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Timing resolution of fast neutron and gamma counting with plastic microchannel plates

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ABSTRACT

The performance of novel plastic Microchannel plates (MCPs) with nano-engineered conduction and emission films have been shown to match the performance of conventional glass MCPs, widely used in image intensifying and event counting devices. In this paper we investigate the timing resolution of event detection with a 5 mm-thick polymethyl methacrylate (PMMA) microchannel plate with 50 μm circular pores hexagonally packed at 70 μm center-to-center spacing, which was developed for fast neutron detection. A detector consisting of the PMMA plastic MCP followed by a chevron stack of conventional glass MCPs for event multiplication was used in the timing experiments. The resolution of event counting was measured with Co-60 (1.17, 1.33 MeV γ) source. The timing accuracy was derived from the time difference of event detection with plastic MCP and a detector with liquid scintillator (BC519) coupled to a photomultiplier tube. The measured $\sim$4 ns FWHM timing accuracy of gamma photon counting agrees well with the results of our predictions performed with the help of a fully 3-dimensonal model of the MCP amplification process. The same model and measurements of photon detection with conventional glass MCPs indicate that substantially better (sub-ns) accuracy can be achieved with smaller pores. Although we could not directly measure the timing accuracy of fast neutron detection with our plastic MCP due to the time of flight limitation of non-monoenergetic source the fast neutron timing resolution should be on the same scale due to the similarity of amplification process once the secondary electrons are produced within a pore.

1. Introduction

The novel microchannel plate (MCP) manufacturing technology enabled separate optimization of the MCP substrate geometry and the electron amplification characteristics of the pore [1,2]. The nano-engineered conduction and emission films required for the MCP operation can now be deposited using atomic layer deposition (ALD) methods, on a variety of substrate materials, including relatively low melting temperature plastics such as polymethyl methacrylate (PMMA) [3]. Similar to conventional glass MCPs, those plastic microchannel plates can detect UV and soft X-ray photons, electrons, ions, alpha particles and neutrals, which produce secondary electrons upon interaction with the input side of microchannel plates. In addition to that, the hydrogen-rich content of the plastic MCP results in the sensitivity to fast neutrons through the proton recoil reaction, and to high energy gamma photons through Compton scattering. The geometry of microchannel plate provides a unique combination of a relatively long absorption length for fast neutrons and MeV gammas ($\sim$several mm for a single plate) and a short escape path for the recoil protons and Compton electrons ($\sim$5–50 μm, the thickness of pore walls). This enables fast neutron and high energy gamma counting with relatively high detection efficiency and high spatial and temporal resolution. One of the attractive features of MCP-based event counting devices is the possibility to operate with virtually no readout noise and thus be very efficient in imaging at very low fluxes (event counting mode) as well as provide signal amplification at relatively large input fluxes (e.g. in image intensifier configurations). The timing accuracy of event counting is critical for time-of-flight applications [4–6] such as: investigation of the signal decay parameters after an external stimulation (e.g. fluorescent life time imaging [7] and active interrogation with fast neutrons and gammas [4,8–10]). The conventional glass microchannel plates can detect single events with accuracy as high as <20 ps [5,6]. The process of fast neutron and high energy gamma photon detection is substantially different from the detection of UV, soft X-ray photons, electrons and ions. In the latter case the secondary electrons are created at the

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front surface of the MCP and the events are amplified through the entire channel length. Interaction of fast neutrons and high energy gamma photons with the plastic MCP substrate can produce secondary electrons along the entire length of the pore (bulk detection) and therefore timing characteristics can be substantially different. In this paper we verified experimentally the upper limit of timing resolution of event detection with the novel plastic (PMMA) microchannel plate with 50 μm pores. The measured data agrees well with the results of our fully 3-dimensional Monte Carlo computer simulations, indicating that the pore diameter is the crucial parameter defining the achievable timing accuracy, as in case of conventional glass MCP technology.

2. Experimental technique

Until recently microchannel plates were only manufactured from lead glass substrates. The glass composition defined both the mechanical and electron amplifying properties of MCPs. The development of nano-engineered conduction and emission films, deposited by the Atomic Layer Deposition enabled separation of MCP functionality from the composition of the substrate [1–3]. In addition to conventional lead glass substrates coated with ALD films novel MCPs were manufactured from borosilicate glass. Both of those glasses were compatible with deposition temperatures up to 300 °C. In addition to conventional detection of UV, X-ray photons, charged particles and neutral atoms the sensitivity of MCP was also recently extended to thermal and cold neutrons by addition of neutron-absorbing ^{10}B and Gd atoms into the glass mixture [11–13]. In the present manuscript we describe the novel mcirochannel plates, which were manufactured from a plastic substrate. That required development of special ALD deposition recipes enabling conformal coating of low-temperature substrates, which soften at temperatures as low as ~150 °C. A 5 mm thick 25 mm in diameter (20 mm active area) plastic microchannel plate with 50 μm quasi-circular pores hexagonally packed at 70 μm centers was manufactured from a PMMA substrate, Fig. 1. The process of high energy gamma and fast neutron detection starts with the production of a Compton-scattered electron or a recoil proton, respectively. These highly energetic particles have a large probability to escape into an adjacent pore and create secondary electrons upon collision with the pore walls. The conduction and emission films deposited on those MCPs are typically in a ~100 nm range and therefore the reaction products easily escape from the plastic walls and excite the secondary electrons in the adjacent pores. Consequently these electrons create an electron avalanche as they are accelerated by the electric field in the MCP pore, Fig. 2. Since that interaction can happen anywhere in the bulk of the MCP the number of output electrons can have substantial variations. The unique capability of ALD films to conformally coat structures with very large aspect ratios [14] enabled deposition of very uniform films in pores, which are 100 times longer (5 mm) than their diameter (50 μm). At the same time, MCP with relatively large active areas (exceeding 10×10 cm^2) can be coated with ALD films providing there are large substrates available. Our experiments indicate that the production yield of MCPs with ~25 mm diameter is quite high and repeatable resistance and gains were measured with MCPs manufactured from glass substrates.

