Optical MCP image tube with a quad Timepix readout: initial performance characterization

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ABSTRACT: A photon counting, microchannel plate (MCP) optical imaging tube has been fabricated using a $2 \times 2$ array of Timepix application specific integrated circuits (ASICs) as the readout anode. A Timepix ASIC is a $256 \times 256$ pixellated CMOS readout chip with each pixel containing an amplifier, discriminator and counter. The counter values, representing either time of arrival, total count or time over threshold, can record the position and time of arrival of the electron pulses from the MCP if the charge collected on its input pads exceed the adjustable lower threshold value. Below we present initial results of the tube’s performance, the quantum efficiency of the bi-alkali photocathode, uniformity of response, spatial and temporal resolution, and dynamic range. Planned improvement to the design based on the new Timepix3 chip will be discussed.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum); Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Hybrid detectors; Vacuum-based detectors

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1 Introduction

The Medipix2 and Timepix [1] ASICs have been successfully used as anode readouts of microchannel plates (MCPs) to detect photons from x-ray to visible, electrons and neutrons [2]. These pixelated readouts have the advantage of very high spatial resolution (ultimately limited by the MCP pore spacing), good time resolution (<20ns), and high dynamic range (from 1 to 200 million counts/s), all while operating at very low gains (< 50000). An optical imager incorporating a bi-alkali photocathode, MCPs and a single Medipix2 ASIC inside a vacuum tube was fabricated in 2008 and demonstrated [3] that these CMOS ASICs inside vacuum tubes could achieve performance levels equivalent to the windowless detectors.

An effort to construct a larger version of an optical MCP image tube using a $2 \times 2$ array of Timepix ASICs was funded by the Medipix2 Collaboration and started in 2011 with Photonis U.S.A. Pennsylvania Inc. as the industrial partner. The use of Timepix ASICs (rather than the Medipix2 ASICs) allows further performance capabilities such as time-tagging of individual events to 10ns or sub-pixel centroiding of events to achieve spatial resolution better than the 55 micron readout pixel size. The first successful vacuum tube attempt was completed in early 2013 and put through a series of standard detector performance tests that we present below after a description of the new tube.

1.1 The quad timepix tube

The detector design is based on the 50mm square PLANACON(R) tube of Photonis [4] (figure 1), with a special anode assembly designed at CERN consisting of 4 Timepix chips mounted on a special Kyocera ceramic header (figure 2) which brings out signals on 321 hermetic pins designed
Figure 1. A schematic cutaway of the Quad Timepix vacuum tube showing a drop-face window with a proximity focused photocathode directly above a chevron MCP pair. A ceramic spacer was used to elevate the $2 \times 2$ Timepix array to achieve the close ($\sim 500\mu m$) gap to the MCP output surface, while still using the existing mechanical format. The Timepix ASICs are wirebonded to the ceramic header.

to mate with a standard zero insertion force socket [5] (figure 3). The 4 dies were bonded to the ceramic using a silver glass die adhesive Hysol QMI2560 from Loctite. For the initial tube, a planar front window with a semi-transparent bi-alkali photocathode was 4.5 mm above a chevron MCP pair, though a drop face window on future tubes can be used for better spatial resolution using proximity focusing.

2 Initial performance tests

For the initial tests, the tube was installed into a specially designed housing that coupled the output and input signal lines to a standard Medipix interface board using a zero insertion force socket. The housing also contained a resistor bias network such that we could bias the photocathode, the MCP chevron stack and the 0.5 mm MCP-Timepix anode gap to control the exiting charge cloud width. This housing was set up in a dark box where various lamps and optics could be used to project focused light onto the photocathode. We fixed the photocathode — MCP gap voltage at 600V ($\sim 133V/mm$ field) and the rear gap at 400V (800V/mm) for most of these tests.

2.1 Sensitivity

The quantum efficiency of the photocathode was measured at the factory before delivery and is shown in figure 4 and is consistent with a good bi-alkali photocathode. Whether the ejected photoelectron creates an MCP event depends on it going down a microchannel, which is proportional to the open area ratio of the top MCP, ($\sim 60\%$). The next efficiency factor is the ability of the Timepix readout to detect the amplified electron cloud. This is dependent on the MCP stack gain, the pulse height distribution, the charge cloud spatial extent, and the pixel charge threshold. figure 5 shows the measured flux (events per second) as a function of the voltage across the MCPs, which increases until reaching a plateau, signifying that most events are detected above 1300V MCP stack voltage.

