

## Single photon imaging at ultra-high resolution

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### Abstract

We present a detection system capable of imaging both single photon/positive ion and multiple coincidence photons/positive ions with extremely high spatial resolution. In this detector the photoelectrons excited by the incoming photons are multiplied by microchannel plate(s) (MCP). The process of multiplication is spatially constrained within an MCP pore, which can be as small as 4 μm for commercially available MCPs. An electron cloud originated by a single photoelectron is then encoded by a pixellated custom analog ASIC consisting of 105 K charge sensitive pixels of 50 μm in size arranged on a hexagonal grid. Each pixel registers the charge with an accuracy of <100 electrons rms. Computation of the event centroid from the readout charges results in an accurate event position. A large number of simultaneous photons spatially separated by ~0.4 mm can be detected simultaneously allowing multiple coincidence operation for the experiments where a large number of incoming photons/positive ions have to be detected simultaneously. The experimental results prove that the spatial resolution of the readout system itself is ~3 μm FWHM enabling detection resolution better than 6 μm for the small pore MCPs. An attractive feature of the detection system is its capability to register the timing of each incoming photon/positive ion (in single photon detection mode) or of the first incoming particle (for the multiple coincidence detection) with an accuracy of ~130 ps FWHM. There is also virtually no dark count noise in the detection system making it suitable for low count rate applications.

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### 1. Introduction

The latest progress in position sensitive detectors based on microchannel plates (MCPs) has led to the development of novel readouts capable of resolving patterns as small as 10 μm [1] when MCPs with small pore sizes are used. At the same time the breakthrough in the CMOS-based pixellated readouts with 50 electrons rms noise levels has improved their accuracy of charge detection. A fully two-dimensional charge encoding and a fine pitch readout enable an accurate event reconstruction of the charge distribution centroid. A detailed description of the XPOL custom

CMOS VLSI ASIC used as *active* collecting electrode of the charge produced by suitable charge amplifiers can be found in Ref. [2].

The combination of a small pore electron multiplying MCP and an accurate charge sensitive pixellated readout (Fig. 1) is one of the most efficient ways to achieve a very high spatial resolution of the detection system. When the MCP is illuminated by a UV lamp, a single electron is extracted from the photocathode or from the MCP surface (as in our case), thanks to the residual photosensitivity of the MCP itself. The electron is multiplied inside a microchannel and the charge cloud is extracted at the bottom by a suitable electric field and finally collected by the fine arrangement of metal pads on the top surface of the ASIC. The ASIC samples the charge cloud and allows

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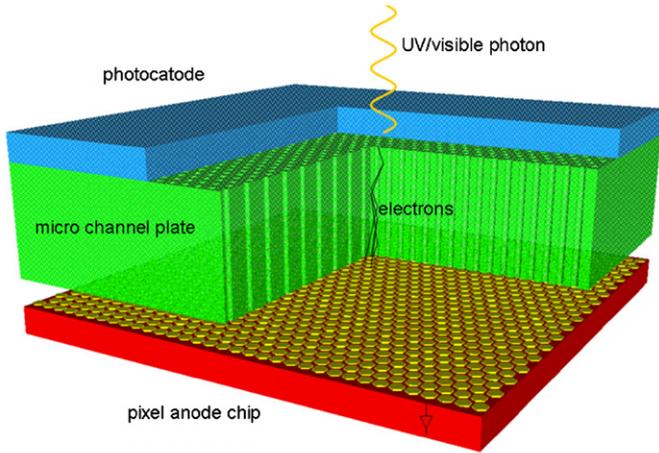


Fig. 1. Schematic view of the high-resolution detection system for single/multiple photon imaging.

to measure with high precision the charge centroid on an event-by-event basis. By collecting millions of photons it is possible to build a high-resolution image.

In this paper we present the experimental results we have obtained with different MCP stacks positioned at 1.1 mm above a charge sensitive ASIC with 105 K sensing units (lithographically patterned with  $50\ \mu\text{m}$  hexagonally packed pixels).

The readout has been used in two different modes of operation:

- the event driven mode (or window mode), when an incoming event triggers the readout sequence and a window of pixels around the charges above threshold is read out at 10 MHz speed;
- the scan mode, when either an external or an internal trigger starts the readout of the entire array of pixels, allowing the detection of the multiple simultaneous events which occur within a  $20\ \mu\text{s}$  coincidence window.

In both modes the spatial resolution has been found to be very high, provided the coincidence photons are spatially separated by  $\sim 0.4\ \text{mm}$ .

