

# Timing Characteristics of Large Area Picosecond Photodetectors

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## Abstract

The LAPPD Collaboration was formed to develop ultrafast large-area imaging photodetectors based on new methods for fabricating microchannel plates (MCPs). In this paper we characterize the time response using a pulsed, sub-picosecond laser. We observe single-photoelectron time resolutions of a 20 cm x 20 cm MCP consistently below 70 picoseconds, spatial resolutions of roughly 500 microns, and median gains higher than  $10^7$ . The RMS measured at one particular point on an LAPPD detector is 58 psec, with  $\pm 1\sigma$  of 47 psec. The differential time resolution between the signal reaching the two ends of the delay line anode is measured to be 5.1 psec for large signals, with an asymptotic limit falling below 2 picoseconds as noise-over-signal approaches zero.

*Keywords:* MCP, TTS, Single photon, TOF, LAPPD, resolution, picosecond, large area, photodetector

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## 1. Introduction

Microchannel plate photomultiplier tubes (MCP-PMTs) are compact vacuum photodetectors [1], capable of micron-scale spatial resolutions [2], sub-nanosecond time resolutions [3, 4, 5], and gains exceeding  $10^7$  [6]. Economical, large-area MCP photosensors with these characteristics would bring much

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needed timing and imaging capabilities to a wide range of applications in fields such as particle physics, nuclear physics, X-ray science, and medical imaging.

The Large Area Picosecond Photodetector (LAPPD) collaboration was formed to develop techniques for making large format (20 cm x 20 cm) MCP-PMT detector systems using scalable methods and low-cost materials, addressing technical aspects of the problem from the photocathode and the gain stage to the readout electronics and vacuum packaging. Fabrication of LAPPDs is based largely on the application of thin-film materials to glass structures. In particular, a technique known as Atomic Layer Deposition (ALD) [7] enables the fabrication of large-area MCP amplification structures by conformally coating inactive, porous glass substrates [8, 9]. The technique is flexible as well as scalable, allowing for the independent optimization of the geometric, resistive, and secondary electron emission properties [8] of the channel plates.

In this paper, we present an analysis of the timing characteristics for 20 cm x 20 cm LAPPD<sup>TM</sup> systems. At sufficient operational voltages, we observe single-photoelectron time resolutions in the range of 50-60 picoseconds, consistent with those of commercial MCPs with comparable pore structures. Differential time resolutions are measured as low as 5.1 psec, with the large signal limit extrapolating below 2 picoseconds. Spatial resolutions are set by the granularity of the economical stripline anode design (see Sec 2) and are measured to be less than 1 mm in both directions with respect to the stripline anodes. The median gain of the most recent MCP stack exceeds  $10^7$ .

### *1.1. Structure of this paper*

Section 2 describes the essential elements of the LAPPD<sup>TM</sup> design. In Section 3 we discuss the theoretical factors that determine the time resolutions of detectors generically, and MCP detectors such as LAPPDs specifically. We also identify the key observables and dependencies to be measured. Section 4 briefly describes the setup used to measure LAPPD timing, and Section 5 describes the measurement strategy. Section 6 describes the algorithms used to construct and fit the LAPPD pulses. Section 7 describes the results; conclusions are presented

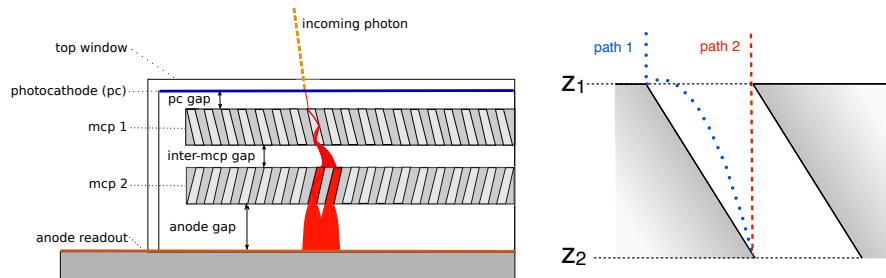


Figure 1: LEFT: The structure of an LAPPD<sup>TM</sup> photomultiplier tube. RIGHT: A schematic of photoelectrons entering the pore of an MCP. Both the dashed red and dotted blue trajectories reach height  $z_1$  at the same time, but arrive at  $z_2$  at different times due to different velocities and path lengths.

in Section 8.

## 2. Essential elements of the LAPPD<sup>TM</sup> design

Figure 1 shows the structure of an LAPPD<sup>TM</sup> [10]. Light is incident on a photocathode, producing photoelectrons. These accelerate across a potential  
 40 gap toward a pair of microchannel plates, which are high-gain structures consisting of thin plates with high secondary electron emission (SEE) enhanced, microscopic pores [1]. Voltages of roughly 1 kV are applied across each plate. Pores are oriented at  $18^\circ$  bias angles in opposite directions. This prevents positive ions, produced by the electron cascade in the lower plate, from reaching  
 45 and damaging the photocathode. It also provides a well-defined first strike for incoming electrons. Each electron entering a pore accelerates and strikes the pore walls, starting an avalanche of secondary electrons. The avalanche builds until the amplified pulse exits the bottom of the second MCP. This electrical signal is collected on an anode structure and passed through the vacuum  
 50 assembly to sampling front-end electronics, which digitize the signal at 10-15 Gsamples/second. Spacing between the MCPs is set by glass grid spacers for the data reported here [10].

Anode coverage over large areas is achieved using a  $50 \Omega$  micro-stripline design [11]. The positions of photon strikes on the photocathode are determined

55 (i) by differential timing along the striplines, and (ii) by calculating a weighted centroid of the charge on adjacent striplines in the tranverse direction. This design allows economical area coverage as the number of readout channels scales linearly with length, rather than quadratically.

### 3. Factors that limit and determine time resolution

60 The timing characteristics of these photodetectors are determined by two key aspects of the detection process:

- Jitter in the formation of avalanches within the gain stage: This is determined by the physical properties of the MCP stack, such as pore diameters and bias angles, operational voltages, spacings between the components, and SEE characteristics.  
65
- Information loss in the transmission and recording of the signal: This includes noise, attenuation of high frequency components as the pulse travels along the striplines, and quantization effects from pulse digitization.

