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Next generation microchannel plate detectors for high spatial and temporal resolution

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ABSTRACT: Multi-anode Microchannel Plate (MCP) detectors provide unique performance, especially with regards to sub 30 ps timing resolution, signal-photon sensitivity, and modular design. Developments for High-Energy Physics applications such as the TORCH project, require increasing the photon rate capability and higher spatial granularity of existing designs.

These demands are being tackled in two ways, firstly by developing a higher granularity custom readout for the TORCH project [1] of 16 × 96 pixels (0.55 mm pitch), to enable their application in using Cerenkov radiation for particle identification. Secondly, for applications such as life science and medical imaging, a novel design has been established, utilising resistive sea technology to introduce charge sharing across multiple pads, thus improving spatial resolution (at the cost of occupancy) beyond the physical pitch of the anode readout. To assess the performance of the novel detector readout, a series of characterization tests are detailed. These include measuring of cross-talk to evaluate spatial resolution, analysing single-pad pulse height distributions to determine gain, and timing single-pad responses to assess transmission time spread (TTS).

Developing charge-sharing techniques achieves megapixel-scale spatial resolution by using a resistive layer for charge collection [2]. A ceramic insulator between this layer and the anode spreads the charge across multiple pads via capacitive coupling, thus making spatial resolution independent of anode pad size [3]. Within this configuration each 'pixel' of the anode is connected to a channel of the TOFPET2d electronics [4], which measures the timestamp and charge of all 256 channels

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individually. This research details results and optimisation methods of using this electronic readout to train neural networks to reconstruct single photons comparing the method to previous algorithmic techniques. Characterisation of the resistive sea MCP detector is discussed, including uniformity, timing and amplitude walk correction.

Keywords: Analysis and statistical methods; Data processing methods; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Electron multipliers (vacuum)

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Contents

1 Introduction

Single photon timing Microchannel plate (MCP) detectors, with granular resolution and high timing resolution (<50 ps) are an important area of development for numerous applications in particle physics, medical imaging and life sciences. The MCP amplifies single photoelectrons into charge clouds of 1–10 million electrons, distributed across the detector anode [5]. This paper present two projects attempting to push the spatial resolution of MCP detectors whilst preserving high timing resolution. First a new MCP-PMT, with 16×96 pixel layout for the TORCH Cerenkov particle ID detector [1], then a novel approach using multichannel timing electronics [4] with time-over-threshold discriminators and machine learning to side-step the complicated non-linear calibration for timing and imaging.

2 Characterisation of the TORCH MCP-PMTs

This section breaks down results using two TORCH MCP- PMTs with 16×96 pixel layout (with serial numbers (SN) A1240515 and A3241111). The gain, quantum efficiency, uniformity, charge sharing/cross talk, and transit time spread were characterised.

Gain/quantum efficiency uniformity. Scans were run to measure the relative change in photocurrent/gain to assess the uniformity of the detector. A laser was scanned across the input face of the detector, measuring photocurrent at each position using the MCP input face as a collector. This produces a relative measure of QE uniformity across the active area, as shown in figure 1 left. There is a good uniformity for A3241111. A similar setup is used on the instrumented device A1240515 but this time measuring the photocurrent collected on the anode. The gain uniformity of A1240515 is shown in figure 1 right.

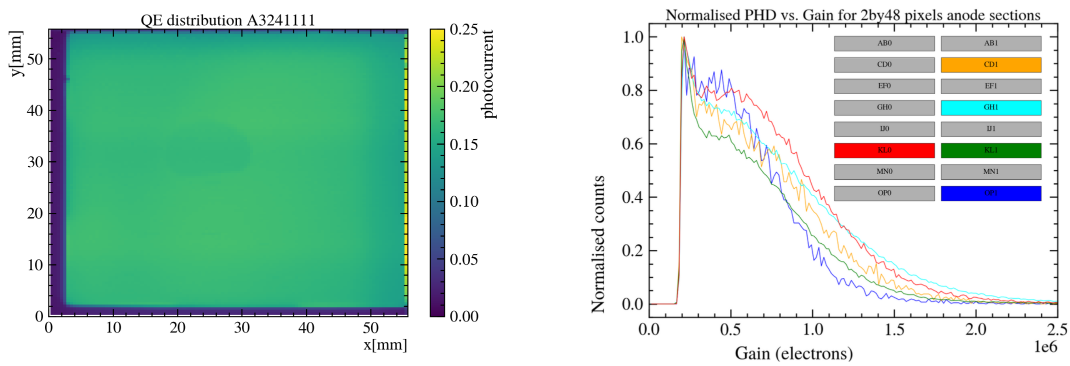

Figure 1. Figure (left) Photocurrent uniformity for A3241111. Gain uniformity measured at 5 positions for SN: A1240515 (right). Each 1D coloured distribution covers an area of 48×2 pixels.

