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INMM/ESARDA Annual Meeting

Silicon Photomultiplier Characterization and Minimization of Cross-talk to Enable Radiation Detection in Harsh Environments

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Introduction

Department and University: Nuclear, Plasma, and Radiological Engineering (NPRE) Department at the University of Illinois Urbana-Champaign (UIUC)
Academic Advisor: Angela Di Fulvio
NSSC Research Focus Area(s): Radiation Detection
Planned Graduation Date: December 2023 (MSc Thesis)

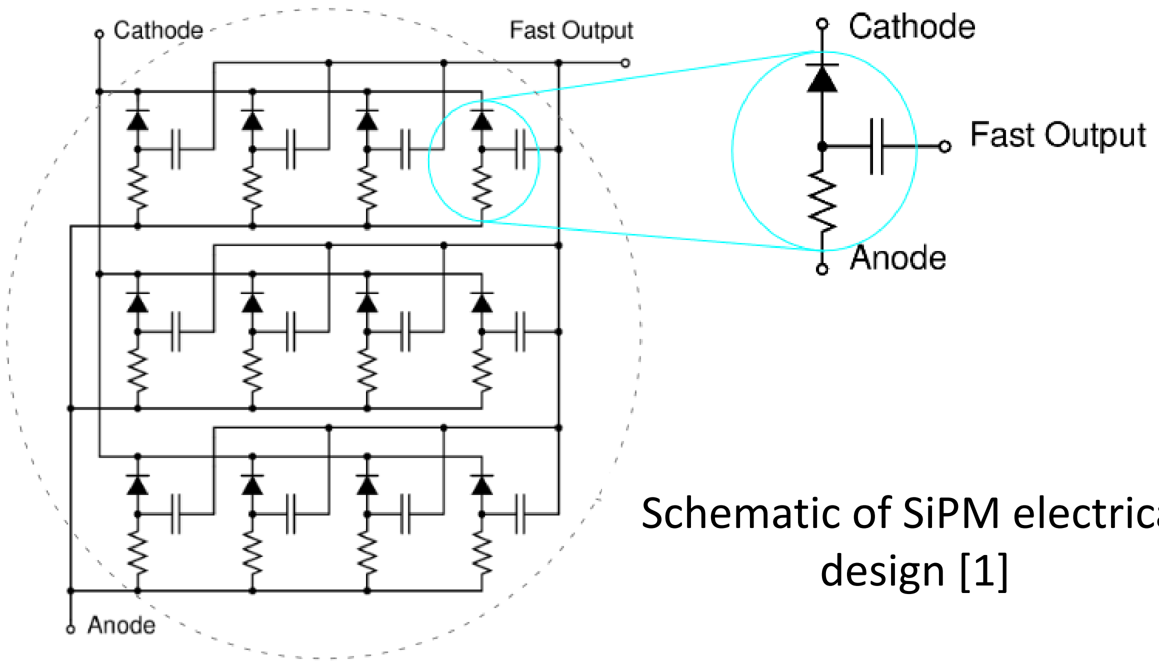
Lab Mentors and Partner National Laboratory: Thomas Weber, Jon Balajthy, and Melinda Sweany at Sandia National Laboratory

Mission Relevance of Research:

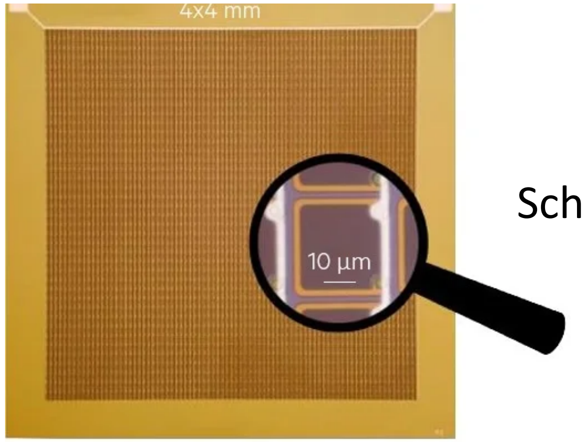
My research focuses on characterizing silicon photomultipliers (SiPMs) to enable their use in harsh environments. This work is highly relevant to the mission of the National Nuclear Security Administration (NNSA), which seeks to deploy radiation detectors in harsh environments to help prevent nuclear weapon proliferation and reduce the threat of nuclear and radiological terrorism worldwide.
Within the framework of the NSSC, I was awarded the Keepin Fellowship in Summer 2022. This opportunity enabled me to start an internship at Sandia National Laboratory, which is still ongoing. Part of this work is supported by the UIUC-SNL LDRD project entitled "Development of High-Fidelity Radiation Detection Models with SiPM Readout".