2.2 Uniformity

A yellow LED was used to scatter off a diffuse screen to provide a uniform light distribution across the tube input window (figure 6). As mentioned above, the sensitivity per pixel is dependent on the threshold of the pixel and the gain of the MCP stack. The extreme variation observed at the
Figure 2. Image of the brazed tube assembly with the four timepix chips before the installation of the MCPs and the input window with a photocathode. Note the wirebonds on either side of the abutted chips and the ceramic spacer.

Figure 3. The finished tube: left is the input side, right is the output header on the bottom side.

lower gain seen on the left image of figure 6 is due to the strong gain variation of the MCP output. This gain variation is caused by a Moiré beating of the two MCP pore patterns, i.e. sometimes a microchannel pore on the top plate illuminates one, two or three pores on the bottom plate, resulting in different gains. If the gain (voltage) is increased such that the charge threshold of the readout pixel is exceeded for all possible pulseheights, then one count is detected for each event and the response becomes more uniform across the detector. Rotating one MCP by 90 degrees with respect to the other can also decrease the gain Moiré pattern.

2.3 Spatial resolution

The spatial resolution of this tube was not expected to be good, given the large 4.5mm gap of the photocathode-MCP distance for the “proximity” focus. We projected onto the front photocathode an image of a circular pinhole mask array, spaced approximately $2 \times 1$ mm (figure 7). The input
Figure 4. The quantum efficiency of the Quad Timepix Tube photocathode.

Figure 5. Detected events per second vs. high voltage across MCPs. Saturation of this curve above \( \sim 1300 \text{ V} \) indicates that the pulse height of most incoming events exceeds the fixed charge threshold.

spots were 50 µm diameter except for a row in the center where they were 25µm. After focusing and raising the voltage of the photocathode gap to 600V, the width of the spots was minimized at 165 µm FWHM.

2.4 High spatial resolution capability using time over threshold mode

When a Timepix pixel is in Time over Threshold mode, the pixel counter counts clock cycles for the duration that an event pulse is above threshold, which for the Timepix amplifier design is proportional to the input signal amplitude. This ability to measure amplitude allows the charge distribution from an MCP charge cloud to be mapped and centroided to determine a position of arrival finer than the pixel pitch of 55µm. This had been demonstrated before using windowless UV detectors [6] but not in a sealed tube. In this mode, the input flux must be low enough such that events do not overlap in a single frame, contaminating the centroid determination. Downstream
Figure 6. Flat field response of the Quad Timepix in counting mode at two different MCP gains. The strong pattern on the left image is due to the coherent Moire beating of the hexagonal microchannel pore spacing, resulting in gain variations such that in some regions the gain is barely high enough to exceed the event charge threshold (left image). Raising the voltage of the MCPs by 200 volts increases (right image) the gain in all regions such that most events are counted, reducing the response variation. The unresponsive dark areas at the intersections of the 4 ASICs is believed to be caused by contamination of the die adhesive wicking to the surface.

Processing off chip calculates an X,Y position, which can be accumulated into a two dimensional histogram of arbitrary format, limited by the signal to noise ratio of the amplitude determination.

Figure 8 is such an image of a uniform flat field, binned to 8192 x 8192 (3.4 µm pixels). In this case, the Timepix readout has resolved the input MCP pores, whose hexagonal spacing is 32 µm. Note the hierarchy of spatial resolutions: the ability to resolve input light flux is ultimately limited by the large photocathode proximity gap (165 µm) which is sampled by the finer MCP pore spacing (32 µm) which is then measured to better than 5 µm by the readout ASIC. Future tubes can take advantage of a drop face window with a 0.5mm proximity gap sampled with 6 µm pore microchannel spaced on 8 µm centers. We expect such a tube to exceed a spatial resolution of ~ 25 µm FWHM at event rates of 600 events per frame or 2.4MHz (assuming a kHz frame rate).

2.5 Event timing

Microchannel plate detectors are known for their excellent event time resolution that can be less than 100ps, so it seems natural to test the Timepix ASIC in its Timing mode, which is limited by its clock speed, in this case 50 MHz (20ns). In Timing mode, an event above threshold starts an accumulation of clock counts until stopped by the shutter closure. (Because of this logic, earlier events in time register higher numbers, so, in plots below, time increases from high numbers to low numbers, or right to left.) Small amplitude charge inputs just near the charge threshold will cross the threshold later than a much larger event, resulting in a timing “walk” where measured time is dependant on amplitude [7]. This can be observed in figure 9, where a single charge event from an MCP lands on many pixels, with the larger signals in the center and smaller signals on the periphery Therefore, Gaussian shaped charge clouds result in a “halo” of later times around the central core of earlier times. On the right of figure 9 is a distribution of the pixel times associated with a single event, with many pixels up to 100ns late. A possible solution would be to adopt
the earliest time associated with a single charge event, which will probably be in the center with the highest amplitude. The next version of the ASIC, the “Timpix3” [8], will measure both time and amplitude in each pixel, allowing the possibility of doing a walk correction to the measured time interval.