#### 3.1. Jitter in the MCP signal formation, with respect to photon arrival

70 The amplification process in an MCP detector is subject to fluctuations in the transit of the initial photoelectron (PE) and in the evolution of the avalanche. These fluctuations introduce a jitter in the start time ( $t_0$ ) and development of the MCP pulse with respect to the incoming photon. This jitter is largest for single-photoelectron pulses, independent of signal processing considerations. In the limit of many photoelectrons, it should decrease statistically <sup>1</sup>.  
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The most significant factor driving single-PE jitter is the “first strike”. This is illustrated schematically in Fig 1, on the right. The dotted blue and dashed

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<sup>1</sup> The exact relationship between time resolution and  $N_{phot}$  is complicated, depending on whether the photoelectrons enter one or several MCP pores, and whether the avalanche ultimately saturates.

red photoelectrons accelerate across the photocathode gap, typically a few hundred volts. Both PEs reach the top plate ( $z_1$ ) at the same time with the same energy. The PE on the dotted blue trajectory immediately strikes the pore, while the dashed red trajectory continues deeper into the pore. A secondary electron produced at the strike-point of the dotted blue trajectory starts with O(1) eV initial energy before accelerating towards  $z_2$ . The original photoelectron on the dashed red trajectory accelerates towards  $z_2$  over a shorter path, and starting with O(100) eV energy. Thus, the dashed red trajectory arrives at position  $z_2$  before the dotted blue one. The difference is O(10) picoseconds for these two strike points. There are many more possible trajectories for secondary electrons produced along path 1, and there are many different first strike points within the pore. Given the current 20  $\mu\text{m}$  diameter and  $8^\circ$  bias of the default LAPPD<sup>TM</sup> pores, these variations in trajectory lead to an O(10) picosecond jitter in  $t_0$  of the avalanche. However, this jitter can be reduced by shrinking the pore size. Excellent single-PE time resolutions have been achieved using MCPs with pore diameters below 10  $\mu\text{m}$  [12].

The number of secondaries and the randomization of their initial directions and energies further contribute to fluctuations in the development of the avalanche. The larger  $N_{\text{secondaries}}$ , the more these fluctuations will average out, and the more each individual pulse will behave in accordance with the mean behavior. A key way to reduce this is to increase the photocathode gap energy so that the first strike produces a large number of secondaries and to coat the pore surface with materials optimized for high secondary electron emission [8, 13].

In addition to variability from the first strike, some jitter in the time evolution of the avalanche is driven by the transition between the two MCPs of the gain stage. The avalanche from the first MCP will spread into a finite number of pores in the second-stage MCP. Depending on which pore in the first MCP is struck, fluctuations in this charge spreading will affect both the saturation and the timing of the resulting pulse.

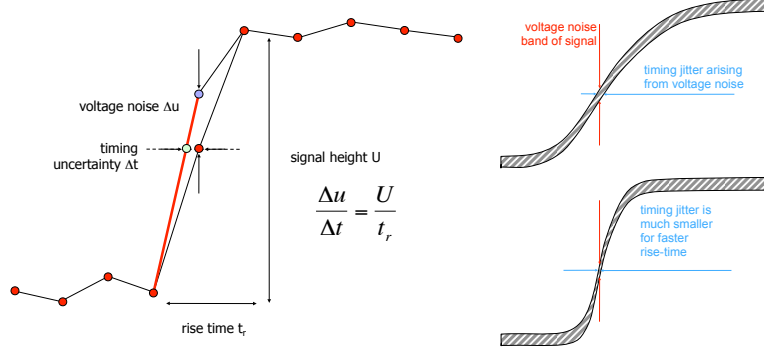


Figure 2: LEFT: an illustration showing how voltage noise translates into timing uncertainty for determining the time a signal crosses a threshold. RIGHT: two sketches showing how the impact of noise on timing also depends on the risetime of the signal.

### 3.2. Uncertainties in extracting the arrival time from the MCP signal

Even if an MCP provided a precisely repeatable signal with fixed  $t_0$ , there would still be uncertainty in the arrival of that MCP signal due to limitations  
 110 on extracting the signal from noise. Here we briefly discuss these issues, based largely on material from Ref [14, 15, 16].

Figure 2 demonstrates how the presence of noise introduces an uncertainty in the threshold crossing time of an otherwise repeatable signal. The right two plots in Fig 2 show the dependence of the size of the timing uncertainty for a  
 115 given noise level on the rise time of the signal, which defines the slope between voltage and time.

By sampling more points along the rising edge, the uncertainty in the timing of the signal goes down with  $\sqrt{N}$ , assuming that the Nyquist-Shannon condition is met. Then, the time resolution can be described by Ritt's parameteriza-  
 120 tion [15, 16], shown in Equation 1.

$$\Delta t = \frac{\Delta u}{U} \times \frac{t_{rise}}{\sqrt{n}} = \frac{\Delta u}{U} \times \frac{t_{rise}}{\sqrt{f_s \times t_{rise}}} = \frac{\Delta u}{U} \times \frac{\sqrt{t_{rise}}}{\sqrt{f_s}} = \frac{\Delta u}{U} \times \frac{1}{\sqrt{3f_s \times f_{3dB}}} \quad (1)$$

Where  $\frac{\Delta u}{U}$  is the noise-over-signal,  $t_{rise}$  is the rise-time of the signal, and  $n$  is the number of samples taken along the rising edge of the signals,  $f_s$  is the

sampling rate, and  $f_{3dB}$  is the highest frequency component of the pulse. The noise is assumed to be uncorrelated white noise, an assumption that might not  
125 be generically true in real life experiments.

The noise of the system is determined primarily by the design of the readout, particularly the electronics. The 15 Gsample/sec PSEC4 chip developed for LAPPD<sup>TM</sup> readout has a noise per channel of 700  $\mu$ V [17]. The oscilloscope measurements presented in this paper have noise levels around 3 mV. With  
130 gains above  $10^7$ , the LAPPD<sup>TM</sup> system is capable of achieving noise-over-signal values well below 0.001.

The rise time of the pulses is determined by the geometry and operational parameters of the MCPs, as well as the intrinsic analog bandwidth of the anode and front-end. Figure 3 shows that the highest frequency components of the  
135 signals above noise ( $\sim$  500 MHz) are well below the analog bandwidth allowed by the anode design and readout (1.6 GHz for the PSEC4 electronics and 3 GHz for the scope) [11].

Based on these detector parameters and using Eq 1, we estimate that the LAPPD<sup>TM</sup> readout should be capable of time resolutions approaching a single  
140 picosecond. For single-photoelectrons, the overall time resolution is dominated by the O(10) psec intrinsic jitter from the MCPs, rather than the readout. In the limit of many photoelectrons, and for future designs with optimized MCPs, improvements in time resolution will come from improvements to the readout such as higher bandwidth anodes, faster sampling rates, and lower noise  
145 electronics.