Motivations and Objectives

- Silicon photomultipliers (SiPMs) are emerging devices that allow high-efficiency light conversion into an electrical signal while having excellent timing characteristics
- SiPMs are small in form-factor and enable the use of scintillation detectors in compact devices encompassing multiple detectors
- SiPMs are candidates to replaces vacuum photomultiplier tubes (PMTs) for radiation detection in harsh environments but require further characterization
- Robust models that connect the electrical and optical performance to the radiation detection performance of the SiPM are urgently needed
- This work is a collaboration with Sandia National Laboratory to enable the deployment of SiPMs in harsh environments
- Our specific objective is to characterize and reduce the dark counts in SiPMs and develop experimentally validated models



Schematic of SiPM electrical design [1]



Schematic of SiPM [2]

[1] *Microfj Series - Onsemi*. Onesmi, https://www.onsemi.com/pdf/datasheet/microj-series-d.pdf
[2] “What Are Silicon Photomultipliers (Sipms)?” *AZoSensors.com*, 3 Feb. 2021

Technical Challenges and Progress to Date

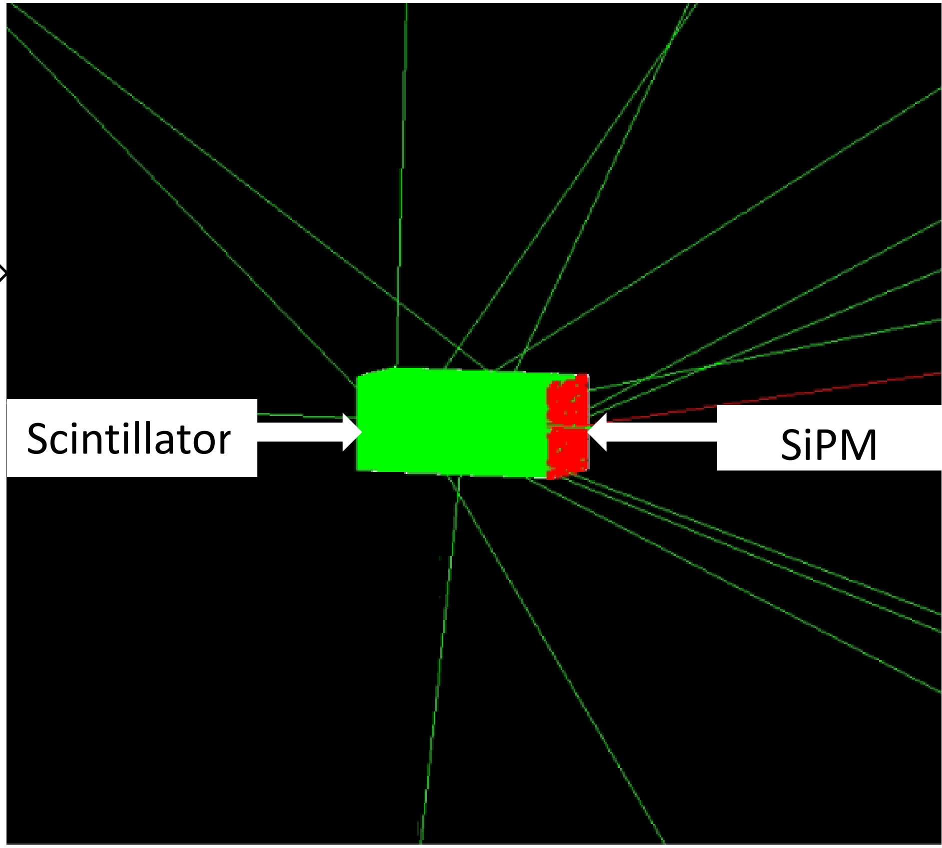
- Overarching challenge that has delayed the deployment of SiPMs in harsh environments is the increase of dark counts and correlated noise with temperature
- A specific challenge that we addressed was to improve the agreement between the simulated responses of an Eljen Technology EJ-276 and EJ-200 coupled to a MicroFJ30035 SiPM and the measured ones