## 2. The experimental set-up

Three types of MCPs of various pore sizes have been assembled on top of the ASIC at the Space Science Laboratory in Berkeley:

- $4\ \mu\text{m}$  aperture,  $5.5\ \mu\text{m}$  pitch,
- $10\ \mu\text{m}$  aperture,  $12\ \mu\text{m}$  pitch,
- $12\ \mu\text{m}$  aperture,  $15\ \mu\text{m}$  pitch.

Except for the  $12\ \mu\text{m}$  pore MCP which has been used in single stage mode, all the other MCPs had a bias angle of  $13^\circ$  and have been stacked in a cascade of two in chevron configuration to reduce the ion feedback.

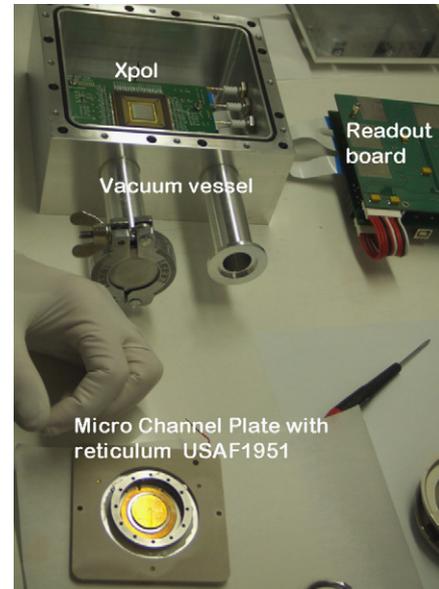


Fig. 2. Assembly phase of the device.

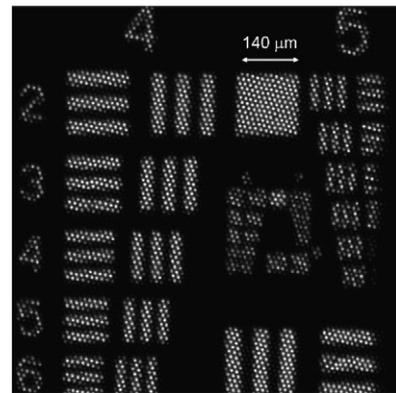


Fig. 3. UV image of the Air Force test pattern obtained with  $10\ \mu\text{m}$  MCP. The white spots correspond to the pore apertures. The spatial resolution of the detector is limited by the pore-to-pore spacing of  $12\ \mu\text{m}$ . The image was obtained at detector gain of  $\sim 5 \times 10^4$  in a single photon acquisition mode.

Fig. 2 shows the vacuum vessel opened with the chip mounted on its motherboard and a MCP prepared for the assembling.

In Fig. 3 the reconstructed UV image of a standard Air Force Resolution Mask (USAF-1951) placed in direct contact with the MCP is shown. In this measurement a chevron stack of two  $10\ \mu\text{m}$  pores MCPs ( $40:1\ L/D$ ) operating at gain of  $\sim 5 \times 10^4$  was used. The clear reconstruction of the MCP pores indicates that the intrinsic resolution of the readout system is much better than the MCP pitch ( $12\ \mu\text{m}$ ). The distribution obtained along a cut through the pores in the squared pattern in the image of Fig. 3 allows to estimate the spatial resolution of the readout. An rms of  $2\ \mu\text{m}$  was measured (Fig. 4) with a gaussian fit to the peaks whose width also includes the electron cloud size.

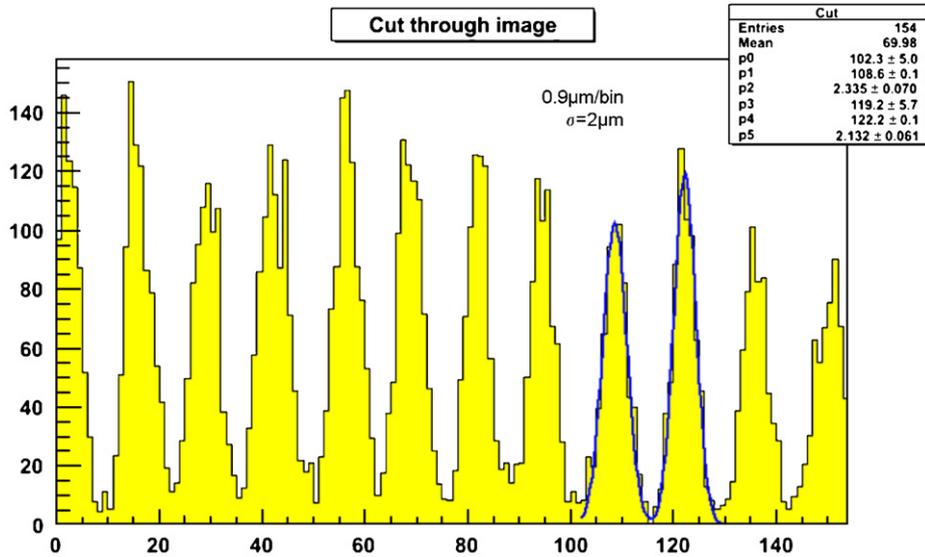


Fig. 4. A profile along a line cut across the MCP pores of Fig. 3. The spatial resolution of the readout is  $\sim 2\mu\text{m}$  rms, capable of resolving every single MCP pore.

