

FAST POSITION AND TIME SENSITIVE READ-OUT OF IMAGE INTENSIFIERS FOR SINGLE PHOTON DETECTION

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ABSTRACT

We present results on novel image intensifier tubes for single photon detection. We have adopted an image charge coupling technique that allows a read-out of image intensifiers with good imaging properties and much superior time resolution than obtainable with the standard phosphor screen read-out. Although combinations of sealed microchannel plate detector tubes with position and time sensitive anode structures have already been reported, our method has the advantage that the superficial electrode array has not to be implemented inside the tube. We couple the image charge from a high-resistive anode layer through the vacuum housing to a wedge-and-strip or delay-line pattern that can be attached from outside. We show results on single photon imaging with special intensifiers produced by Proxitronic GmbH in the visible and UV for an active diameter of 25 mm. The variability of the system, especially a version with a solar-blind UV-cathode and 40 mm active diameter, should open great opportunities for detection tasks in various fields like astronomy, reconnaissance, bioluminescence, atomic physics, and material research, particularly when both good imaging and timing performance are required.

Keywords: simultaneous position and time-of-flight spectroscopy, microchannel plate, image intensifier, single photon imaging, delay-line technique, UV-detector, fast timing read-out, reconnaissance

1. INTRODUCTION

Image intensifiers are used whenever the light intensity is too low to achieve sufficient brightness contrast for a standard camera system, or the desired exposure times are too short to acquire enough light for a sufficient contrast. A most effective light amplification for IR, optical and UV wavelengths is done with a combination of photo-cathode and microchannel plate (MCP) array, the so-called 2nd and 3rd generation image intensifiers.^{1,2} The photo-cathode behind the entrance window is the “film” of an opto-electronic camera system that registers each incoming photon with a certain quantum efficiency defined by the photon energy and the cathode material, emitting an electron which is multiplied in the MCP stack. The amplified intensity is usually imaged on a phosphor screen for optical read-out. Standard video systems or directly coupled CCD chips allow to record the image information with 10 bit spatial resolution (1000 by 1000 pixels).

Although the light amplification and imaging quality (“imaging”) of this technique is generally considered to be sufficient for the vast majority of applications, this optical read-out scheme is very slow compared to the inherent timing information that the single photon detection with MCP could provide (“timing”). The timing resolution can be below one nanosecond if the electronic pulse created during the MCP avalanche process is picked up and amplified with modern timing electronic circuits. On the other hand, the typical timing precision of the optical read-out is determined by the video frequency of 25 or 50 frames per second corresponding to a timing precision of only a few tens of a millisecond, more than 7 orders of magnitude worse than given by the inherent limit of the primary detection process. Therefore we refer to the optical read-out schemes as “static” in the following chapters.

Other applications as for example the reconnaissance of fast moving objects require “dynamic” image read-out techniques, i.e. the frame rate must be dramatically increased or, even better, each detected photon position should be stored with a precise time tag for further fast digital image processing. Recently, camera systems based on CCD with frame rates of about 1000 Hz with 8 bit spatial resolution became commercially available and techniques will certainly progress further. But another physical limit for read-out speed for phosphor/CCD read-out is in the fluorescence decay time of the used scintillation material that ranges from several microseconds to 1.4 ns. So even for the “fastest” scintillator screens the afterglow will blur any fast timing measurements.

However, by means of gated optical intensifier cameras (GOI) remarkable results for time-resolved spectromicroscopy have been reported.³ A fast optical gate with a width below 1 ns is introduced between the scintillator screen and the CCD so that only the light emitted from the screen is registered for a short period, triggered from an external signal. Besides the principal limitation in time resolution due to the scintillator characteristics this technique is mainly useful only for well-controlled repetitive processes and not for a continual detection as an outer trigger signal is always needed to open the shutter and enabling the detection only for a short time interval.

If the required position resolution is rather coarse (e.g. 10 by 10 pixels), a discrete anode pattern with individual electronic read-out channels will give very precise timing information by electronically detecting the charge cloud on each anode segment. Image intensifiers with such read-out schemes are commercially available², however, the coarse position resolution is only sufficient for limited applications. Hybrid systems of discrete anode patterns and phosphor/CCD read-out finally allow a very precise photon detection in time and position (3D-imaging) combining the time resolution properties of electronic charge cloud detection (< 1 ns) and the imaging quality of the optical read-out.^{4,5} However, such systems are rather complicated and although an optimal timing resolution is maintained they still suffer from low frame rates as a “static” read-out process is involved. So far these techniques have only been applied to “open” MCP detector systems for particle detection in vacuum.