Progress to date

- Characterization and analysis of response parameters of multiple SiPM technologies from different manufacturers

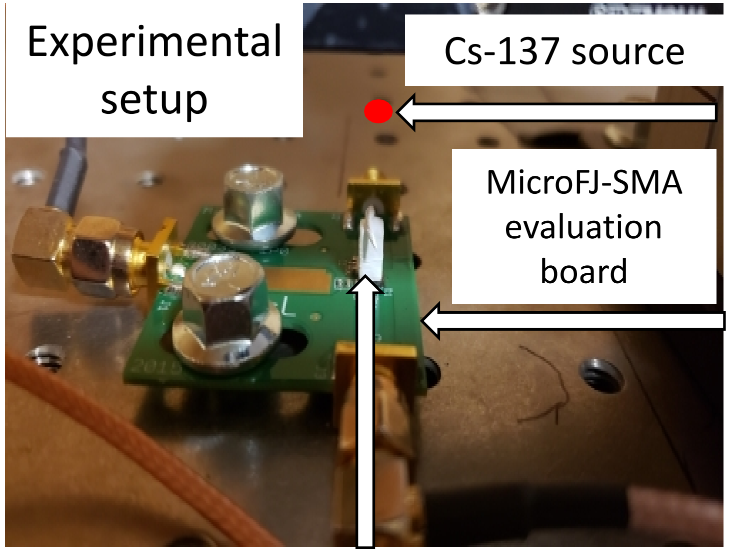
- Detailed simulation of SiPM response while coupled to organic scintillator

- Characterization and reduction of optical crosstalk in SiPMs



Visualization of the GEANT4 simulation of the response of an SiPM coupled to a 3mm x 3mm x 6mm EJ-276 scintillator irradiated by a Cs-137 source

Specific Technical Challenges



EJ-276 scintillator coupled to MicroFJ 30035 SiPM

- Extract response parameters from measurements of SiPM response
  - Dark counts, optical crosstalk, afterpulses
- Use GosSiP to incorporate the parameters into the electrical response
  - Generic framework for simulation of Silicon Photomultipliers (GosSiP) [1]

SiPM characterization workflow

Simulation of radiation transport and light production in the scintillator in GEANT4

