A Hybrid Photodetector using the Timepix Semiconductor Assembly for Photoelectron Detection

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Abstract

We present a hybrid photomultiplier concept which employs the pixelated semiconductor detector Timepix for the detection of the photoelectrons. Timepix has been developed by the MEDIPIX collaboration. It comprises 256 × 256 pixels with 55 μm pixel pitch. By setting an energy threshold it allows to identify single electrons and therefore single photons with high resolution. An appropriate electric field between the photocathode and the Timepix configures an image of the photocathode on the Timepix. A high frequency clock enables the determination of the arrival time of each photon. Test measurements and further design considerations are presented.

Key words: Photo-detection, Hybrid Photon Detector, HPD, Timepix, Medipix
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1. Introduction

Standard photomultipliers are widely used in particle and astroparticle physics. A modified design makes use of a semiconductor instead of a dynode system for photoelectron detection. The semiconductor solution has proven its outstanding ability to separate the single photoelectron signature from noise and from two or more photoelectrons. We present here a hybrid photon detector (HPD) containing a pixelated silicon semiconductor in combination with the TIMEPIX electronics ASIC which shows some further advantages [1].

2. Single photoelectron resolution

A schematic drawing of the proposed HPD concept is shown in Fig. 1. For noise considerations we compare it to a standard photomultiplier (PMT). The photoelectron inside the PMT is directed to the first dynode where secondary electrons are produced with a gain factor g, which has a typical value of $g \simeq 5$. These electrons meet the second dynode and are multiplied there again and so on. The output signal U is proportional to the gain g and the number of dynodes: $U = g^n$. The relative fluctuation dU of the signal is due to the fluctuation dg of the gain at the dynodes. In case of a Poisson-type fluctuation one obtains

$$\frac{dU}{U} = n \ \frac{dg}{g} \ = \ n \ \frac{1}{\sqrt{g}}$$

In the HPD the photoelectron is accelerated in an applied electric field (voltage of 10 to 20 kV) and is absorbed in the silicon sensor producing some thousand electron-hole pairs there. This process refers to $n = 1$ and $g \simeq 3000$ resulting in a much smaller signal fluctuation.

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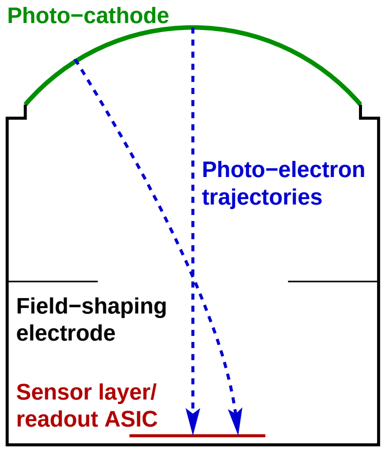

Fig. 1. Schematic drawing of the proposed HPD. It contains a photo-cathode, a field-shaping electrode, sensor layer, and readout ASIC. Two exemplary photo-electron trajectories are drawn to illustrate the cross-focussing optics.

2.1. *Position Resolution*

An important parameter of the silicon sensor is its capacitance and the related electronic noise. Accordingly, the area of the sensor is practically limited to a few mm^2. A sensor composed of pixels of small enough size can overcome this problem and offers a position resolution in addition. Examples of such HPDs are described in [2,3]. As a first approach we consider a geometry of our HPD shown in Fig. 1 which is a design similar to the one in [2]. The cathode diameter is 5cm and the distance to the silicon sensor is 7 cm. We calculated the cross-focussing electric field with the finite element code COMSOL and implemented the obtained electric field in a GEANT4 code to simulate the propagation of electrons released from the photocathode and drifting to the sensor. We assumed an isotropic angular distribution of photoelectrons with photoelectron momentum proportional to $cos(\Theta)$, Θ being the angle between the photoelectron momentum and the direction perpendicular to the cathode surface. This momentum distribution takes account of the effect that electrons which leave the photocathode under large angle have probably lost some kinetic energy in the cathode. Fig. 2 shows an example of a ring type distribution of photons on the photo cathode and the related distribution of electrons on the silicon sensor. The derived point spread function projected to the photocathode area has a width of 0.5 mm FWHM. Further optimization of the electric field configuration will be performed.

