10^8 n/cm^2/s of neutron imaging beamlines are unusually high for most MCP readout methods developed primarily for low flux applications (e.g. EUV and soft X-ray astronomy). However, it has recently been demonstrated that the Timepix readout [36] developed by the Medipix collaboration, can encode photon positions from the MCP signal with ~55 μm resolution at such high fluxes [35]. Our neutron radiography and microtomography experiments with MCP-Timpiex detector [37] demonstrated the high count rate capabilities of those detectors for neutron imaging with spatial resolution defined by the 55 μm pixel size of the Timepix ASIC. However, in the event centroiding mode capable of sub-15 μm resolution [24] the count rate capability was limited to only a few kHz/cm^2 due to the relatively slow serial readout electronics processing rate of 30–50 frames/s [38,39]. To overcome that rate limitation we have developed a fully parallel readout system for a 2×2 mosaic of Timepix readout chips capable of >1.2 KFrames/s. This advance substantially increased the count rate of our MCP detector operating in the event centroiding mode, which was therefore able to provide high resolution neutron imaging over the 28×28 mm^2 active area. This paper presents new results for high resolution neutron imaging performed with our new fast MCP-Timepix detector, at the cold neutron beamline facilities of the Paul Scherrer Institute.

2. Experimental setup

2.1. Detector configuration and readout electronics

The detector used in the experiments consisted of two microchannel plates stacked in a 'chevron' configuration—where the pore bias angles of front and rear MCPs are opposing in order to suppress ion feedback—and installed ~1 mm above the 2×2 array of Timepix chips [36]. The Timepix ASIC consists of a 256×256 array of pixels, 55×55 μm^2 each providing 14×14 mm^2 active area. One side is used for wirebonding connections, thus allowing 2xN mosaic configurations with a small gap (~200 μm in our current readout boards, which can ultimately be reduced to 50 μm) in between the individual chips. The top neutron-sensitive microchannel plate (8 μm pores hexagonally packed on 11 μm centers, L/D=105:1, 3 degree pore bias, 33 mm diameter, produced by Nova Scientific) converted neutrons into electrons through ^{10}B absorption reaction [27,28]. Those electrons were further amplified by the second MCP (10 μm pores on 12 μm centers, $L/D=60:1$, 50 mm diameter, Hamamatsu Photonics) to an output signal of ~10^4–10^5 electrons per incident neutron. During the experiments reported in this paper the bias voltages on the microchannel plates were 1000 and 850 V for the front and the rear MCP, respectively and 600 V in the gap between the MCP and the Timepix readout. The detector assembly was mounted inside of an aluminum vacuum housing with a sapphire input window. The active area of the detector was ~28 mm diameter limited by the dimension of the top MCP, while the Timepix readout was capable of encoding 28×28 mm^2 active area. The newly developed readout electronics utilizes the parallel output signals from Timepix and is capable of processing ~1.2 Kframes/s for the 2×2 array [40]. The signals from two Timepix ASICs are extracted simultaneously over 32 lines/chip at 100 MHz frequency, enabling full data transfer off the 2×2 Timepix array within ~290 μs. That is the detector dead time and represents the minimum time interval between two acquisition frames. The single frame data is transferred over a short vacuum feedthrough cable into preconditioning FPGAs (two of them per 2×2 array) which convert single ended signals into low voltage differential signals (LVDS). The data is then transferred over a ~2 m cable to a fast FPGA board, and subsequently sent to a PC over a standard 10 Gb fiberoptic cable. Currently, all the frame processing is performed in the PC but we plan to transfer part of it to Vertex5 FPGA board or a graphics card. The acquisition software is based on the Pixelman package [41] with the custom hardware library written for our fast parallel system. Not all readout frames are displayed at the high frame rates and only a summary of multiple frames is sent to the Pixelman graphics user interface, while the rest of processing (e.g. event centroiding) is performed real time in PC memory. Multiple acquisition frames with individually controlled temporal parameters (up to 255) can be acquired for a single trigger (generated by the acquisition PC or by the external trigger). Thus different phases of a repetitive process can be imaged simultaneously. The fastest frame rate (corresponding to the smallest dead time) is achieved with externally generated trigger and multiple shutters per trigger. The latter mode was used in the present experiment for centroiding data acquisition.

2.2. High spatial resolution through event centroiding

Although the pixel size of Timepix readout is only 55 μm, imaging of individual neutrons can still be performed with the resolution being comparable with the diameter of an individual MCP pore, utilizing sub-pixel event centroiding [24]. For event centroiding we used the Time Over Threshold (TOT) mode of the Timepix readout, where the pixel signal is proportional to the amount of charge impinging on that pixel. The detector voltages were adjusted such that most registered neutrons produced charge footprints of ~3×3 to ~4×4 pixels wide (Fig. 1). The variation of charge footprint sizes observed in Fig. 1, results from neutrons being absorbed anywhere through the MCP depth or along the microchannel length of the first MCP, resulting in a nearly exponential gain variation from event to event (negative exponential pulse height distribution), due to the low probability of reaching saturation gain levels of the MCP stack. Optimization of MCP voltages somewhat alleviates the spread of gains, but some neutrons still produce only a small footprint at the readout and thus cannot be used for event centroiding. At the highest resolution mode experiments we have rejected all events which did not meet our 3×3 minimum criteria, thus reducing the detection efficiency from the peak value of 70% previously measured with our detector at the ICON beamline [26]. The position of individual neutron detection events was then calculated using a center-of-gravity method based on those event footprints, and an integrated image was built in the PC memory in real time using the derived X,Y centroid positions. The acquisition frame duration was adjusted to the specific neutron beam flux, in order to prevent event overlaps inhibiting accurate event centroiding. That ratio of shutter open time (150–2000 μs) to readout deadtime (~290 μs) was the other QE reduction factor impacting our experiments. We hope it will be eliminated in the future by the development of a new version of Timepix ASIC with a sparsified readout. We must emphasize that the data frames of neutron counts obtained with our detector, do not have any readout noise whatsoever, even at the ~1.2 KHz readout frame rates. This can be observed in Fig. 1 where only pixels with neutron detection events have non-zero values.

All radiographic images shown in this paper were normalized by the open beam images in order to eliminate the non-uniformity of detector response (e.g. multifiber modulation of microchannel plates, Timepix preamplifier gains), variation of beam intensity, etc.