Towards a Quantitative & Open-Source Assessment of PMT Performance

Lindsey Wang[1, 2], Manuel Schottdorf[3]

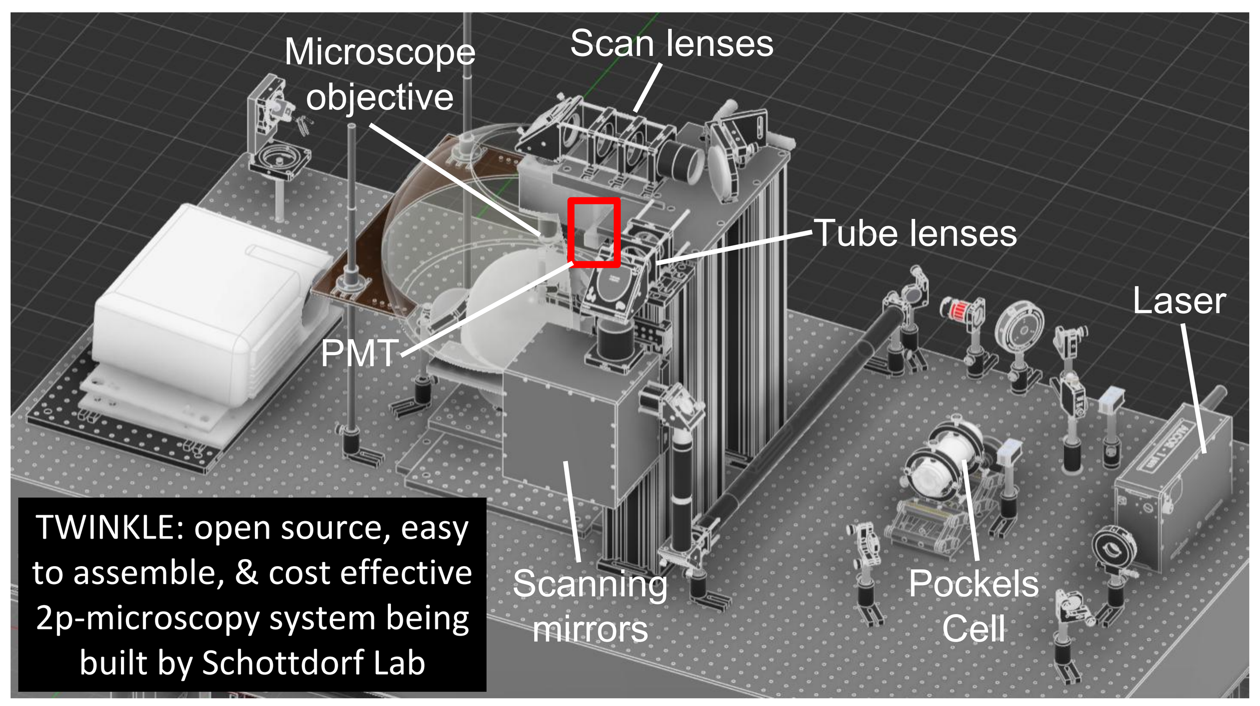
Departments of Electrical & Computer Engineering[1], Mathematical Sciences[2], and Psychological & Brain Sciences[3], University of Delaware, Newark DE

Overview

Photomultiplier tubes (PMTs) are photon-counting optoelectronic devices that play a critical role in multi-photon and confocal microscopy. Despite their sophisticated hardware, extreme sensitivity to light, and critical role in modern imaging, no open-source reliable measurement technique exists to characterize their performance and degradation. In this project, we begin to develop a system to analyze PMT health.

Background

- **Two-photon (2p) Microscopy**
  - Fluorescent imaging technique of live specimens
  - High resolution up to few hundred nanometers
  - Multi-photon excitation of fluorescent molecule



TWINKLE: open source, easy to assemble, & cost effective 2p-microscopy system being built by Schottdorf Lab

- **Key Components of TWINKLE 2p-Microscopy System**
  - Laser: femtosecond pulsed laser
  - Pockels Cell: electro-optical modulator for to control laser intensity
  - Scanning mirrors: move laser beam to raster image
  - Scan & tube lenses: magnify sample fluorescence to fill objective's back aperture (image collection)
  - PMT: collect sample fluorescence