In this test the gain was two orders of magnitude lower than the gain required for other high-resolution readouts such as the cross delay line readout [3].

It must be noted that a low gain operation should substantially extend the lifetime of the instrument, which is limited by the well-known scrubbing of MCP pores.

A higher resolving power was obtained by mounting  $4\mu\text{m}$  pores MCP on top of the ASIC. Fig. 5 shows the reconstructed UV image of the same region of the USAF mask of Fig. 3 with a zoom around groups 6 and 7.

The width of the bars in the resolution mask depends on the group number and on the position of the element within the group itself, according to the formula:

$$\text{Width (mm)} = 2^{-n-1-(m-1)/6},$$

where  $n$  is the group number and  $m$  the group element.

This means, e.g., that the last element of group 6 has a width of only  $4.4\mu\text{m}$  and a line density of 114 line pairs/mm. In Fig. 6 a cut through the first horizontal bar of group 6 shows a spatial resolution of  $3\mu\text{m}$  FWHM.

Due to the unique high sensitivity of the readout ASIC, operation is possible even with a single MCP. The problem that arises by working in these conditions is the presence of ion feedback which can restart spurious avalanches. With a single  $12\mu\text{m}$  pore MCP of 120:1 aspect ratio, illuminated with UV photons, we have checked that only a few percent of the detected events were caused by the ions. These events have been easily rejected by our data processing by setting an upper threshold to the total event charge value.

A  $1\text{mm}^2$  flat field image obtained in single stage is reported in Fig. 7.

To demonstrate the sensitivity of the system to multiple coincidence detection a full frame readout at high UV flux has been performed and data recorded on hard disk for offline post-processing analysis. We are currently

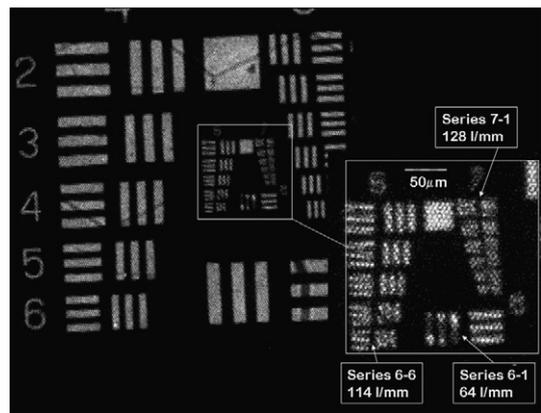


Fig. 5. UV image of  $\sim 1\text{mm}^2$  region of the USAF mask around groups 4, 5, 6 and 7 (the same as Fig. 3) obtained with a  $4\mu\text{m}$  pore MCP. The structure of the micropores is clearly visible and all the bars of group 6 elements are distinguishable (enlarged view). The hexagonal shape of the bundles which group together the tiny glass tubes are also visible in the top and left side of the image.

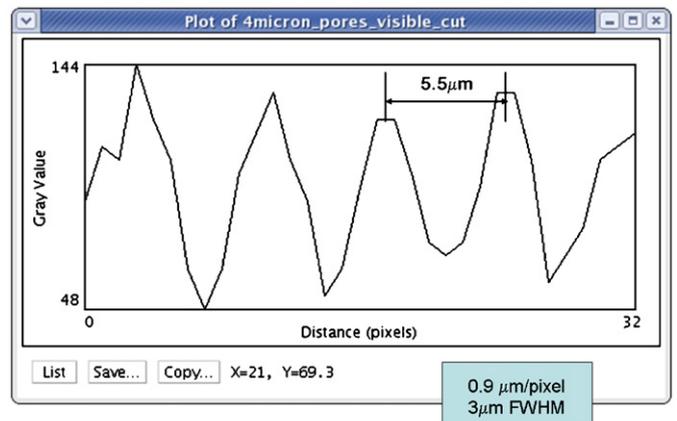


Fig. 6. With a cut through the first element of group 6 a spatial resolution of  $3\mu\text{m}$  FWHM was measured.