The most promising method to achieve the goal of good imaging quality and precise timing information and high detection rate for image intensifiers is an electronic read-out technique with specially shaped electrodes as anode. Several techniques exist, they have in common that they measure the centroid of the MCP charge cloud on anode patterns that are discrete but allow due to a special structure and shape a continuous position resolution. The centroiding of the electron cloud position is done by charge evaluating or timing electronic read-out circuits. In the next chapters we will describe the application of such methods to standard image intensifiers and will present a new technique that allows a very effective and simple image intensifier design. With this design one can make use of most modern electronic read-out schemes and one will finally be enabled to produce compact single photon detection devices with optimized characteristics for various applications as astronomy, atomic physics, material science, UV-spectroscopy, bioluminescence, reconnaissance and even for quality control at industrial production lines.

2. IMAGE INTENSIFIERS WITH QUASI-CONTINUOUS ELECTRONIC READ-OUT ANODES

The quasi-continuous electronic read-out schemes for image intensifiers follow the techniques that have been established for open MCP detector systems.⁶ In an image intensifier with MCPs these are sealed in a vacuum tube (fig. 1) as this is required for their operation. A photo-electron emitted from the cathode is accelerated towards a stack of one or more MCPs where it hits the micro-structured MCP surface. With a quantum efficiency of at least 60% an electron avalanche will be induced within a single channel, as an electric field accelerates the electron and gives rise to further electron emission when it hits the channel wall with sufficient kinetic energy. This yields up to typically 10 000 electrons at the exit of the respective channel, depending on the actual accelerating voltage and diameter-to-length ratio of the channel. Having more than one MCP stacked face-to-face gives rise to a much larger charge cloud as the electron output

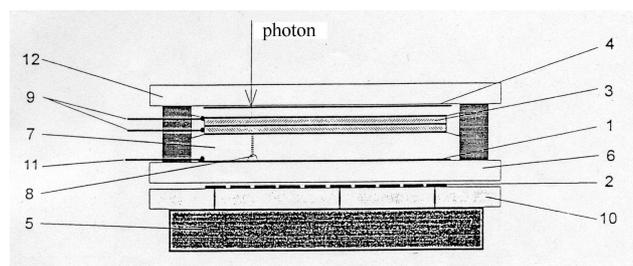


Figure 1: Sketch of an image intensifier
 12- front window, 4- photo-cathode, 9- MCP stack, 1- screen (anode), 2- rear side (image charge propagation), 10- Image charge pick-up electrode.
 Further details see text.

of the first MCP is further amplified. Saturation effects usually limit the useful number of MCPs stacked to three and the charge output to about 10^7 electrons.⁷ This electron cloud contains in its centroid the accurate position information about the respective channel of the front MCP that has “fired”, i.e. which started the avalanche process initiated by the photo-electron. Assuming the photo-electron was projected from the cathode without position deviation, the charge cloud centroid will define the position of the photon impact with a resolution that is only limited by the pore distance of the MCP (typically 10 micron). This is considerably more precise than achievable with a phosphor screen read-out where the finite cloud size blurs the optical response of the screen.

If the phosphor screen is replaced by a centroiding anode pattern with electronic pulse read-out not only the inherent position information can be maintained but also the pulse rise time follows the time structure of the charge cloud building up in about a nanosecond. Thus, also the time information on the photon detection is available with sub-nanosecond precision. A commercially available image intensifier² already uses such a centroiding anode, the resistive anode⁸, to take advantage of these opportunities. The electronic read-out principle requires a set of four charge integrating preamplifiers, pulse shapers and digitizers as the position information on the charge cloud centroid hitting the resistive sheet of the anode is encoded in charge ratios measured at corner contacts of the anode. The time information on when exactly the photon hit the detector can be deduced with sub-nanosecond precision from the MCP exit contact using modern timing electronic circuits and it can be precisely correlated to the measured position in an event-mode multi-parameter data acquisition for digital processing. The required electronic charge evaluation and digitization circuits limit the number of photons to be detected to a few 10 000 counts per second if a position resolution of 10 bit shall be maintained. Digital read-out speed limitations can further reduce the event (single photon time and position information) rate.