↓

List mode of the scintillation pulses

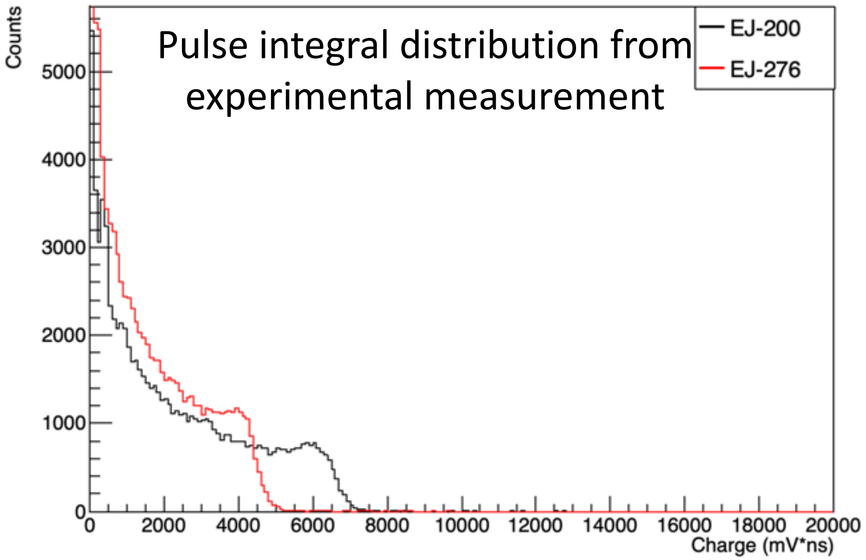
↓

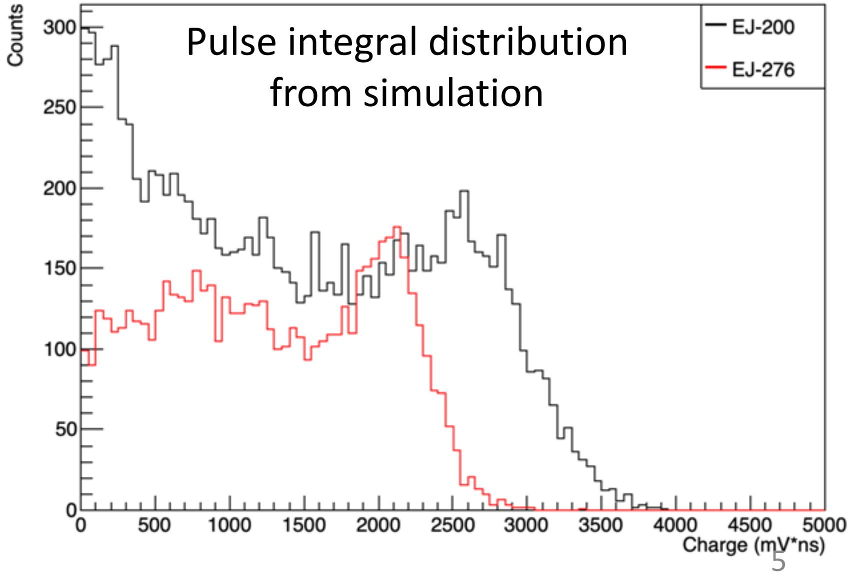
GosSiP simulation of the SiPM electrical response

↑

Experimentally extract parameters of SiPM response

[1] P Eckert et. al (2012) “Study of the response and photon-counting resolution of silicon photomultipliers using a generic simulation framework”