### 3.3. *Relevant observables*

The timing limitations imposed by the properties of the gain stage can be measured by studying the absolute timing of the detector in single-PE operation with respect to a photodiode triggered by the laser (see Section 4). It can  
150 be characterized by the width of the Transit Time Spread (TTS). The limiting factor for multiple photoelectron operation is driven by the noise over signal (N/S) quality of the readout and can be measured using differential timing: the

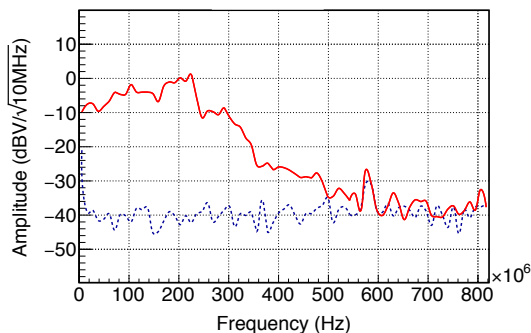


Figure 3: Frequency spectrum of the MCP signal plus noise (solid red) overlaid on the pure noise spectrum (dashed blue). Signal dominates over noise only up to around 500 MHz.

difference in arrival times of the two pulses at opposite ends of the delay line anode. In differential timing measurements, fluctuations in the start and development of the signal cancel out, leaving only the uncertainties due to noise in the readout. This observable we will refer to as the Differential Time Spread (DTS), and it improves with increasing signal size (or decreasing noise), regardless of whether the large signal is achieved by more photoelectrons or higher gains.

The timing characteristics of LAPPD<sup>TM</sup> systems will be relevant to different applications in different ways. Looking at some examples from high energy physics, water Cherenkov (WCh) detectors are single-photon counting devices; events are reconstructed using precision measurements of each individual emitted photon. The timing requirements are less demanding (<100 psec), but the timing capabilities are more limited due to the intrinsic jitter of the gain stage on the single-PE TTS. Time-of-flight (TOF) detectors require much better time resolutions, but also look at much larger signals - typically 50 photoelectrons produced by a high energy particle traversing a radiator [14]. For these applications we are more concerned with the large-signal limits of LAPPD<sup>TM</sup> systems, determined by the readout. These large-signal resolutions can be characterized by looking at the DTS. In this paper we will discuss both the TTS and DTS, as



well as their dependence on operational parameters such as voltage and S/N.

#### 4. Experimental setup

In this section we will briefly describe the test setup used to characterize  
175 LAPPD<sup>TM</sup> detector systems. More detailed discussions of the characterization  
facility can be found in Ref [18].

For all of the measurements, signals are produced by shining UV light from  
a sub-picosecond pulsed Ti:Sapphire laser on a thin aluminum photocathode 2  
mm above the gain stage. The arrival time of the MCP pulses can therefore be  
180 measured precisely against a trigger signal derived from these laser pulses. Using  
a statistical technique described in Sec 5, we can achieve low light intensities  
and study the characteristics of MCP pulses derived from single-photoelectrons.  
The laser spot size is roughly 1 mm, and a motorized stage is used to study the  
response and different locations on the detector surface. The shapes of the pulses  
185 are measured using a fast oscilloscope and written to disk for offline analysis.

This paper presents the results of two separate studies. One set of measure-  
ments was performed on an unsealed LAPPD<sup>TM</sup> detector system inserted into  
a larger, steel vacuum chamber (the “8-inch Chamber”) [18]. The other study  
was performed on a vacuum tight, resealable glass LAPPD<sup>TM</sup> detector, known  
190 as the “Demountable” [18].

##### 4.1. The 8” chamber

Early studies of 8” microchannel plates were performed before the glass  
vacuum packaging for LAPPDs was developed. A complete detector stack was  
assembled with proper electrical contacts, and inserted into a larger, stainless  
195 steel vacuum chamber (Fig 4). Laser light entered the chamber through a quartz  
window and was directed onto the MCP stack using mirrors. Signals were  
brought out of the chamber through SMA feedthroughs. Due to the limited  
number of feedthroughs, only four striplines could be instrumented at a time.  
One key advantage of the 8” chamber was the ability to independently control  
200 the voltages at each stage of the MCP stack.

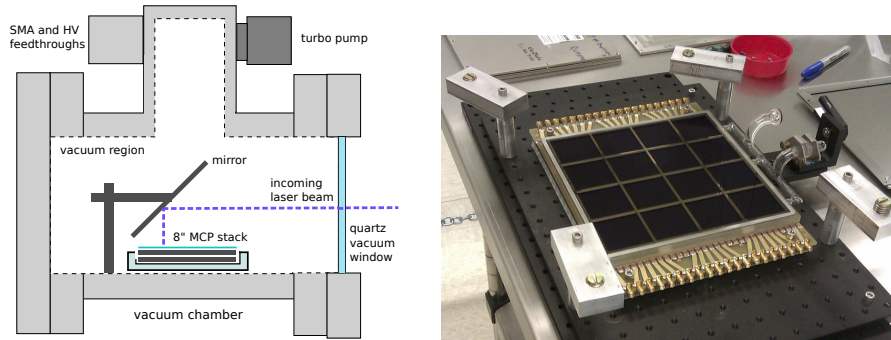


Figure 4: LEFT: A schematic illustration of the 8" MCP test-chamber. RIGHT: A picture of the assembled demountable LAPPD before placing and sealing the top window.

#### 4.2. The Demountable detector

The Demountable assembly is an 8.66" x 8.66" glass vacuum tube detector made from LAPPD<sup>TM</sup> production parts, whose differences from the sealed detector of the design goal are that: 1) the tube is actively pumped rather than hermetically sealed; 2) the seal between the fused silica top window and the tube  
 205 body is with an O-ring rather than an indium seal; and 3) the photocathode is a thin aluminum layer rather than a bialkalai film, as the Demountable is assembled in air. Inside the demountable we place a stack of 2 ALD-functionalized 8"x8" MCPs, with spacers in the three gaps: a) between the MCP stack and the  
 210 anode; b) between the two MCPs; c) between the MCP stack and the photocathode [10]. The spacers are ALD-coated with a resistive layer. The resistances of the spacers and plates set the respective operational voltages, and allow signals to pass from the photocathode through the stack to the anode strips, which are DC terminated with 10 kΩ resistors [10]. Thus, unlike the 8" chamber, this  
 215 voltage divider does not allow independent voltage control over each component. High voltage electrical contact is made by connecting to the aluminum side of the top-window on end-tabs where the window extends past the vacuum region of the Demountable body.