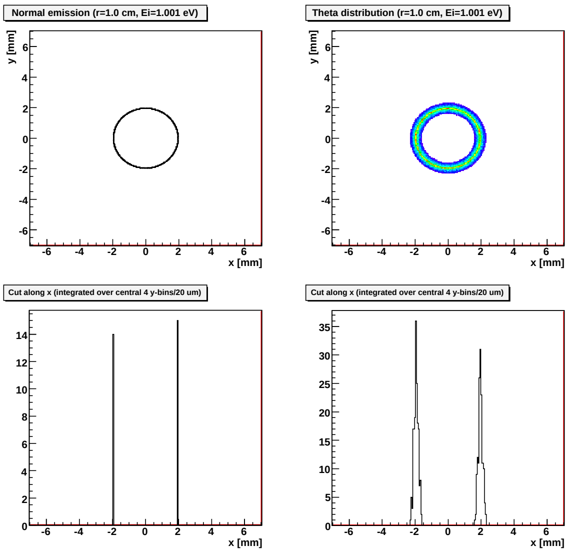

Fig. 2. Image of an illuminated ring on the photocathode. Left: neglecting the photoelectron momentum distribution; right: including the photoelectron momentum distribution. bottom: intensity profile of the top images along the line y=0.

2.2. *The Timepix Detector*

The pixelated silicon sensor is connected to a special read out ASIC called Timepix which was developed by the Medipix collaboration [4]. Medipix is a world wide collaboration of institutes producing and evaluating semiconductor pixel detectors for a variety of applications, see [5]. The Timepix detector consists of a 300 μm thick silicon layer and a pixelated electronics layer ASIC which are electrically connected to each other in each pixel by bump bonds. The assembly contains a matrix of 256 × 256 square pixels with a pixel pitch of 55 μm, see Fig. 3. Each pixel electronics cell comprises a charge-sensitive preamplifier, a discriminator and a counter. Frames of a given frame time are started one after the other. During the frame time the counter can count clock pulses. The counter is read out at the end of the frame time.The Timepix can be operated in two modes depending on the use of the internal clock. In the Time-over-Threshold mode the clock pulses are counted only during the time when the signal is above threshold while in the timing mode the counting of clock pulses starts when a signal exceeds the threshold and runs until the end of the frame time. Thus, the Time-over-Threshold mode enables the measurement of the legth of a pulse and the timing mode enables the determination of an event time with a precision inverse of the clock frequency.

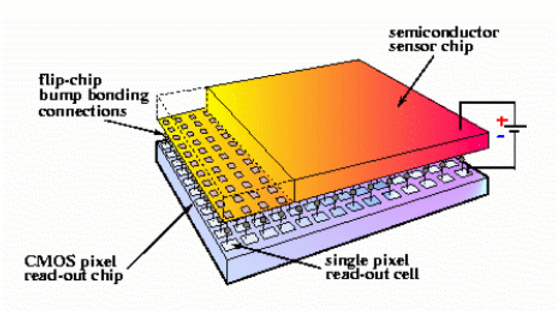

Fig. 3. Schematic drawing of the Timepix detector.

2.3. *Test Measurements*

A test of the proposed HPD was performed [6] in collaboration with C. Joram and J. Seguinot from CERN. A CsI photocathode was illuminated with a flash lamp. The released photoelectrons were accelerated in a proximity formed electric field (6 to 20 kV voltage) onto the silicon sensor of the Timepix. The time signal from the flash lamp was delayed by 3 μs and was used as shutter signal for the Timepix. Fig. 4 shows the obtained time distributions. A prompt peak coinciding with the time of the flash is clearly visible. The width of the distribution extends to more than 100 ns. Further, Fig. 4 shows that the peak position depends on the acceleration voltage indicating a time-walk effect. The dotted line in Fig. 4 (left) shows a relatively small time distribution ($\sigma = 10.5$ ns) for the events which triggered single pixels only. Those events refer to electrons which deposit their total kinetic energy in one single pixel leading to a steep rise of the voltage signal. This is an additional indication that time walk influences the time distribution.

We performed a detailed model calculation of the energy deposited by the photoelectron in the pixels and the charge signal arriving at the pixel electrode. Further we calculated the time response of Timepix to this energy distribution, see [6]. With this simulation we can reproduce the measured time distribution as shown in Fig. 5. Considering the pixel geometry of 300 μm thickness compared to 55 μm width it becomes quite obvious that the electron-hole pairs which are created in the top 10 μm of a pixel diffuse during their drift to the electrode and very probably end at more than one pixel electrode. A straight forward solution to this problem is a thinner silicon sensor and a larger pixel pitch.