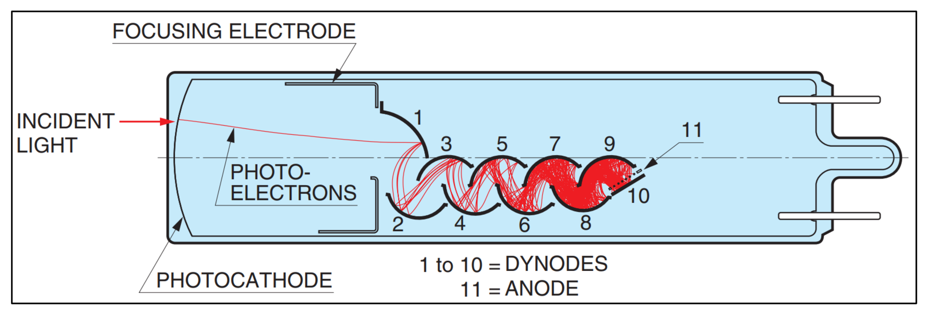
ND Filter (ND=3+4)

- **Ancillary Equipment for PMT Analysis**
  - Data acquisition system (DAQ)
  - LED, OPT101 (photodiode), neutral density filters
  - Transimpedance amplifier (TIA), 1N4005 (diode)
  - AD8047A (opamp), CD74HC390 (ripple counter)
  - Oscilloscope, waveform generator
- **Benchmarks for PMT Analysis**
  - Peak height: amplitude of photon events
  - Peak count: frequency of photon events
  - Peak width: transit time of photon events

Methodology

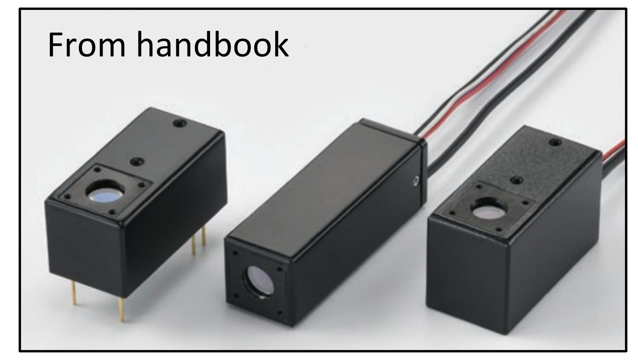
Photomultiplier (PMT) Design & Operation

- **PMT Design**
  - Light-sensitive devices in vacuum tube w/anodized aluminium light-tight housing
  - Collection window (input light) → focusing electrodes → photocathode (photoelectric effect) → dynodes (electron cascade & amplification) → collection anode (current)
  - Gain & sensitivity (control voltage; 0.0-0.8V)