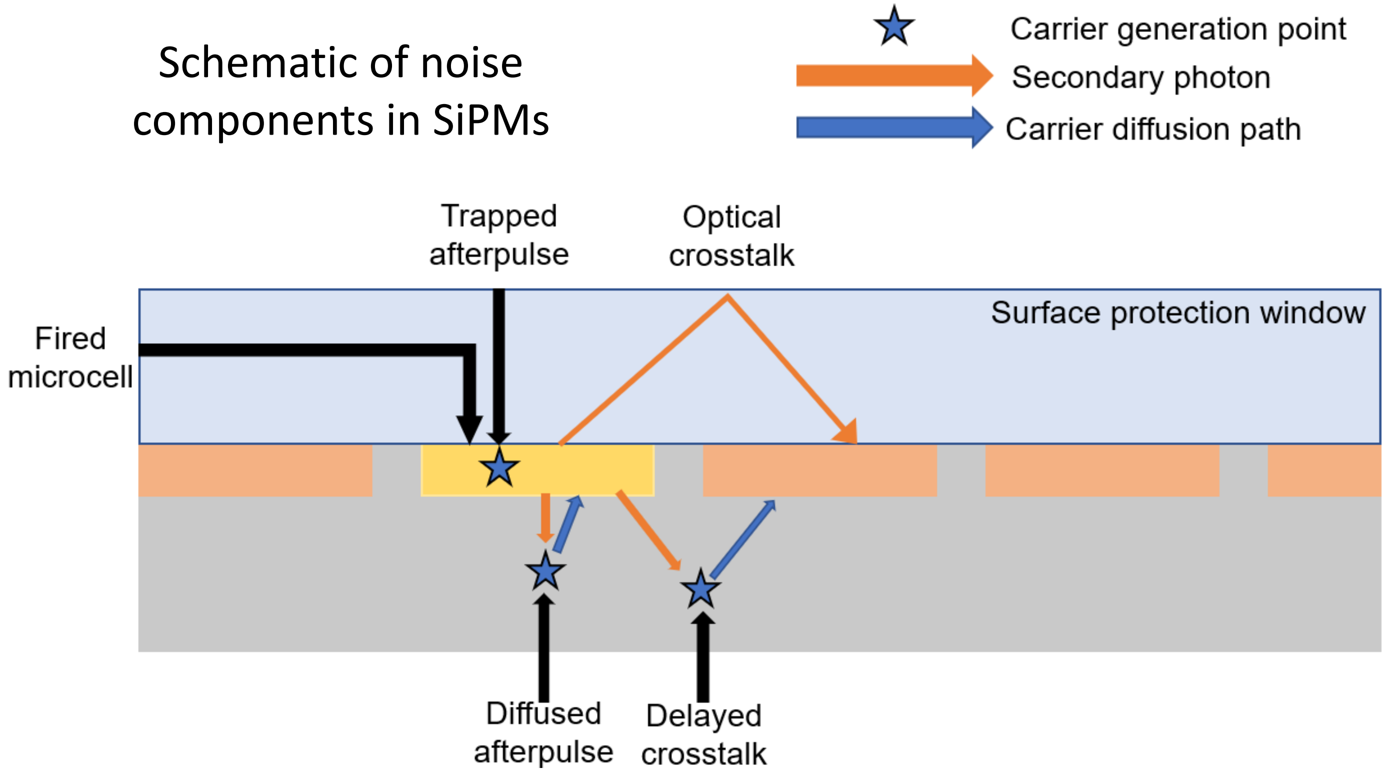


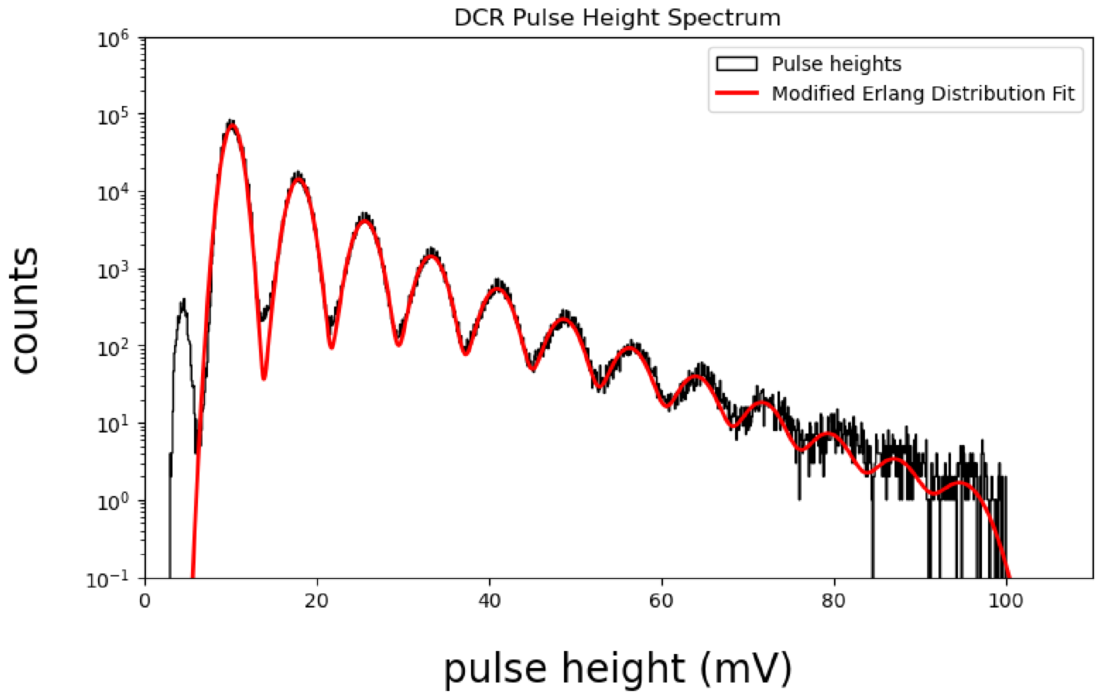


Dark Count Spectrum Analysis

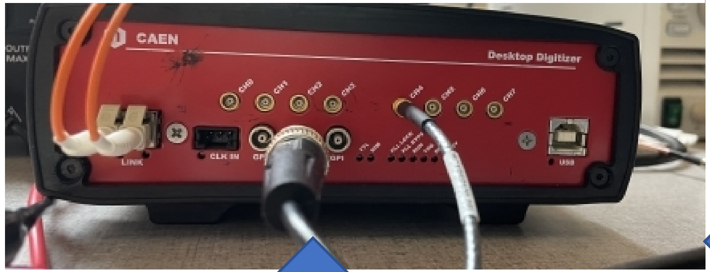
- Dark counts occur in SiPMs when thermal carriers trigger an avalanche of electrons
- The amplitude of each dark count signal can be recorded to create a dark count spectrum
- From this spectrum, performance parameters can be extracted
    - Gain, crosstalk probability, avalanche noise, electronic noise