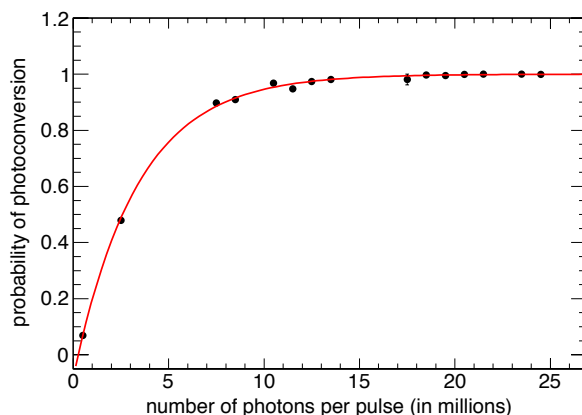


Figure 5: Probability of the Ti:Sapphire laser pulse generating an MCP signal on the aluminum photocathode, plotted as a function of pulse energy. At sufficiently high laser intensities, this probability approaches unity; as the laser is attenuated below roughly 10 million UV photons per pulse, the fraction of laser pulses producing an MCP signal begins to drop and eventually approaches zero.

## 5. Measurement strategy

220 A pulsed, sub-psec laser was used to characterize the time resolution of the large-area MCPs. Absolute timing of the MCP response was measured in relation to a fast photodiode triggered by the laser. Single-photoelectron operation was achieved by controlling photon statistics.

The average UV laser power, of order 100 nano-Watts, was sufficient to produce many photoelectrons per pulse, even with a low quantum efficiency (QE) aluminum photocathode. Without attenuation, the fraction of laser pulses with an observed MCP signal was 100%. However, the beam could be attenuated to the point where some fraction of laser pulses produced no discernible signal, as determined from the oscilloscope data using analysis techniques described in  
 230 Section 6.1. Once the detector was operating in a regime where the fraction of events with good pulses was sufficiently low, the probability of producing more than one PE was statistically suppressed. Figure 5 shows the relationship between average UV intensity and the probability of an MCP signal. The slope of

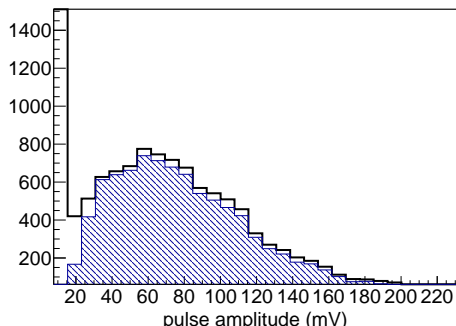


Figure 6: The amplitude distribution of pulses from the 8" chamber (in thick black), showing the separation between the peak of the distribution and the pedestal near zero. The shaded blue region shows the same distribution after applying the TOT cut and requiring only one pulse.

this plot at low laser intensities can be used to extrapolate to higher intensities,  
 235 providing a statistical handle on the number of photoelectrons. This approach  
 does not depend on the choice of photocathode or precise knowledge of the QE.

## 6. Analysis techniques

### 6.1. Pulse selection

Pulses are separated from background on the basis of a time over threshold  
 240 (TOT) cut. Pulses are identified as a region of the signal trace where the charge  
 exceeds a predetermined threshold of 5 mV for a duration longer than 1.0 nsec.  
 We explored several possible pulse selection methods, but found this technique  
 to be simple, robust, and effective at separating signals from white noise and RF  
 interference from the laser. The result of this cut on the amplitude distribution  
 245 of the MCP pulses is show in Fig 6. This analysis requires events where only one  
 pulse is identified, although the number of events with  $N_{pulses} > 1$  is negligible.

### 6.2. Timing algorithms

Several time reconstruction algorithms were tested : constant-fraction dis-  
 crimination, fitting with a Gaussian distribution, and template fitting. These

250 approaches are taken largely from Reference [14].

A simple, but nonetheless effective technique for reconstructing pulse arrival times is to use a Constant-Fraction Discriminator (CFD). This technique is robust and simple, but does not capture the full information contained in the pulse shape, and it suffers from a time slewing for pulses of different shapes.

255 Another technique is to fit a partial range of the pulses with a Gaussian distribution. As illustrated by Fig 7, pulse shapes from the LAPPDs are non-Gaussian. Any naive fit of a Gaussian distribution to these pulses will yield worse transit time spreads than simple CFD methods. However, the pulses can be well approximated by a Gaussian function from the rising edge to a point, slightly past the peak of the pulse.

260 This method is implemented in two steps. First, we fit the pulse peak with a Gaussian to determine the peak time. Next, using the fitted peak as a reference, we define a fit range and apply a Gaussian fit along the rising edge. This give results close to those of the template fit but is less robust, with a higher failure rate for slightly misshapen pulses.

The most robust method for extracting pulse arrival times is to fit the MCP pulses with a data-derived template waveform. Templates are created by selecting pulses, using a stringent pulse quality cut, and averaging them together. In some instances this process was repeated a second time, where the fitted time using the original template was used to line the pulses up before combining them to create a more narrow pulse shape. Since the TTS of the pulses ( $<100$  psec) is considerably smaller than the typical pulse width (FWHM $<1$  nsec), iterative template-making does not substantially improve the results. Once the template has been created, it is used to fit individual pulses. Pulses are interpolated and shifted by a continuum range of time delays until a  $\chi^2$  comparison is minimized over a predetermined range of the template. Figure 8 shows an example pulse with the result of the template fit overlaid.