Although with this single photon counting technique both the time and position information is precisely maintained for each photon at an event rate of 10 kHz a significant limitation for image acquisition speed can arise for certain applications. Even with low CCD frame rates one can collect more photons per time interval than with single photon counting as each frame can contain many detected photons and the image quality is just a function of the number of totally acquired photons. This leads to long exposure times for photon counting detectors if a high image contrast is required. If the photon rate, i.e. the light intensity, increases or more than one photon is detected within a microsecond this technique reaches its limits whereas the “static” optical method can handle much higher photon fluxes without information degradation, the time information being always coarse, though. To increase the event read-out speed and to eventually detect showers of photons that arrive almost simultaneously another technique of a centroiding anode must be applied: the delay-line method.⁹⁻¹³

The delay-line technique collects the electron cloud on a discrete anode pattern. This pattern consists either of a set of perpendicular “fingers” (for x- and y-direction) that collect the charge and lead the induced electrical pulse to a pair of external signal propagation delay-lines⁹⁻¹¹, or the propagation delay-lines are directly collecting the charge and work both as “antenna” and position encoding structure.^{12,13} The delay of the signal propagation is introduced either by discrete chips^{9,10} or by forming long signal transmission lines, meander shaped on a substrate^{11,12} or wound around a solid support as a wire helix¹³ (see figure 2). The position is encoded in the arrival time difference between both ends of the delay-line, for x- and y-direction respectively. As the charge cloud is spread over several fingers/turns a centroiding allows a position resolution not limited by the pitch distance but only by the precision of the timing electronics and digitization. As only very fast electronic circuits are used, this position decoding method principally allows single photon/particle rates far beyond 10^6 per second. Due to redundancies in the read-out scheme even multiple hits can be analyzed with very low dead-time. Recent electronic developments allow to maintain this acquisition speed also for the digitization and digital image processing.¹⁴

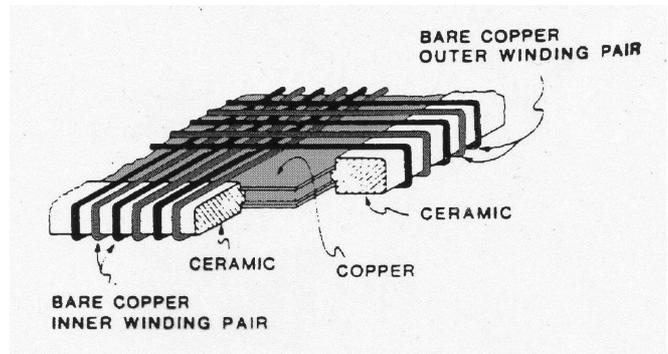


Figure 2: Helical wire anode. The wires act simultaneously as pick-up structure and delay-line for the signal propagation.¹³

Approaches to implement a helical wire delay-line anode into an image intensifier to take advantage of these favorable features have been undertaken¹⁵ and are currently renewed. But due to the thermal stresses any anode experiences in the production process of a sealed image intensifier tube this task is very difficult. The helical wire anode is rather fragile and

sensitive to tension changes during the baking process so that no commercial image intensifier with delay-line read-out is available at the moment. It is generally a difficult and expensive task to implement any delicate micro-structured centroiding anode into the image intensifier.

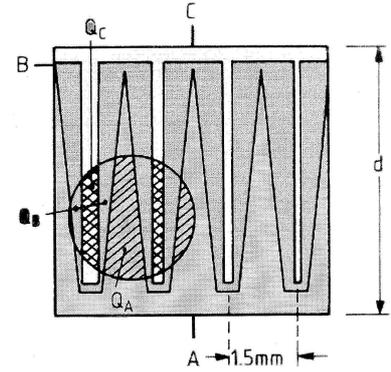
One solution is to adopt a novel technique of image charge read-out¹⁶, as already applied for open MCP detectors¹⁷, to image intensifier. The charge cloud collecting anode to be implemented into the intensifier is simply a highly resistive sheet. The image charge induced by the electron cloud footprint couples through the vacuum wall on the rear side to a separate centroiding electrode structure¹⁸. This electrode (anode) is very similar to the ones used in open detector systems since except the resistive anode most will collect and process an image charge as effectively as a real charge made of an electron cloud. Furthermore, the image charge method has further advantages that can improve the imaging characteristics of charge sharing anode patterns as the wedge-and-strip¹⁹ and the vernier²⁰ read-out.²¹