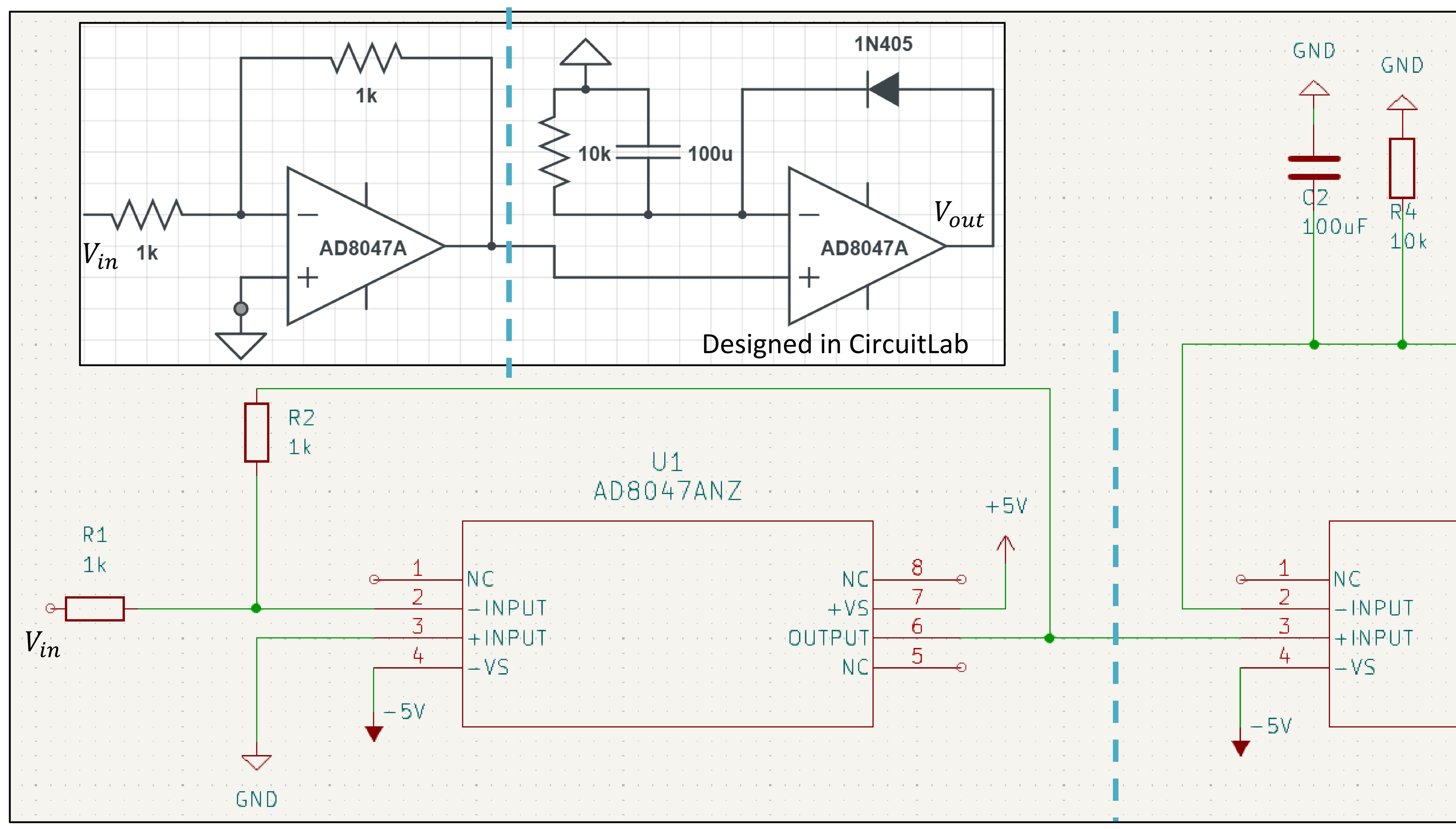
Innerworkings of linear-type PMT (from handbook)

- **Definitions**
  - Photon: fundamental particle of light
  - Photoelectric effect: incident photon converted to electron when incident on surface
  - Secondary emission: "secondary" electrons released from metal when bombarded by high-energy particles



Left: H16200 Series, Center: H16201 Series, Right: H16204 Series

- TWINKLE uses H16201P-40 PMTs
  - Red: power
  - Black: ground
  - White & blue: control voltage
  - 15V operation
  - GaAsP photocathode



Inverter (left of dotted line) + max detector (right of dotted line) circuit schematic for peak height analysis. Output of inverter is fed into input of max detector. Top left is simplified design.

Peak Height Analysis

- PMT (TIA) output = negative voltage (collection of electrons) → inverter + max detector circuit → DAQ for data collection & plotting
- For given PMT, systematically scan through light & gain settings to determine performance relationships

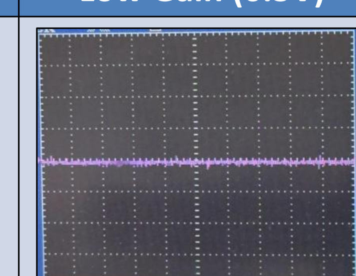
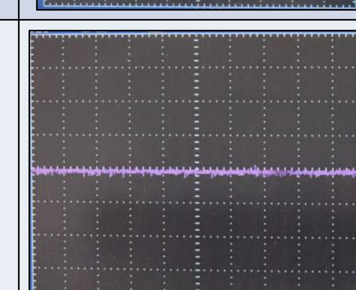
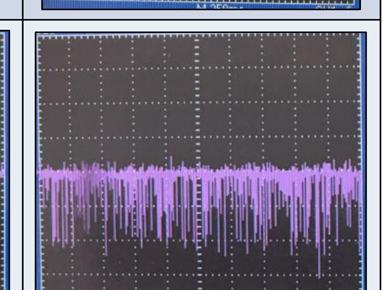
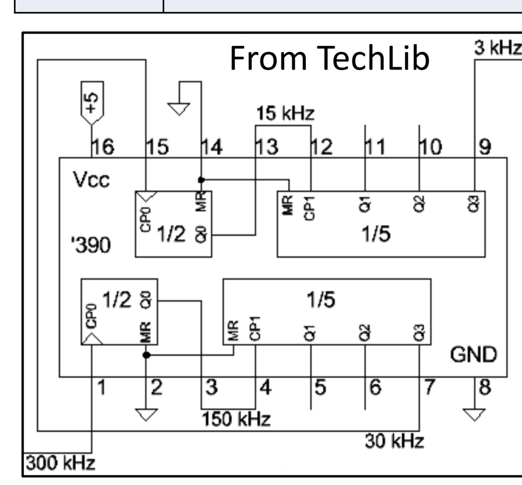
AF5796	Low Gain (0.5V)	High Gain (0.8V)
Dim LED (0.05 pW)		
Bright LED (0.8 pW)		