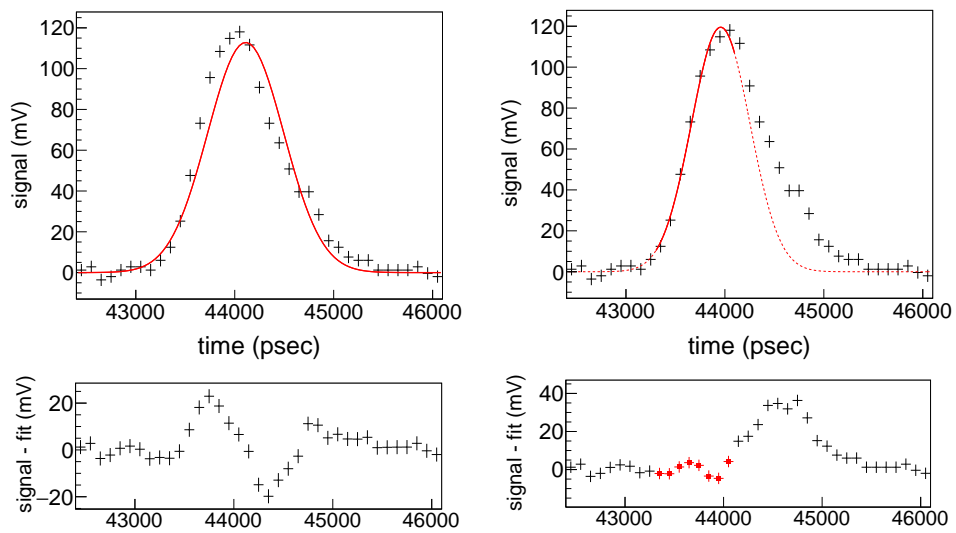


Figure 7: Two examples of Gaussian fits to an MCP pulse, plotted above a graph showing the difference between the fitted curve and data points. The error bars correspond to 3mV white noise on the oscilloscope. On the left plot, the pulse is fitted over the full range. The right plot shows the prescription used in the data analysis of fitting the rising edge only. The solid line and closed circles on the right correspond to the region used in the fit. The dashed line and open points are included to show the fit beyond the range of interest.

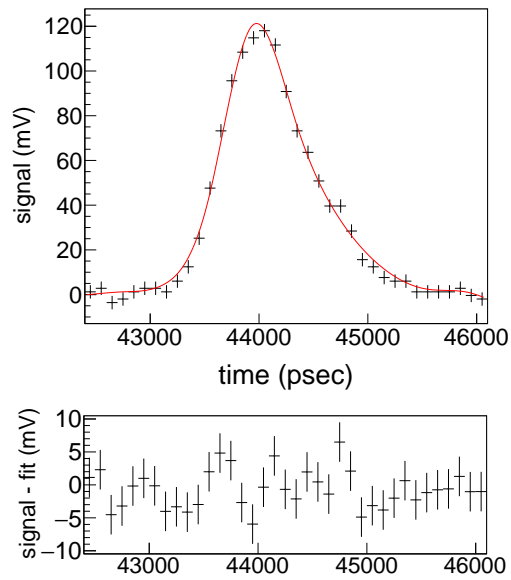


Figure 8: Best fit of the template shape to an example pulse, plotted over the full range of the pulse. The lower plot shows the difference between each data point and the fitted curve, with 3 mV error bars corresponding to oscilloscope noise, over the range of interest.

## 7. Results

### 7.1. The single-photoelectron response

280 Figure 9 shows the single-PE transit time spread for pulses produced in the 8" chamber, fitted using the template-fit method. The RMS of the distribution is 58 psec and the sigma of the fitted Gaussian distribution is 50 psec. Numerical integration of the TTS finds that 68% of the events fall within  $\pm 47$  psec. These observed resolutions are robust, over the choice of algorithm and over the  
285 location of the laser beam on the surface of the detector. Figure 9 also shows the transit-time spread reconstructed using the template method, compared with reconstructions using the Gaussian fit and the constant-fraction algorithm. The derived TTS is consistent to within 10 psec, regardless of which of these methods was used.

290 The absolute time resolution, measured with respect to an external trigger, is dominated by jitter intrinsic to the gain stage. As was discussed in Sec 3.1, single-PE jitter from different strike points in the pore should be of order of tens of picoseconds, whereas the anode and digitization are capable of single-psec sensitivity for large signal-to-noise ratios. Thus, the time resolution for single-  
295 photoelectrons remains above 40 psec as noise over signal (N/S) approaches zero, in contrast with differential timing, which approaches single picosecond resolutions in the large signal-limit (see Section 7.2).

The spatial uniformity of the time resolution was tested by performing a scan over a 7 mm x 7 mm square of the MCP. Figure 10 shows the fitted time  
300 resolution ( $\sigma$  of the Gaussian fit to the TTS) for 30 measurements taken over over this area. The TTS was found to be uniform over distances larger than the O(10) micron scale of the capillary structure, and even transitioning from one stripline to the next. The mean resolution is 51 psec, and the RMS from point-to-point is 6 psec. Displacing the beam spot by 7mm in the direction  
305 transverse to the striplines, the peak signal will shift entirely from one stripline to its nearest neighbor. We found that fitting the arrival time on the dominant stripline alone was adequate to obtain single-PE resolutions consistently below



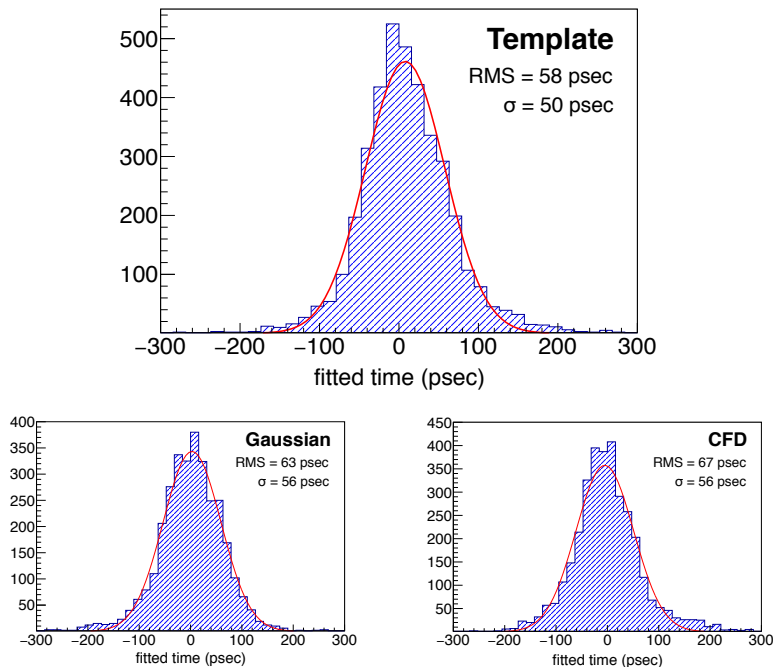


Figure 9: The single-PE transit-time spread measured for the LAPPD<sup>TM</sup> stack inside the 8” chamber, derived using the three different fit methods (see text). TOP: Using the template fit method. The RMS of the distribution is 58 psec; The sigma of the fitted gaussian is 50 psec. Numerically integrating the distribution, one finds that 68% of all events fall within  $\pm 47$  psec. LOWER LEFT: Using the gaussian fit method. The RMS of the arrival times is 63 psec, and the fitted sigma is 56 psec. LOWER RIGHT: Using the CFD algorithm. The RMS of the arrival times is 67 psec, and the fitted sigma is 56 psec. Given the inherent limitations of these fit methods, the non-Gaussian character of the reconstructed TTS and wider tails compared to the template fit are expected.