The first experiments of MCP read-out with wedge-and-strip (W&S) anodes via image charge detection²² have shown that a very good imaging is indeed easily achievable when the sheet resistance is within certain limits and the distance between the resistive sheet and the electrode pattern is favorable. Experiments with about 100 nm Germanium layer on typically 2 mm glass, ceramics and G10 substrate showed very promising results (see fig. 4). An open 45 mm MCP detector system was irradiated by high energetic α -particles. A hole mask with 1 mm holes at 2.5 mm distance was imaged showing fair linearity and resolution although a very poor MCP stack was used here. Both the resolution limit and linearity were found to be below 50 micron, the latter investigated only in the central 30 by 30 mm. So far, no systematical investigations as function of resistance and substrate have been performed but the basic characteristics could be determined: If the Ge-layer is too conductive the transmission to the electrode decreases, whereas too low conductivity reduces the transmitted pulse height at high particle flux (~ 1 MegaCount/s), probably due to charge building up on the layer as the time constant for discharging increases. If the distance between electrode and Ge-layer is too small, discretization effects occur as the image charge is not broadened sufficiently by the geometry to allow a centroiding between the distinct electrode pitches. If the distance is too large the pulse height obviously is reduced and distortions at the anode borders will occur. The dielectric constant ϵ_r of the substrate material plays also a role here and leads to an “effective substrate thickness” as function of thickness and ϵ_r .

On the base of these first results an image intensifier with high-resistive screen (see figure 1) was designed and built by Proxitronic GmbH in Bensheim, Germany. Meanwhile this technique seems to be well established at least for W&S read-out as shown in the following paragraph.

3. A PHOTON COUNTING IMAGE INTENSIFIER FOR ASTRONOMY

On the base of the new image intensifier, an existing four-segment W&S anode was placed directly at the rear side of the image intensifier, and a read-out electronics scheme from an existing open detector system for space born telescopes²⁴ a photon counting detector system was developed for the use in ground observation telescopes.²⁵ The application of MCP



$$x/d = \frac{Q_C}{Q_A + Q_B + Q_C} \quad y/d = \frac{Q_A}{Q_A + Q_B + Q_C}$$

Figure 3: Wedge-and-strip read-out principle: The charge cloud center-of-mass can be deduced from the ratio of charge on the three anode segments.

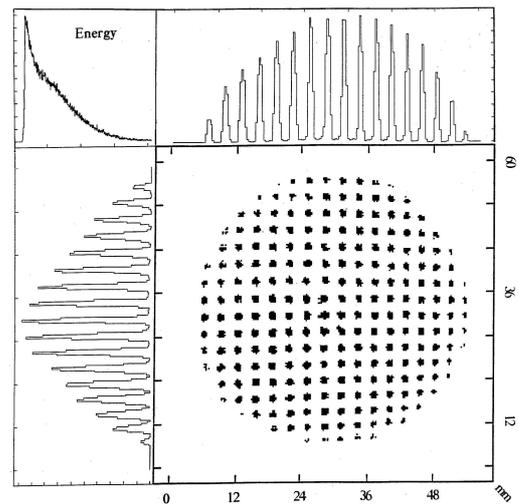


Figure 4. Imaging performance of a Ge-W&S anode with a double MCP stack of 40:1 MCP, 45 mm active diameter (see text)

detectors with centroiding and thus time sensitive read-out systems is very common for astronomical space missions due to the advantages described in the first chapters. To adopt this technique also for ground based observations (not in vacuum) a sealed detector is required.

The photon counting detector is equipped with a bi-alkali photo-cathode and has a maximum quantum efficiency of about 30 % in the blue and near UV spectral range decreasing to 10 % for green and below 1 % for red light. The active diameter is 25 mm. The distance between the photo-cathode and the first MCP is only fractions of a millimeter so that the emitted photo-electron is guided on a straight path towards the MCP by the applied voltage difference of 400 V. Almost each photo-electron is transferred into an electron avalanche in the triple stack of MCPs driven by a bias voltage of typically 2700 V. An additional 400 V between MCP stack exit and high-resistance sheet (Ge-layer on ceramics) is applied so that the electron avalanche produces a well defined footprint on the Ge-layer.

The displacement charge portions induced on the four electrodes of the 27 mm active W&S anode are processed with the same number of amplifiers, pulse shapers and analog-to-digital converters interfaced to a computer. From the digitized charge portions the position information can now be calculated with a simple algorithm similar to the one of the three-segment anode in fig. 3. A timing signal is also picked up by the electronic circuit and is correlated with real time via an on-board quartz clock.