Schematic of noise components in SiPMs





DT5730 Desktop Digitizer



DT5810B Digital Emulator

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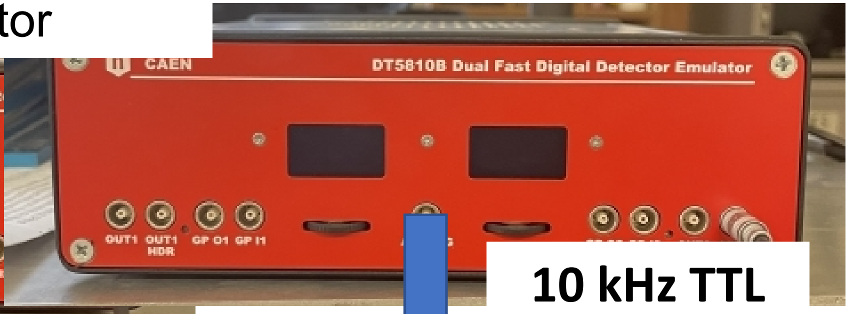
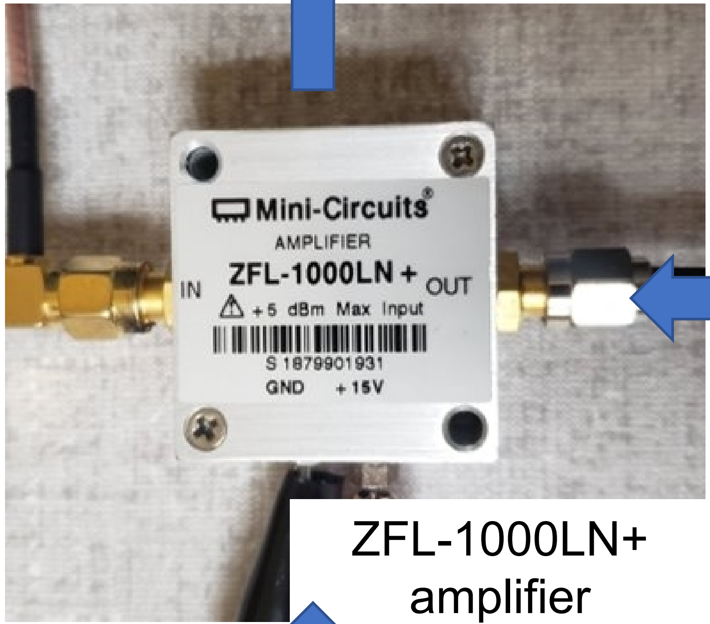
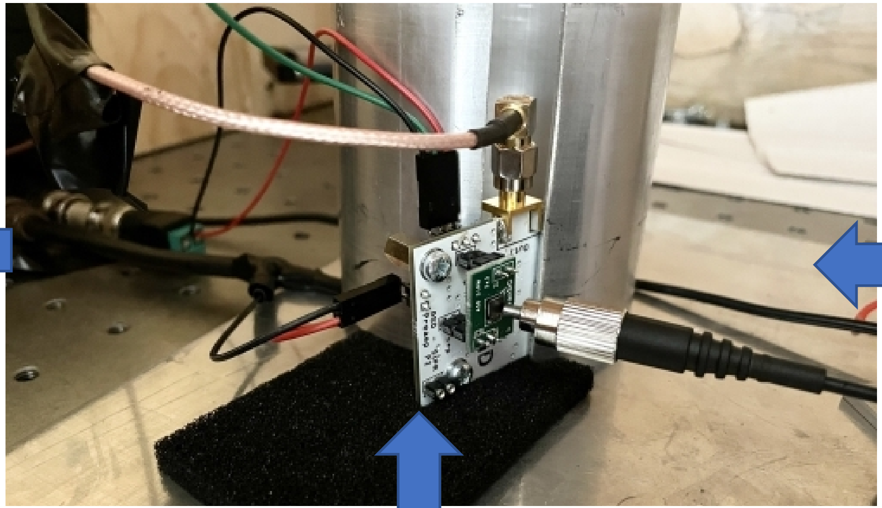