A chevron stack of conventional glass microchannel plates (40:1 L/D, 10 μm pores, 13° bias) placed behind the PMMA MCP was used in our measurements for the event multiplication (Fig. 3) in order to minimize the gain variation. A phosphor screen positioned 6 mm behind the glass microchannel plates was used for charge collection, as well as for some event localization with a limited spatial resolution (due to a large charge spread in the 6 mm gap). The individual high energy gamma and fast neutron events were imaged with a video camera focused on the output side of the phosphor screen, Fig. 4 The response of the MCP to gammas and fast neutrons was observed to be quite uniform, although the ultimate characterization of the ultimate spatial resolution and uniformity is to be studied in our near future experiments. The dark counting rates of the detector was on the scale of ~1 count/cm^2/s at the full gain of ~10^6 used in the measurements reported below. The gain of plastic MCP was not measured separately from the gain of the entire detector in the present measurements. The main task of the plastic MCP in this experiment was to convert fast neutrons and high energy gammas into an electron signal amplified later by the conventional glass MCP chevron.

The timing resolution of the event detection with plastic MCP was measured by a coincidence technique. A Co-60 gamma source (41.2 μCi) producing two gamma photons (1.17 and 1.33 MeV) was placed in between the plastic MCP detector and a detector with BC519 liquid scintillator followed by a PMT, which was used

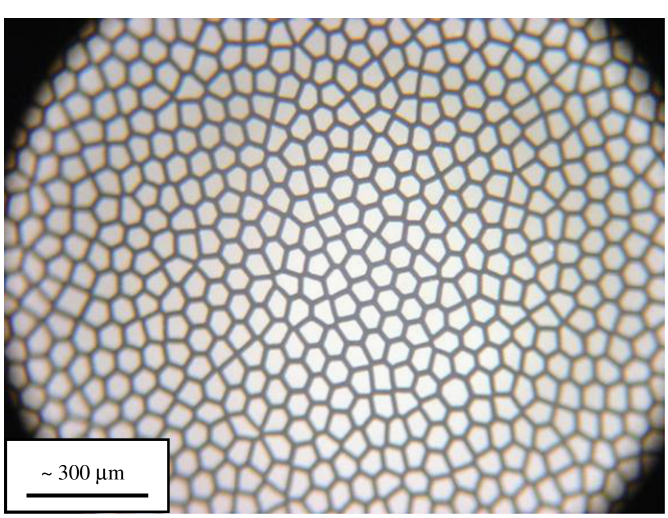

Fig. 1. Optical microscope image of the polymethyl methacrylate (PMMA) plastic MCP substrate with ~50 μm pores and ~70 μm center-to-center spacing. The MCP is 5 mm thick and 25 mm in diameter. Although the pores shape is not exactly circular, the size of the pores is relatively uniform across the active area. The plastic MCP was functionalized by ALD conduction and emission films.

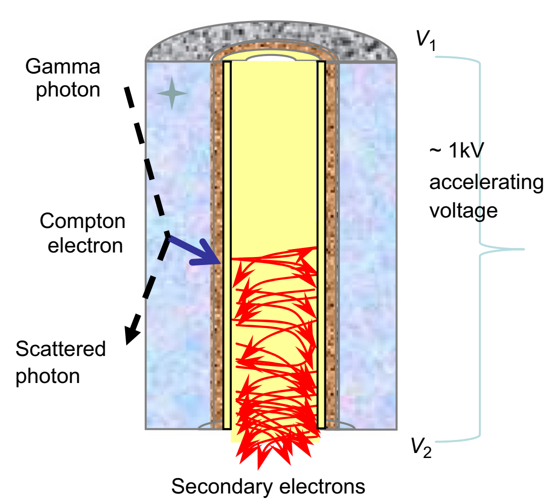

Fig. 2. The principle of high energy gamma detection in plastic MCP. Compton scattering in plastic initiates an electron avalanche inside the pore. The scattering can happen anywhere in the bulk of the MCP and therefore timing resolution is limited by the avalanche development time inside the pore. Compromise between the pore size and timing resolution has to be found as smaller pores will have thinner MCPs (L/D is to remain constant). The sensitivity to low energy gamma photons is very low due to the absence of high-Z materials in the plastic MCP.