Fig. 5 shows the image of a shadow mask in front of the detector, illuminated homogeneously by green light at photon fluxes of about 10 000 per second. The obstacle width was 70 micron, the grid constant 0.6 mm. A radial correction algorithm was applied here to correct for a slight barrel distortion, i.e. photons detected at the edges of the detector seem to be shifted inwards. The reason for this behavior is not yet understood. The open Ge-W&S detectors showed no significant non-linearities.^{22,23}

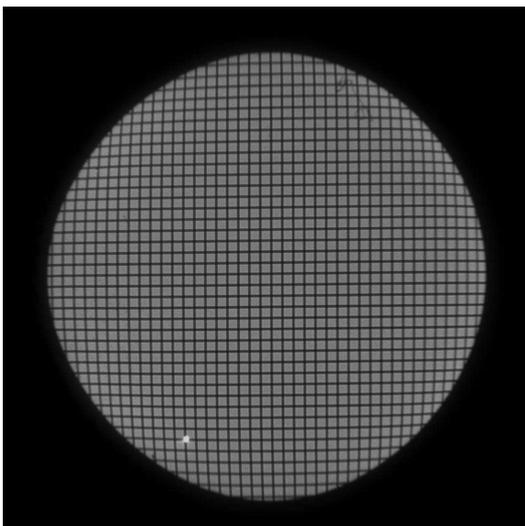


Figure 5: Imaging performance of the photon counting detector with image charge read-out by a four-segment W&S anode (see text).

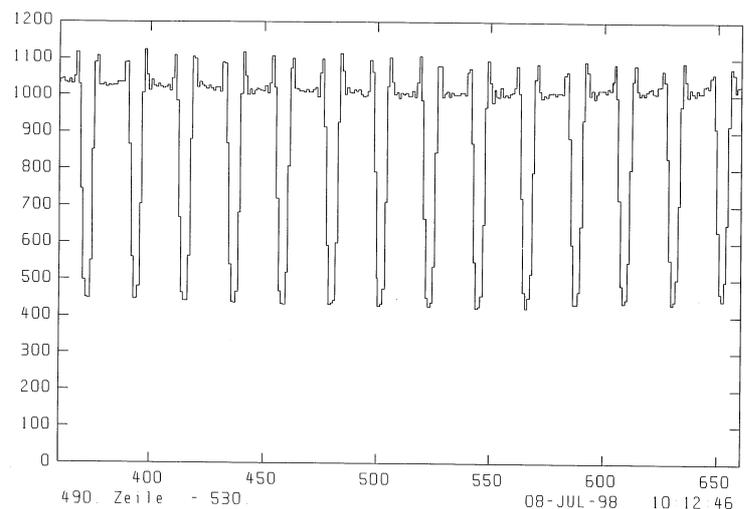


Figure 6: Horizontal cut through the grid mask. A diffraction pattern is visible due to a finite distance between mask and detector.

From figure 6 the position resolution can be deduced to be about 30 micron in the center corresponding to almost 10 bit spatial dynamics. This is mainly limited by the electronic signal-to-noise ratio. Other anode concepts as the vernier anode²⁶ could easily be applied to this image intensifier to overcome this resolution limit of the W&S anode. The position resolution would then reach the limit given by the pore distance of the MCP (here about 10 micron).

The homogeneity of the gain was found to be rather uniform in the central region, falling to about 60 % of the central gain near the edge. That reduces the achieved position resolution near the edge but does not affect the uniformity of the detector response which is very good. The bright spot in figure 5 is a defect of this detector, probably in the MCP stack

giving rise to unprovoked electron emission. Also, the bi-alkali photo-cathode emits thermal electrons at a rate of about 25 per second per cm^2 giving rise to a corresponding dark count rate, mostly uniformly distributed.

In summary, the detector concept is very successful and three fully specified photon counting detectors for astronomical or other applications currently exist. The achievable results with this detector and the application range is not so different from the commercial image intensifiers with resistive anodes, but the novel concept of an image charge transmitting high-resistive anode allows an easy and less costly image intensifier design with variable and exchangeable read-out anode. For example if improved position resolution is required a vernier anode can be applied. A vernier technique can also increase the event acquisition speed for a given resolution demand.

Unfortunately, all charge integrating techniques suffer from the limitation in the signal-to-noise ratio, effectively limiting the product of position resolution and read-out speed.²⁷ A good position resolution requires a rather long electronic charge integration time, on the other hand a reduction of this integration constant to increase the read-out speed reduces the signal-to-noise ratio and thus the relative position resolution. And as the active detection diameter of a detector increases the absolute spatial resolution gets more coarse. Even the vernier technique can improve this limitation factor only by about an order of magnitude but at the cost of a significantly more complex electronic read-out scheme.