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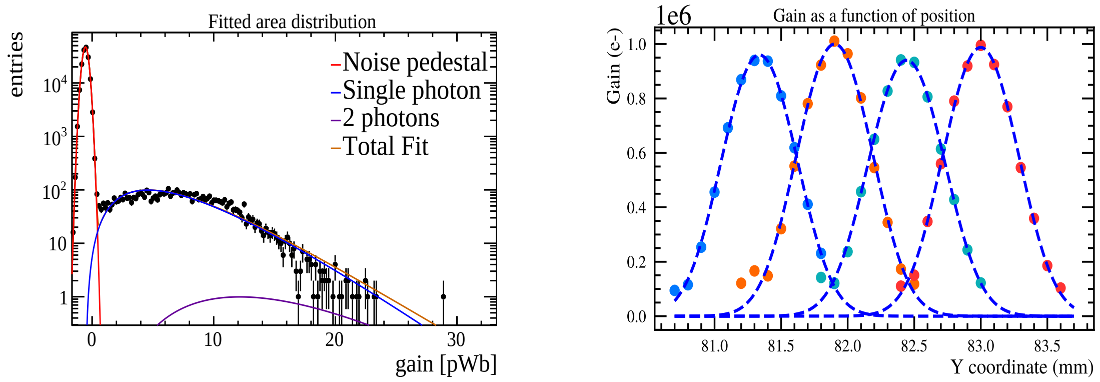
Charge sharing. To measure the charge spread across the pads, the setup was as follows. A focused, attenuated laser pulse (beam size <50 µm) was swept across four pixels, with the charge pulse area read out on an oscilloscope, integrating over a given time before moving to the next position. A Polya model [6] is fitted to obtained distribution to determine the gain. An example can be seen in figure 2(a). This is done at each position to see how the gain, hence collected charge varies for each pixel at a given laser position. Figure 2(b) shows gain variation as laser spot position is stepped across the 4 pixels. Fitting a top hat of the pixel size convolved with a Gaussian function yields a FWHM of roughly 0.65 mm.



(a) Example of fitted distribution of MCP-PMT's voltage pulse.

(b) Gain calculated from Polya model fit for all 4 channels.

Figure 2. Results of the scan over 4 pixel by sweeping the laser along the y direction in 0.1 steps. Fit of a top-hat convolved with a Gaussian to Gain data (dashed blue in figure b).

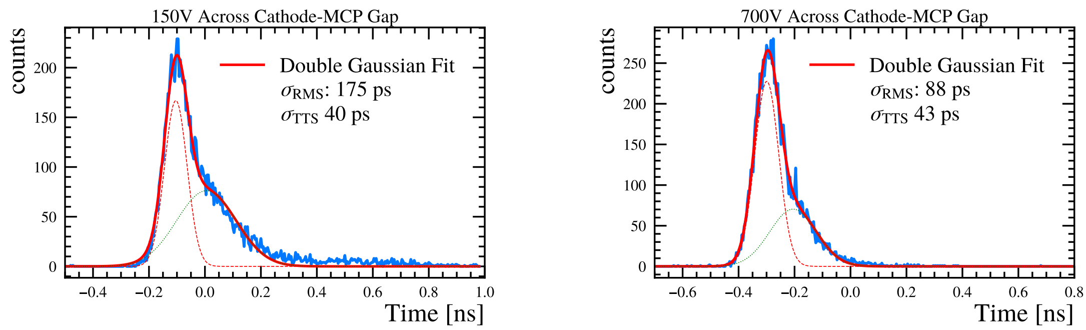


Figure 3. The TTS distribution at 2 cathode voltages (150 V, 700 V). A marked improvement in the RMS is seen at the higher of the two potentials.

Transit time spread. Figure 3 shows the TTS for two different cathode-to-MCP gap voltages. The data was taken by splitting a pulsed laser signal and sending part to a photodiode to act as a reference, and the rest to the instrumented MCP-PMT. From the skew measurement of the two pulses, we infer the time it takes for a photoelectron generated at the cathode to produce a pulse at the anode. An improvement in the root mean squared calculated from data is seen when the voltage applied between the cathode and MCP is increased.

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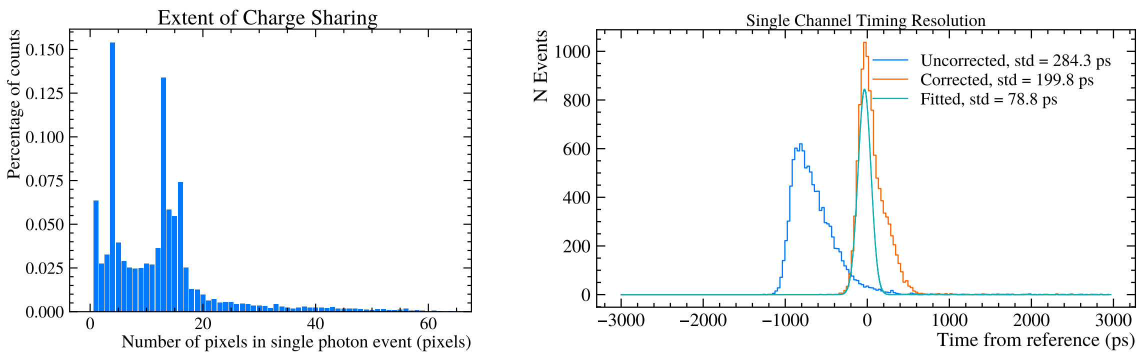
3 Resistive sea Micro-channel Plate Photomultiplier tube

A Time-Correlated Single Photon Counting (TCSPC) camera with 256 channels, each achieving a 60 ps RMS timing resolution and a photon rate of 480 kHz, is essential for applications requiring single-photon sensitivity and high spatial granularity. Each anode pixel connects to a TOFPET2d channel [4], enabling individual timestamp and charge measurements. The design enhances spatial resolution to megapixel scales via charge-sharing techniques, maintaining a temporal resolution of 60 ps.