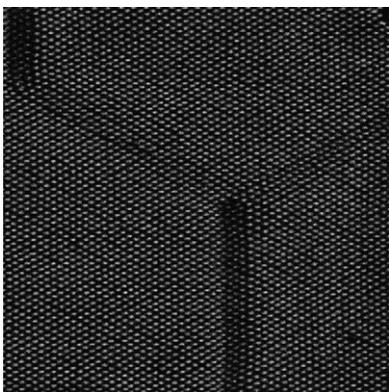


Fig. 7. Flat field image obtained with a 12µm pore MCP operating in single stage. The hexagonal bundles which tie together the microchannel tubes of the MCP are clearly visible.

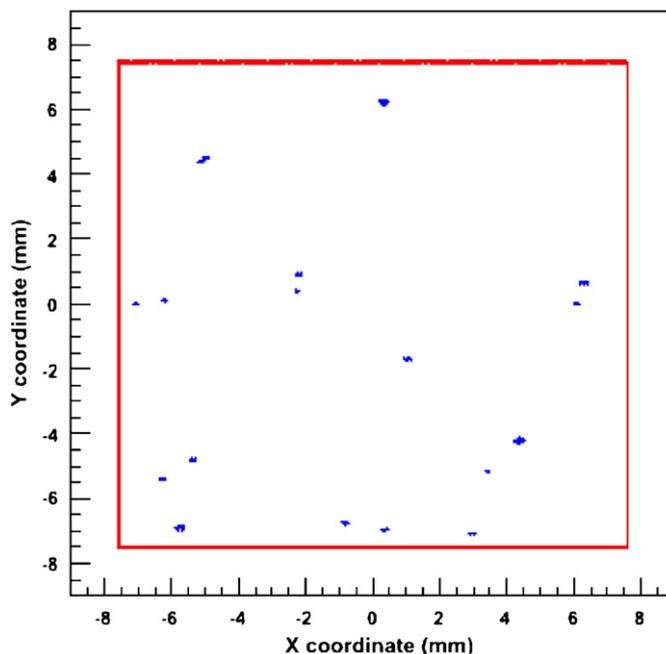


Fig. 9. Typical multi-photon event taken with a 12µm pore, single stage MCP.

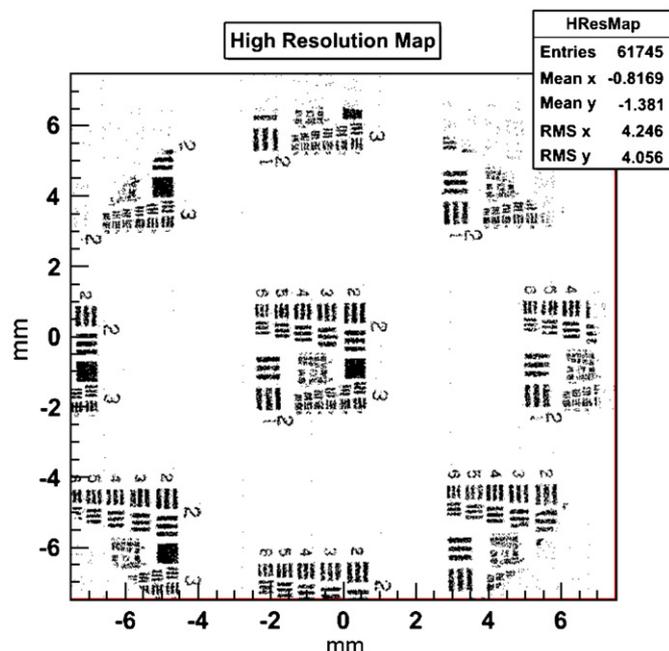


Fig. 8. Wide field image obtained with a 12µm pore MCP operating in single stage and multi-photon modality.

implementing an algorithm for the online event centroiding in the full frame modality.

Fig. 8 shows the reconstructed wide field image of the USAF mask acquired with multi-photon events in full frame modality. The picture is the cumulative map of the centroid position of the reconstructed multi-clusters events. The intensity of the UV illumination was increased to the level when each 20µs coincidence window had ~20 detected events. The frame-processing algorithm rejects the overlapped events as well as the events caused by the ion feedback. A typical full frame picture taken with multiple coincidence photons with 12µm pore MCP in

single stage configuration is shown in Fig. 9. We estimate that the spatial resolution of the detection system operating in coincidence mode is only slightly worse than the one obtained in single event driven mode.

### 3. Conclusions

An ultra-high spatial resolution single photon counting imaging detector based on a MCP coupled to the 0.18 µm CMOS ASIC (300 × 352 pixels, 15 × 15 mm<sup>2</sup>) was built and successfully tested.

The 4 µm pores of the MCP were well resolved indicating a few micron spatial resolution capability.

Good uniformity, high signal/noise ratio and stable operation conditions were achieved with different MCPs.

Images in single photon readout mode and multi-photon mode were acquired.

### References

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