2.6 Scintillator readout

A possible application of an imaging phototube is as a scintillator readout to determine the position, amplitude and arrival time of a high energy photon such as a gamma or x-ray. We tested this by coupling a 2 inch diameter bismuth germanate (BGO) crystal to the input window of the Quad Timepix tube. As we brought a radium watch dial close to the scintillator, we detected pulses of contemporaneous optical photons corresponding to individual gamma ray interactions in the BGO crystal. In Timing mode, even two or more gamma events in a single frame can be separated by measuring the time of arrival of the optical photon hits. Figure 10 shows the distribution in time of all of the pixels associated with one gamma-ray event. In this case, the time distribution is much larger than the walk distribution of figure 9, and is a real effect, consistent with the fluorescence optical decay time of BGO of 300 ns.

2.7 Imaging field test

As a final test, we mounted a lens (focal length 500 mm) on the front of the detector housing and brought the camera and readout electronics into the field to image the Oakland-San Francisco Bay Bridge (figure 11, left). We also used a commercial CMOS camera to capture a color image of the foggy night scene for comparison. The obvious difference is the poor spatial resolution of the Quad Timepix tube, discussed above. Note the insensitivity to the red lights in the image, as expected given the bi-alkali QE of figure 4.
**Figure 8.** Uniform input flat field response in TOT mode where a two dimensional histogram is made from the list of X and Y centroids calculated for each event. In this mode individual microchannel pores are resolved (zoom on upper right). An optical microscope image of an equivalent MCP input surface shows a similar pattern of pores (lower right). Note that though the anode readout of the event centroid has very high resolution, the actual detector resolution to input optical photons is limited by blurring caused by the input proximity gap between the photocathode and top MCP.

**Figure 9.** Individual events in Timing mode. In this zoomed Timepix image (left), the color represents the time stamp associated with each 55 μm pixel’s charge hit. The histogram on the right side is a histogram of the time distribution of a single event arriving over many pixels, with each bin 20 ns. (Time increases towards the left and the vertical axis is the number of pixels at that time). The edges of the charge event are late because of time walk of the discriminator to charge pulses near threshold.

To demonstrate some the unique aspects of this camera, we took the same image in timing mode, where we accumulated an event list in X,Y,T mode, and created a 3-D histogram “data cube” with the time axis measured against the power grid line frequency (60Hz in the U.S.A.) and binned as its phase. We then could extract a light curve of amplitude (number of counts per voxel) vs. phase at various X,Y locations. Figure 12 shows three such light curves of 3 different pixels.
Figure 10. Distribution of the arrival times of the many photons from a single radium gamma ray event. Time increases towards the left and the bin size is 20ns. The 280 ns FWHM of this gamma ray event is consistent with the 300 ns optical decay time of BGO.

Figure 11. Image of the Oakland-San Francisco Bay Bridge using the Quad Timepix tube (left) and a commercial CMOS color camera (right).

in the Bay Bridge image. Not only did we detect the double pulse of light per cycle typical of high intensity gas discharge lamps, but we also saw three different phases used by the local power company, separated by 120 degrees of phase

3 Conclusions

Using a pixellated CMOS ASIC readout like the Timepix, we have been able to fabricate a prototype optical photon counting image tube that can determine position and time of arrival of optical (350–550nm) photon events at low MCP gain. The readout spatial resolution exceeds that of the proximity gap resolution as well as the sampling frequency of the MCPs, both of which could be easily improved with a drop face window and finer pitch MCPs, respectively. The timing resolution is ultimately limited by the Timepix clock frequency, but in practice is limited by the amplitude walk introduced by the spread of the event charge cloud over many pixels resulting in many input amplitudes per event.
Figure 12. Light curves from 3 different pixels of the Quad Timepix image from figure 11. The periodic intensity fluctuation is due to the AC power grid voltage (60 Hz) and three different phases separated by 120 degrees. Peak to peak period is 8.33 ms

The next generation of this ASIC, the Timepix3 [8], can measure time and charge amplitude concurrently in each pixel, which would allow a time walk correction and a sub-pixel high spatial resolution centroid per event. The timing stamp can be as fine as 1.56 ns and the chip has a sparsified event readout, with an expected event output rate of \( > 8 \text{MHz} \) per ASIC (10% spatial overlaps). There is also the possibility of using thru-vias instead of wirebonds at the chip edges, which might allow ASIC arrays larger than the \( 2 \times 2 \) used in this first prototype.

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References