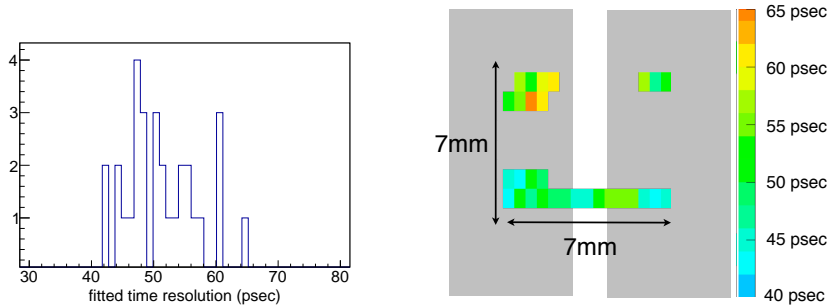


Figure 10: LEFT: A histogram of the fitted sigma of the TTS measured at 30 points over a 7mm by 7mm square. The mean value of the fitted time resolution is 51 picoseconds, and the RMS from measurement to measurement is 6 picoseconds. RIGHT: A plot showing the locations and values of each measurement, relative to the stripline pattern. The color scale represents the range of measured time resolutions (color online).

65 picoseconds, even in the region where signal is split between the two striplines (Fig 11).

310 The width of the TTS depends on operational voltages, particularly across the gaps between the various stages of the MCP chain. As the gap voltages drop below critical values, the time resolution resolution degrades. Figure 12 shows how the shape of the MCP pulses in the 8" chamber depend on changes to the three voltages across the gaps in the MCP stack. The most dramatic effects were seen from changes in the voltage across the gap between the two  
 315 MCPs. Figure 13 shows the fitted sigma of the TTS as a function of the potential difference across the anode gap, inter-MCP gap, and photocathode gap. Optimal timing was achieved with all of these voltages set above 200-300 Volts. The dependence was strongest for the inter-MCP gap and photocathode gap, consistent with the observation that this gap had the largest impact on pulse  
 320 shape.

Similar relationships between gap voltages and time resolution were observed in the Demountable detector. In the Demountable, we did not originally have access to grid spacers with resistances well matched to those of the MCPs.  
 325 Consequently, the voltages across all three gaps were below 100 V when the

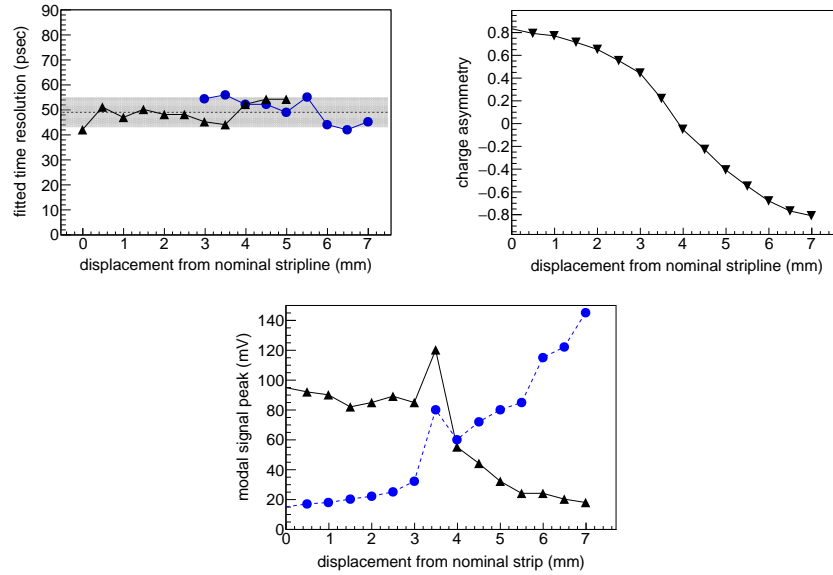


Figure 11: UPPER LEFT: The fitted time resolution as a function of approximate displacement, measured on the nominal stripline (black triangles) and the neighboring stripline (blue circles). The dashed line and shaded band indicate the mean and RMS of the measured resolutions over the scan. UPPER RIGHT: The asymmetry in charge measured on the two neighboring striplines, plotted as a function of approximate displacement from the nominal strip. An asymmetry of 1 means that all of the charge is on the nominal stripline and -1 means all of the charge on the neighbor. BOTTOM: The modal signal peak, as a function of displacement from the nominal strip. Black triangles correspond to the peak signal on the nominal stripline and blue circles, the neighboring strip. The spike in signal size at displacement  $\sim 3.5$  mm is not understood, but the fractional signal on each stripline is consistent with the location of the beam.

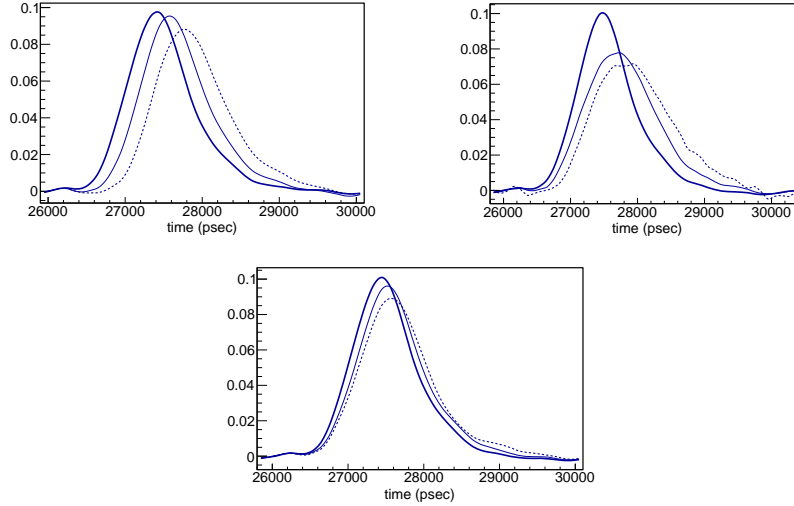


Figure 12: UPPER LEFT: Average pulse shape in the 8" chamber for three different photocathode voltages: 500 V (thick line), 200 V (thin line), 100 V (dashed), with 1 kV across each MCP, 500 V across the inter-MCP gap, and 400 V across the anode. UPPER RIGHT: Average pulse shape for 500 V (thick line), 200 V (thin), and 100 V (dashed) across the inter-MCP gap, with 400 V across the anode and photocathode. LOWER LEFT: Average pulse shape for 500 V (thick line), 200 V (thin), and 100 V (dashed) across the anode gap, with 400 V across the photocathode and 500 V across the inter-MCP gap.