The delay-line method, again, seems to be a promising approach. A certain signal-to-noise ratio is also required but it affects the position resolution only in second order. Only the timing resolution of the electronics limits the absolute position resolution for a given delay-line and the read-out speed is very high due to the different electronic concept. Therefore we designed a prototype delay-line anode for image charge read-out. The final goal is to produce such anodes for image charge read-out with different active sizes that are low priced and compatible with our existing electronic read-out scheme.

4. A DELAY-LINE ANODE FOR THE READ-OUT OF IMAGE INTENSIFIERS

One of the main constraints in designing a delay-line anode capable of image charge read-out was a low price and suitability for mass production. The other was that we preferred to use differential amplifier units as the first electronic signal read-out stage. These have been already developed for our existing detector system for charged particle/photon detection with open MCP-stacks and helical delay-line anode.¹⁴ As substrate we have chosen a commercial 40 micron thick polyimide foil with 12 micron copper coating on both sides that is used for flexible printed electronic circuit boards. These foils can be processed by photo-etching processes known from ordinary stiff printed circuit boards at low production costs. The circuit design can be edited with standard programs producing Gerber files.

The design follows ideas of Eland¹⁰ and Siegmund *et al.*¹¹ The fingers of the anode that collect the image charge are formed as a row of diamonds which are connected by thin tracks to an external delay-line formed by meandering tracks. The fingers for x- and y-direction are on different sides of the substrate (see figure 7). This design solves the problem of the crossovers between x- and y-fingers in an elegant way. The cross talk was found to be low enough even without intermediate ground plane.¹¹ Only very little of image charge response gets lost as the active anode area is almost fully covered by the diamonds.¹⁰ Of course, this anode can not be used to detect real charge from a MCP stack as the existing delay-line read-out anodes do.

The external delay-lines are not formed as single meander lines with ground planes¹¹ but as L/2-shifted double meander lines as used for differential signal propagation in high frequency technique. This is due to the favored read-out with differential amplifiers instead of “normal” timing amplifiers. As the signal from the fingers enters the meander a signal is influenced on the “ground” meander on the other side of the substrate. The resulting differential signal is transmitted on the shifted double meander line. If the meander design has the right geometrical shape a proper signal transmission line is thus formed with reduced signal speed and rather long total delay in the direction perpendicular to the meanders. When we started this project it was not clear if this transmission concept would work at all for our purpose with asymmetric signal input. So we designed a first prototype anode without optimizing the meander just to check if such an anode layout will perform at all. We did not verify favorable electro-magnetical properties of the meander line by calculations before the prototype was built.

However, even with this first prototype anode with neglected design of an optimized meander geometry we could already show that the concept indeed works. We mounted the anode behind the Ge-layer on a ceramic waver of an open

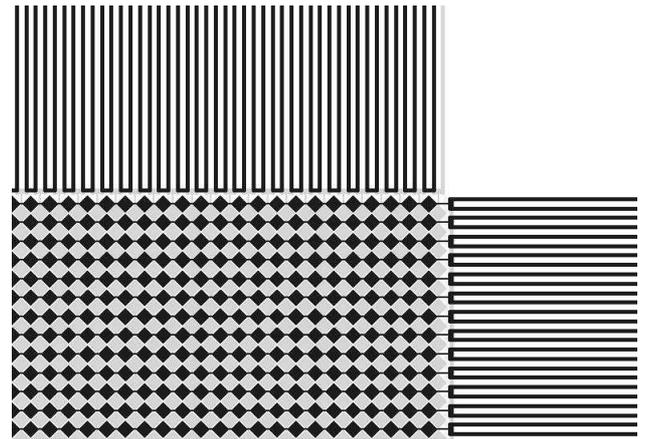
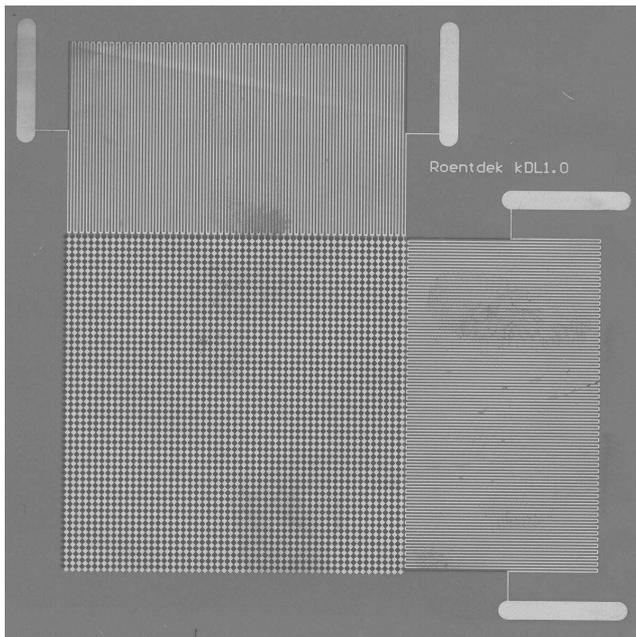