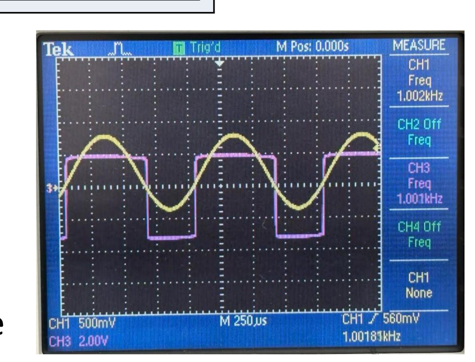
Table of PMT AF5796 outputs for various gain & LED settings on oscilloscope (500mV/div). Sharp peaks represent single photon events. Higher gain → more frequent + higher amplitude photon events

Peak Count Analysis

- PMT (TIA) output → inverter → Schmitt trigger → ripple counter
- Schmitt trigger: removes noise & digitizes analog signal (square waveform generator); comparator circuit w/positive feedback
- Ripple (asynchronous) counter: digital sequential circuit w/flip-flops; only first flip-flop receives external clock



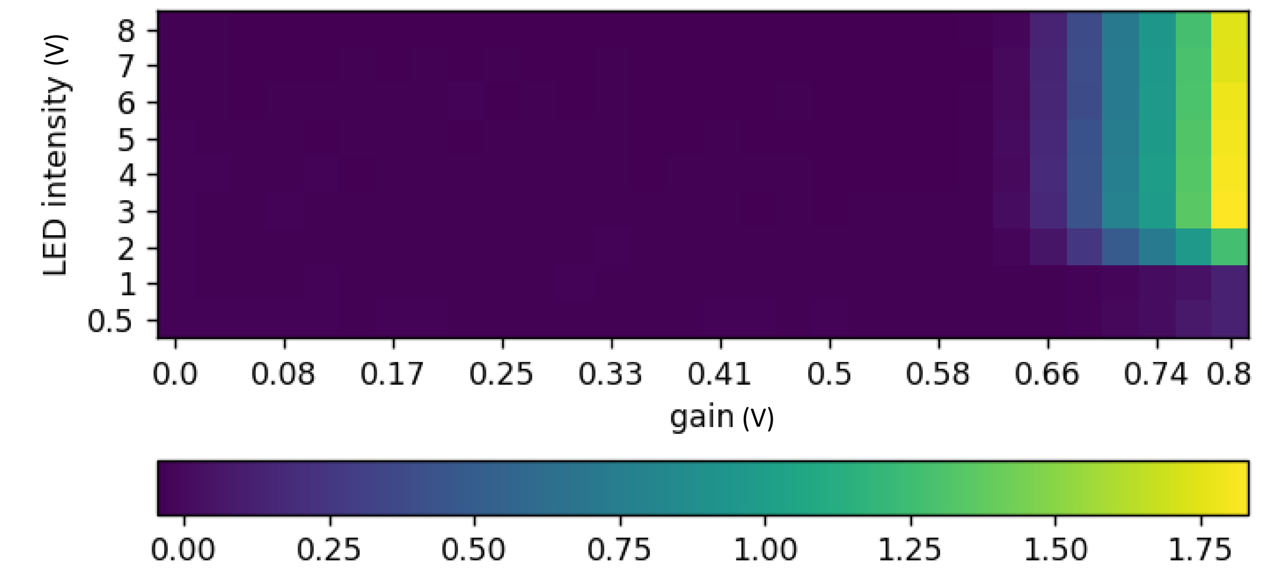
Left: Divide-by-100 ripple counter example



