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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 × 20 cm MCP consistently below 70 ps, spatial resolutions of roughly 500 μm, and median gains higher than 10^7. The RMS measured at one particular point on an LAPPD detector is 58 ps, with $\pm 1\sigma$ of 47 ps. The differential time resolution between the signal reaching the two ends of the delay line anode is measured to be 5.1 ps for large signals, with an asymptotic limit falling below 2 ps as noise-over-signal approaches zero.

1. Introduction

Microchannel plate photomultiplier tubes (MCP-PMTs) are compact vacuum photodetectors [1], capable of micron-scale spatial resolutions [2], sub-nanosecond time resolutions [3–5], and gains exceeding 10^7 [6]. Economical, large-area MCP photosensors with these characteristics would bring much 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 × 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 × 20 cm LAPPD$^{\text{TM}}$ systems. At sufficient operational voltages, we observe single-photoelectron time resolutions in the range of 50–60 ps, consistent with those of commercial MCPs with comparable pore structures. Differential time resolutions are measured as low as 5.1 ps, with the large signal limit extrapolating below 2 ps. Spatial resolutions are set by the granularity of the economical stripline anode design (see Section 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$^{\text{TM}}$ 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 in Section 8.

2. Essential elements of the LAPPD$^{\text{TM}}$ design

Fig. 1 shows the structure of an LAPPD$^{\text{TM}}$ [10]. Light is incident on a photocathode, producing photoelectrons. These accelerate

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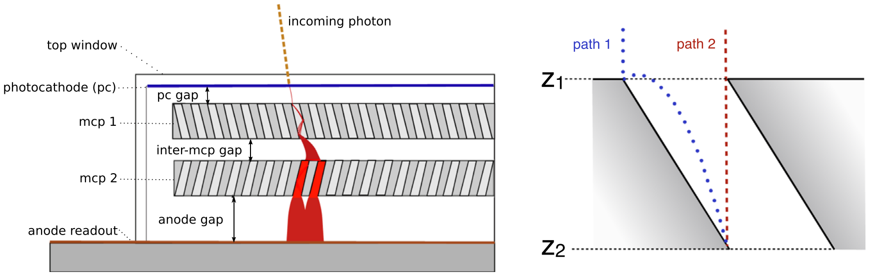

Fig. 1. Left: the structure of an LAPPD^{TM} photomultiplier tube. Right: a schematic of photoelectrons entering the pore of an MCP. Both the dashed red and dotted blue trajectories reach height z_1 at the same time, but arrive at z_2 at different times due to different velocities and path lengths.

across a potential 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° bias angles in opposite directions. This prevents positive ions, produced by the electron cascade in the lower plate, from reaching 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 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 Ω micro-stripline design [11]. The positions of photon strikes on the photocathode are determined (i) by differential timing along the striplines, and (ii) by calculating a weighted centroid of the charge on adjacent striplines in the transverse 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

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.
- 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*

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.[1]

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 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 μm diameter and 8° bias of the default LAPPD^{TM} 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 μm [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 $N_{secondaries}$, 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.

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 on extracting the signal from noise. Here we briefly discuss these issues, based largely on material from Ref. [14–16].

Fig. 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 given noise level on the rise time of the signal, which defines the slope between voltage and time.

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[1] 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.