MCPs were operating at full voltage. In a later study, these spacers were replaced with a higher resistance set. Figure 14 shows the average pulse shape for the demountable with the low resistance and high resistance grid spacers, along side the corresponding TTS distributions. Consistent with observations  
 330 in the 8" chamber, the Demountable with low voltages across the gaps delivered time resolutions above 100 psec, while later studies with higher gap voltages demonstrated resolutions below 80 psec.

Further improvements in LAPPD<sup>TM</sup> single-PE time resolution may be achieved through reductions in pore size [19], and higher yield of the first strike in the  
 335 pore resulting from higher SEE surface coatings.

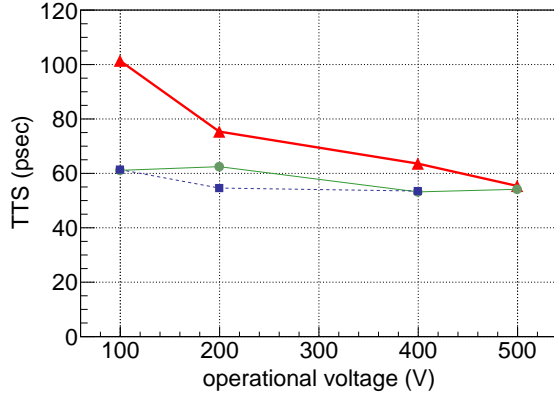


Figure 13: Transit-time spread of MCPs in the 8" chamber, plotted as a function of the key operational voltages: across the gap between the photocathode and top of the first MCP (green circles), between the two MCPs (red triangles), and between the bottom of the second MCP and anode (blue squares). Timing for all gap voltages is preferred to be above 200 V, and performance is most sensitive to the photocathode and inter-MCP gaps.

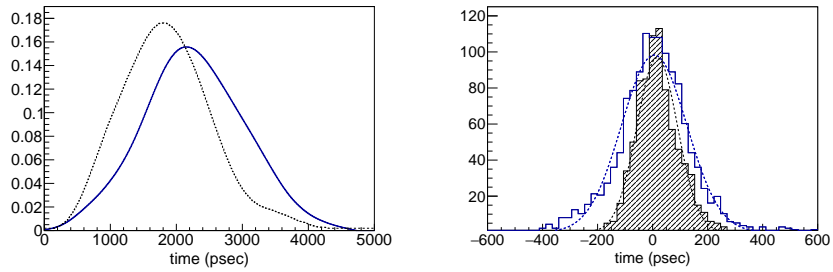


Figure 14: LEFT: Average pulse shape for 2 different configurations of the demountable LAPPD<sup>TM</sup>: one with low voltages (<100 V) across all of the gaps (blue solid line), and one with higher gap voltages (dashed black). RIGHT: The TTS for the two configurations. The high gap-voltage configuration is the shaded black histogram, with  $\sigma=78$  picoseconds for the fitted Gaussian (dashed line). The TTS for configuration with low gap voltages is shown by the blue solid line, with a fitted  $\sigma$  of 128 psec.

## 7.2. Differential timing and the large-signal limit

Even for single-photoelectrons, the pulse-by-pulse jitter cancels out when one looks at the differential time resolution - jitter in the difference between the arrival of the signal at the two ends of the anode. Differential timing resolution is not limited by the intrinsic properties of the gain stage except inasmuch as they provide large signal. Rather, differential time resolution is limited by the characteristics of the pulse such as the rising edge and size of the pulse, and electronics characteristics such as noise-over-signal (N/S), analog bandwidth, and sampling rate.

The Differential Time Spread (DTS) thus provides a handle on the time resolving characteristics of the detector system, minus those of the MCP stack. It indicates the limiting TOF-resolution for large, multi-photoelectron pulses.

Figure 15 shows the differential time resolution for single-photoelectrons in the Demountable LAPPD<sup>TM</sup>, operating at 2.7 kV, which corresponds roughly 1.25 kV per MCP. The RMS of the distribution is 6.8 psec. The sigma of the fitted gaussian is 5.1 psec, although the shape of the distribution is non-gaussian. The bell-bottomed shape of the DTS distribution is expected since it is effectively the sum of multiple Gaussians, each corresponding to the resolution for a particular range of pulse sizes. Small pulses have a broader Gaussian, while large pulses are more narrow. Even so, by simply cutting more tightly on the quality of the  $\chi^2$  of the template fit we achieve a more Gaussian subset of 66% of the original DTS distribution with an RMS of 4.8 psec and fitted Gaussian of 4.3 psec (shown on the right in Fig 15). Some of this limiting resolution is due to the finite spot size of the laser beam ( $\sim 0.5$  mm), and limitations of the digital readout of the two independent oscilloscope channels used to measure each side of the stripline.

The data sets can be further divided into bins of N/S. Figure 16 shows the relationship. Even with single-PE data, N/S levels as low as 0.006 were achievable, due to the very high pulse amplitudes of the Demountable (see Fig 18). As expected, pulses with smaller N/S (corresponding to larger signals) demonstrate better time resolution. A linear fit to these points intersects with

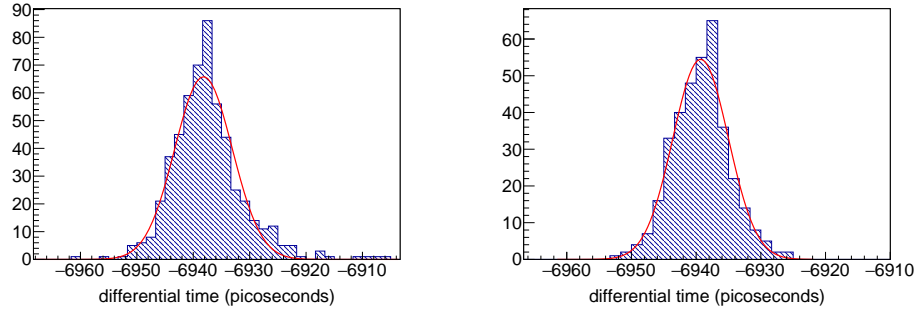


Figure 15: LEFT: Differential time spread for the demountable detector, fitted with a gaussian. The RMS of the distribution is 6.4 psec, and sigma of the gaussian is 5.1 psec. RIGHT: With a modest cut on  $N/S < 0.01$ , the sample is reduced by only 44%, leaving a DTS distribution with a more gaussian shape with RMS 4.8 psec and fitted sigma of 4.3 psec.

the y-axis at a resolution close to 1 picosecond for large signals. In contrast, the single-PE absolute time resolution is dominated by intrinsic jitter in the MCP stack and remains above 40 psec, even in the large-signal limit (Figure 17). The  
 370 fluctuations in avalanche formation that dominate the single-PE TTS, cancel in the differential timing measurement. This explains the robustness of the relationship between the differential time resolution and  $N/S$ , measured with different MCP stacks and at different times.