Figure 4(a) depicts the level of charge sharing with the laser centrally positioned within the active area of the 40 mm PMT. This distribution is highly dependent on the gain of the PMT and the electronic thresholds of the individual channels within the TOFPET2d electronics. Within this research, it is desirable that the data include minimal number of 1-pixel events. Events with single pixels are less desirable as there is no charge sharing; hence the limiting spatial resolution is the anode pad size.



(a) Illustrates the degree of charge sharing.

(b) Amplitude walk corrected timing data a single channel.

Figure 4. Fitted Gaussian to the amplitude walk corrected timing data for each independent channel of the TOFPET2d electronics.

To characterize the resistive sea PMT, uniformity measurements and amplitude walk calibration were performed. Figure 4(b) depicts the timing resolution of a single pixel in TOFPET2d electronics after the amplitude walk correction, with the mean timing resolution of the 256 channels from the fitted values being 81.7 ps.

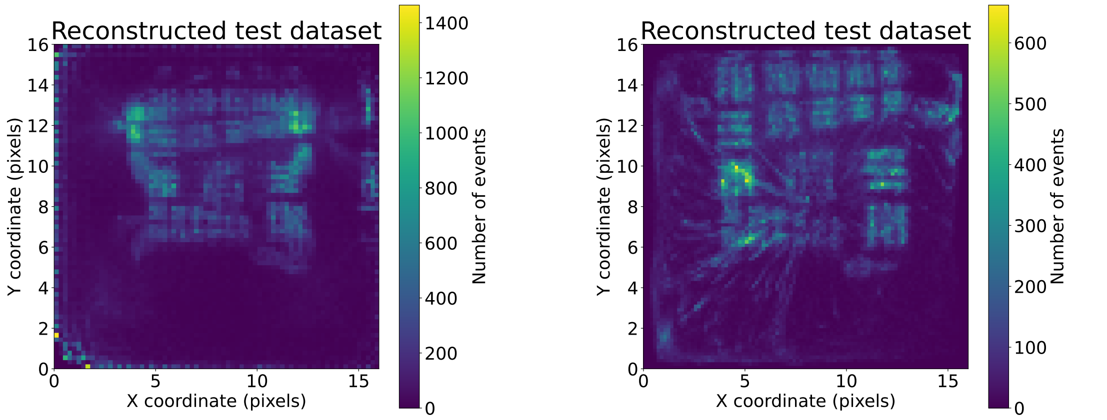
3.1 Comparision of algorithmic and machine learning reconstruction of single photons

Table 1 shows the resolution of the position of the reconstructed photon. The convolutional neural network improves the resolution from an RMS of 1.46 mm or 0.88 pixels (with a pixel width of 1.656 mm) to 0.11 mm or 0.07 pixels.

Table 1. A comparison of the algorithmic and machine learning methods for single photon reconstruction in one dimension (X position).

Method:	**Algorithmic**		**ML methods**	
(Units: mm)	FWHM	RMS	FWHM	RMS
X position	3.42	1.46	0.26	0.11

The model architecture consists of a 2D convolutional layer followed by three fully connected layers. All layers use ReLU activation and the Adam optimizer with its default learning rate [7]. To compare these data analysis methods, a United States Air Force (USAF) mask has been used as a recognition image, as a standard tool for evaluating the spatial resolution of imaging systems.



(a) USAF data reconstructed with centre of gravity analytical algorithm.

(b) USAF data reconstructed with a trained convolutional neural network.

Figure 5. Comparison of data analysis methods to reconstruct the USAF image.

It features a series of patterns with progressively smaller lines and spaces, used to assess the detector's ability to distinguish closely spaced lines, expressed in units of line pairs per millimetre (lp/mm). By employing the trained neural network and the 'centre of gravity' algorithm to reconstruct the USAF chart as a recognition image, the MTF (Modulation Transfer Function) of the algorithms can be compared.

Figures 5(a) and 5(b) show preliminary results comparing the resolution of the reconstructed single photons using the analytical method in comparison to the trained neural network. Qualitatively, these images confirm that the trained neural network provides higher spatial resolution. Current measurements are in hand to calculate the MTF of both the analytical and machine-learning method, using a knife edge.

4 Conclusion

In summary, these proceedings introduce the characterization of two novel readout configurations MCP detector devices: a new MCP-PMT, with 16×96 pixel layout and a resistive sea MCP-PMT. These results demonstrate promise in higher granularity readout. Preliminary results demonstrate machine learning capabilities to further improve the spatial resolution of single-photon event reconstruction.

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