Figure 7: Layout of the prototype delay-line anode for image charge read-out. The black diamonds/tracks are on one side of the substrate, the gray shaded on the other. The pitch of the structures is 1 mm. The diamonds cover 53 by 53 mm, the height of the meanders is 30 mm.

MCP detector. The MCP stack consisted of a pair of 80:1 MCPs with 12.5 micron pore size and 40 mm active diameter. At 2600 V MCP stack bias the charge output was above 10^7 electrons per incoming particle. The MCP was irradiated by high energetic α -particles. Two sets of shadow masks were placed in front of the MCP-stack to verify the imaging characteristics, a hexagonal mask with 0.2 mm obstacle width and an underlying mesh with 70 micron wires. The voltage between MCP and Ge- layer on the 1.2 mm thick ceramic sample was 200 V, projecting the electron cloud onto the layer. The image charge was picked up by the new anode. Unfortunately, due to the poor impedance characteristics of this meander geometry its transmission was reduced and the signal heights at the ends of the delay-line were found to be rather low.

For signal read-out our standard front-end electronics box²⁸ with six channels differential amplifiers and constant fraction discriminator outputs was connected to the anode and MCP stack. The norm-signal time sequence was measured by a computer-controlled time-to-digital (TDC) unit with 130 ps resolution capable of an event rate or data acquisition (DAQ) speed of over 1 MegaCount/s in histogram mode.^{28,29} The signal propagation speed on the shifted meander line was 25 % of c (vacuum speed of light) leading to a single pitch delay of 0.8 ns/mm across the meander. The used TDC system thus limits the achievable position resolution to about 80 micron.

Figure 8 shows the image of the shadow mask. The hexagonal structured 0.2 mm wires are clearly visible and even the 70 micron grid structure at the TDC resolution limit is just visible. We expect the position resolution to be even better if a TDC with smaller time bin size is used. The bright spot is produced by a defect of the MCP. There are some linearity deviations which we can clearly attribute to electronic cross talk due to the far from perfect impedance adaptation of the meander line itself and between the meander line and the amplifiers. However, from our tests we are very confident that an improved layout will solve these problems.

Encouraged by this first success we have placed such an anode behind an image intensifier with Ge-screen of 25 mm active diameter equipped with a bi-alkali photo-cathode, similar to the one used with the W&S anode in the previous chapter. Unfortunately, the gain of this image intensifier was rather low which adds to the problem of already too low signal transparency of the actual anode. However, even with a signal-to-noise ratio of only about 6 we could achieve a rather promising UV induced image of a shadow mask with 0.4 mm obstacle width (squares) and the 0.2 mm obstacle hexagons, acquired with 600.000 events (photons) per second (see figure 8).