The measured differential time resolution of 5.1 psec corresponds to a spatial  
 375 resolution in the direction along the striplines of roughly 0.44 mm. Figure 19 shows the average time delay between the two ends of a stripline as a function of position along that stripline. These data show a linear relationship with a slope of roughly  $0.57c$ , in agreement with the measured speed of signal propagation along the micro-striplines [11].

## 380 8. Conclusion

LAPPD<sup>TM</sup> detector systems are capable of providing absolute time resolutions for single-PEs consistently below 100 picoseconds, and typically below 60 picoseconds. Moreover, the large gain and high signal-to-noise ratio make LAPPD pulses easy to separate from background. While absolute time resolu-

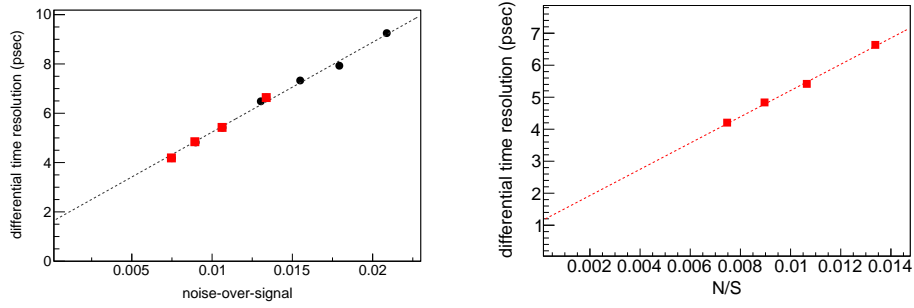


Figure 16: LEFT: Differential time resolution as a function of Noise/Signal, plotted for data collected using the Demountable detector in 2014 (red squares) and the 8" chamber in 2012 (black circles). Error bars are smaller than the marker size. The intercept of fitted line intersects at 1.6 psec. RIGHT: Same plot, for 2014 demountable data only. The intercept of the fit intersects with 1.1 psec.

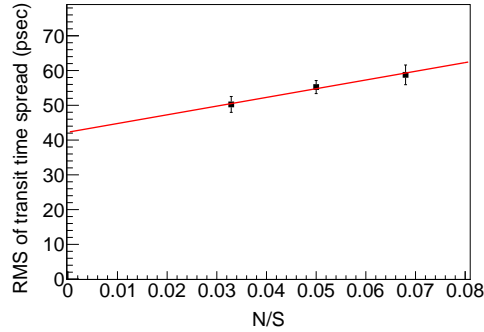


Figure 17: Single-photoelectron time resolution measured in the 8" chamber, binned by noise/signal ( $2\sigma$  error bars). Slight improvements are seen with larger signals, but the single-PE resolutions are limited by fundamental constraints such as pore diameter and asymptotically approach 42 psec for large S/N.



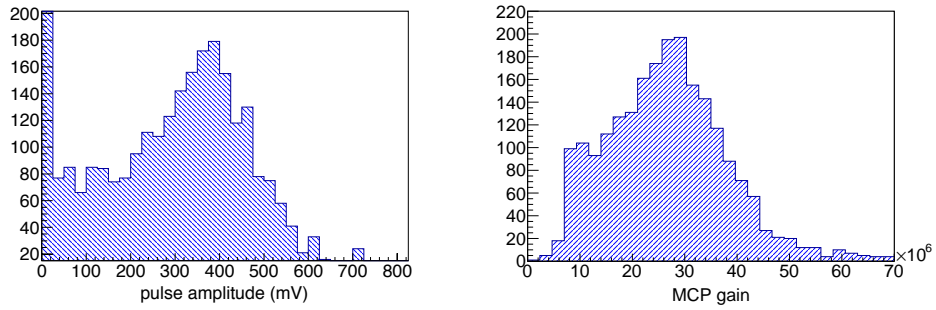


Figure 18: LEFT: Distribution of signal amplitudes from the demountable LAPPD<sup>TM</sup> operating at 2700 V, including pedestal events (zero bin). RIGHT: The reconstructed MCP gain distribution for good pulses, with peak at around  $3 \times 10^7$ .

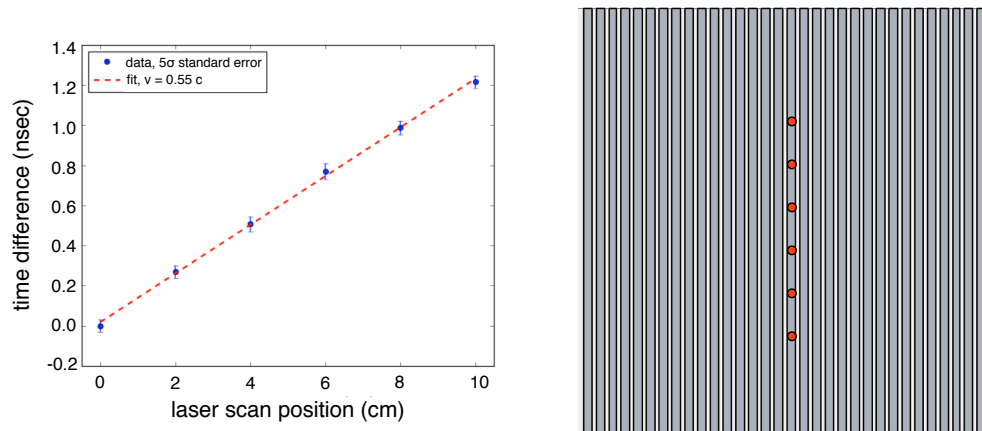


Figure 19: Mean differential time between the arrival of the pulse at the two ends of the microstripline anode, plotted as a function of position along the anode (left).

tion of single-photoelectrons is limited by intrinsic factors such as pore geometry and operational voltages, differential time resolutions between the two ends of a microstripline are limited largely by the RF characteristics of the low cost, silk-screened glass anode and by the oscilloscope readout. In this paper, we observe differential time resolutions below 5 picoseconds for large signals, with an extrapolated resolution below 2 picoseconds as N/S approaches zero. Further improvements to the gain structure and readout can enable even better single-PE and large signal performance.

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