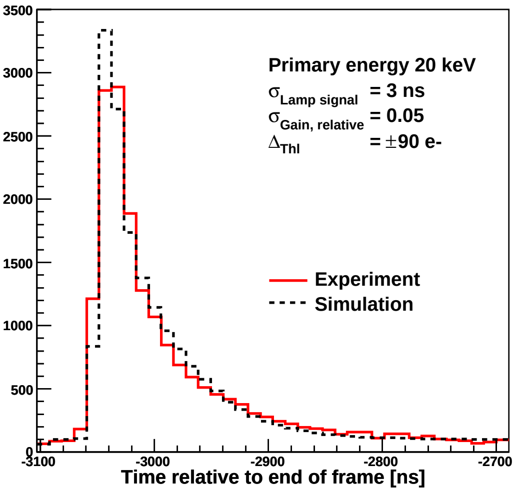

Fig. 5. Comparison between the experimental data for 20 keV (solid curve) and the simulation (dashed curve).

3. From Timepix to Photopix

The Timepix ASIC has been developed for application in a gaseous tracking chamber with Micromega grid [8]. We used it in our tests because it meets a number of the requirements of the HPD. For the application in a HPD with high time resolution a further development of an optimized ASIC which we call Photopix is desired. The Photopix should comprise parameters presented in table 1. Besides an optimized silicon thickness and pixel size the rise time of the pulse shaper should be reduced and the clock frequency enlarged. The implementation of two counters per pixel is necessary to obtain a dead-time free system. Such an HPD is an asynchronous device which needs no triggering. It is a *digital photomultiplier* because its output is the time information of each detected photon. A further advantage of our proposed HPD compared to other HPDs with silicon sensor is due to the high parallelism of the system. The rate in each single pixel will be relatively low so that the electronics can easily process the signals. Accordingly, the rate in the total system can be quite high. A detected rate of 40 MHz would lead to 1 % non-linearity only. Further, the read-out electronics on the Timepix which collects the data from the pixels can preprocess the data (i.e. zero suppression etc) before sending them to the computer. The HPD delivers the maximum information one can achieve: for each detected photon the arrival time is measured. This information can be handled depending on the application. As an

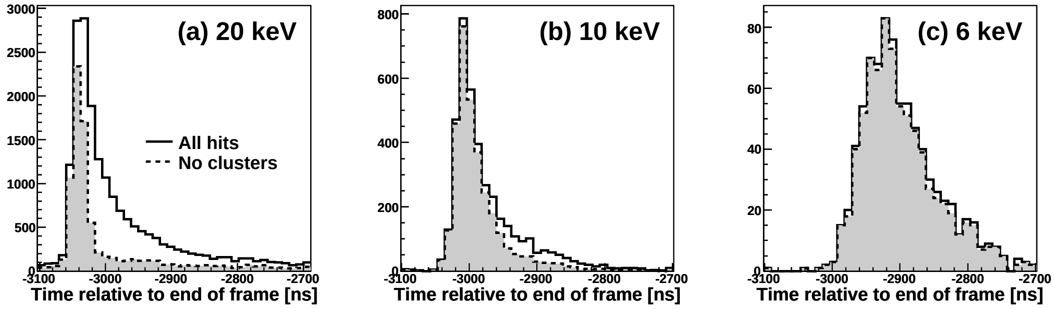

Fig. 4. Measured event time distribution relative to the end of the acquisition frame for photo-electron energies of (a) 20 keV, (b) 10 keV, and (c) 6 keV. The origin of the time axis corresponds to the end of the frame. The peak is attributed to photo-electrons that are emitted from the photo-cathode by flashes of the discharge lamp. The solid curves contain all hits, whereas the dashed curves refer to single-pixel events only.

	Timepix	Photopix
pixel size [μm]	55 × 55	110 × 110
sensor thickness [μm]	300	100
rise time [ns]	130	$\simeq$ 40
clock [MHz]	100	500
matrix read out	serial	parallel
DAQ mode	frame	continous

Table 1
Parameters of the Timepix and the Photopix detectors

example, for the measurement of light flashes the system can be used as a PMT with flash ADC.

4. Conclusions and outlook

In our experiments we have successfully demonstrated the operation of the Timepix detector in an HPD test set-up. Photo-electrons of energies between 6 and 20 keV were detected. Without the time-walk due to charge-sharing among neighboring pixels, i.e., when considering only single-pixel events, a time-resolution of 10.5 ns was measured which agrees well with the detector clock frequency of 100 MHz.
For use in astroparticle physics experiments we are going to improve the timing behaviour of the electron detection by using a sensor with reduced thickness and enlarged pixel area. Further, we will investigate the imaging behaviour in a prototype set-up with cross-focusing field configuration.

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