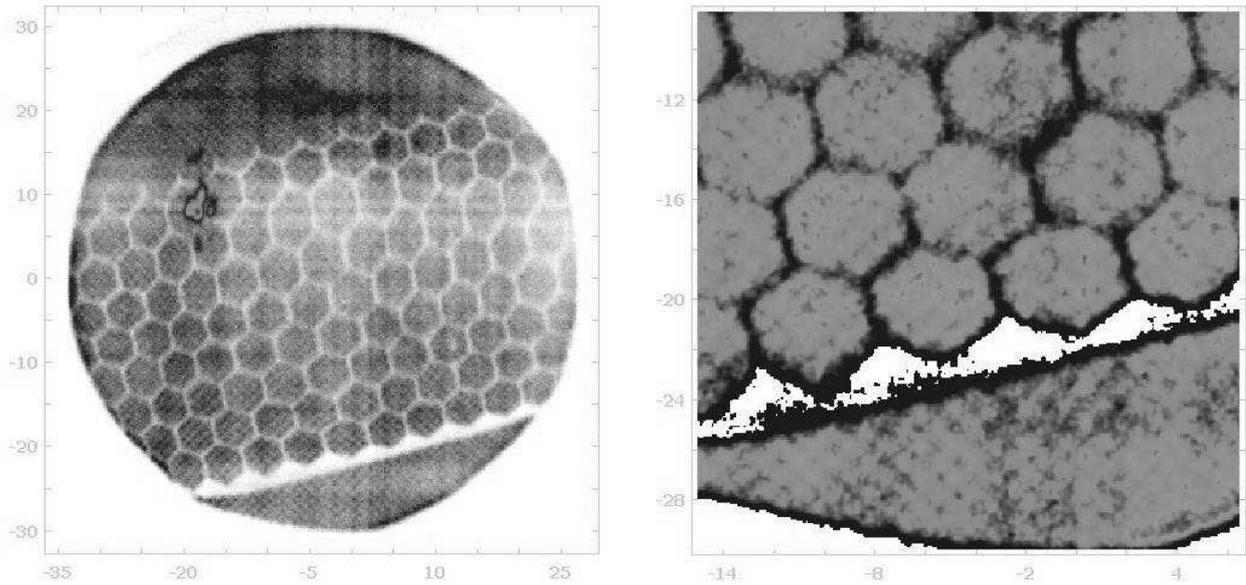


Figure 8: First results on the imaging properties of the prototype delay-line anode for image charge read-out. An open MCP detector shaded with a 70 micron grid and 0.2 mm hexagon wire structures was irradiated with high energetic α -particles. The 70 micron structure is just visible, at the resolution limit of the used TDC. The non-linearities of the current prototype are due to a still imperfect meander layout and impedance misadaptations.

5. CONCLUSIONS AND OUTLOOK

We have demonstrated that we can provide a photon counting detector system for a wide spectral band ranging from UV to IR with special photo-cathodes for certain applications which is superior to existing commercial systems. With the concept of image charge read-out from a high-resistive sheet the image intensifier production becomes much simpler. Such a “standard” image intensifier can be equipped with different read-out anodes according to the actual application needs: very high spatial resolution, fast multiple pixel read-out or fast timing and position read-out with delay-line technique. Especially from the latter concept we expect soon to have a detection system in an industrial standard that combines most of the favorable performance features, a very good position resolution with precise timing information at very high counting rates and last not least low production costs.

We will soon receive a 40 mm active diameter image intensifier with increased gain equipped with a solar-blind UV photo-cathode from Proxitronic. With an improved anode layout we expect a position resolution well below 50 micron (10 bit) for this detector. The existing electronic read-out system will combine that with a timing precision below 1 nanosec at MHz DAQ-speed. Image intensifiers with even bigger active diameters like 80 mm are technically already feasible, the relative position resolution would thus even be increased.

The main applications for these photon detectors we envision in astronomy, atomic physics, material research and reconnaissance

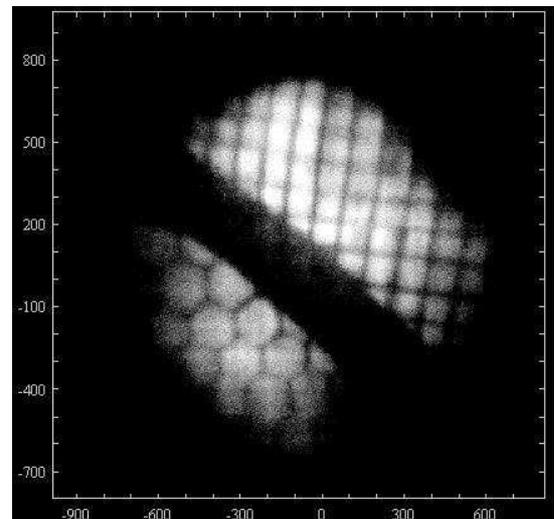


Figure 9: First image obtained with a 25 mm image intensifier with bi-alkali photo-cathode and high-resistive anode read out with the prototype delay-line anode. The detector was illuminated by UV-light, the mask consisted of a 0.4 mm square and 0.2 mm hexagonal wire array, the center shaded by another 6 mm strip. The non-uniformity is produced by the inhomogeneous illumination.

tasks. However, due to the improved performance these photon counting detectors can become useful or even superior also in application fields where “static” detector systems with CCD have been the only choice so far. We already see applications for industrial quality control at production lines.

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