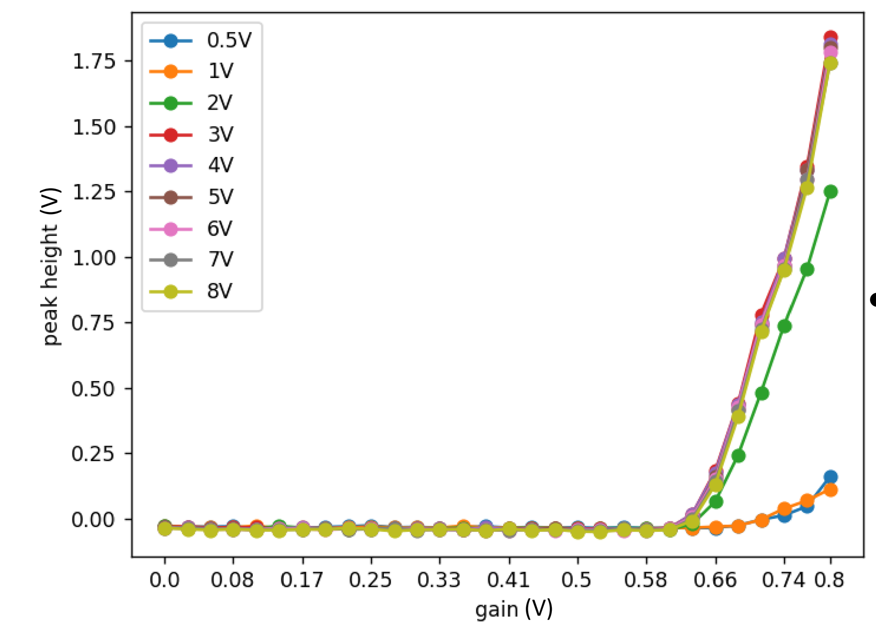
Above: Sine wave (yellow) digitized by Schmitt trigger (purple)

Results (Contributions)

- **Peak Height Analysis (PMT signals)**

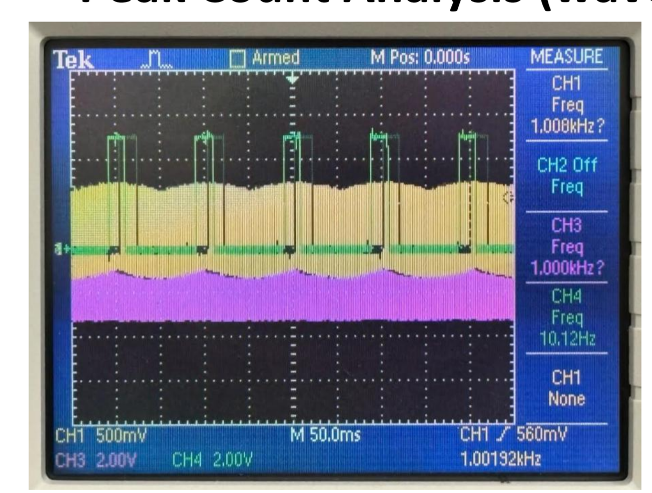


- Above: peak height plot across gain settings w/varying input light to determine sensitivity
- Peak height independent from light once adequate photon input reached (since photons all have same energy)



- Left: gain vs. peak height w/varying input light (in legend)
- Exponential growth from ~0.6V gain typical for working PMT

- **Peak Count Analysis (waveform generator)**



- Left: sine wave (yellow) @ 1kHz → Schmitt trigger output (purple) → ripple counter output (green) @ 10Hz
- Half-wave rectified sine wave mimics PMT output after TIA & inverter

Future Work (2nd Semester of Thesis)

- Continue peak count analysis (w/ high-speed surface mount ripple counter)
- Analyze peak width to further characterize dynodes
- Design system & publish open-source documentation for community use for evaluating PMT health

Selected References

[1] Schottdorf M, Rich PD, Diamanti EM, Lin A, Tafazoli S, Nieh EH, et al. (2025) TWINKLE: An open-source two-photon microscope for teaching and research. PLoS ONE 20(2): e0318924.

[2] Hamamatsu. Photomultiplier Tubes Basics and Applications.

[3] NI-DAQmx Python Documentation. From https://nidaqmx-python.readthedocs.io/en/stable/