10 kHz TTL

10 kHz TTL



ZFL-1000LN+ amplifier

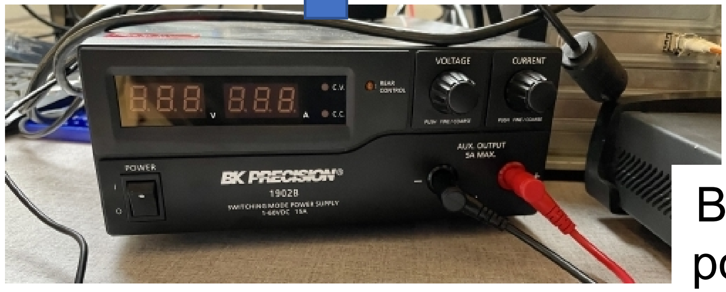


Overvoltage 6V

SiPM

CAEN SP5601 Light Source

15V



BK Precision power supply

DCR Setup

Dark Count Pulses and Data Processing

Decay removal model

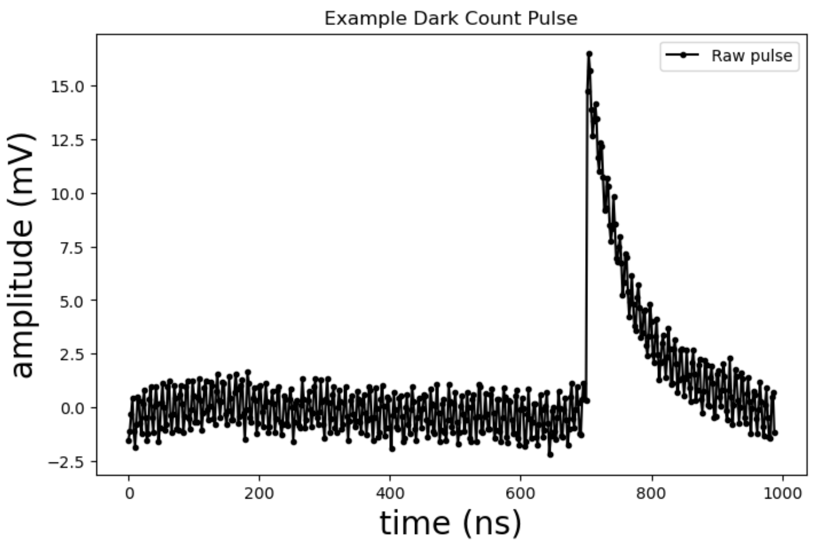
$$V_i = V_{0_i} + \frac{1}{\tau}\sum_{j=1}^{i} V_{o_j} \times (t_j - t_{j-1})$$

where $t_{j-1} = 0$

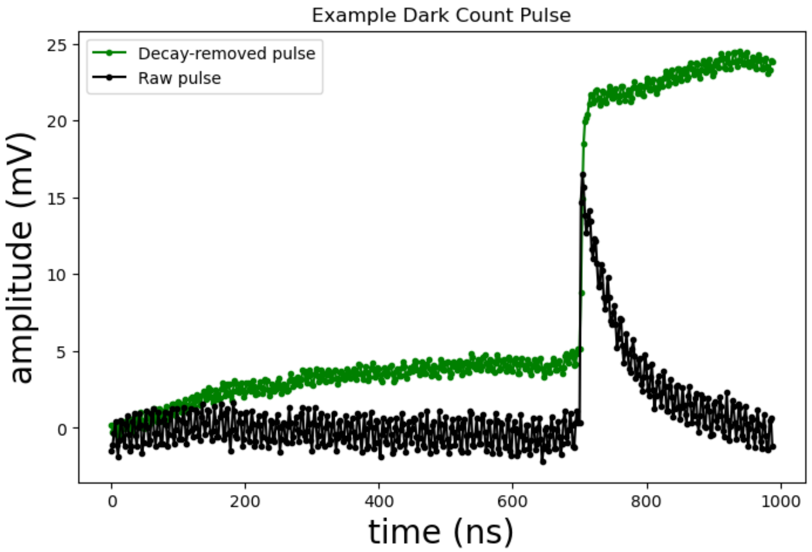
and $V_0 = V - V_{min}$

t=time in nanoseconds V= volts in millivolts τ= microcell recharge time

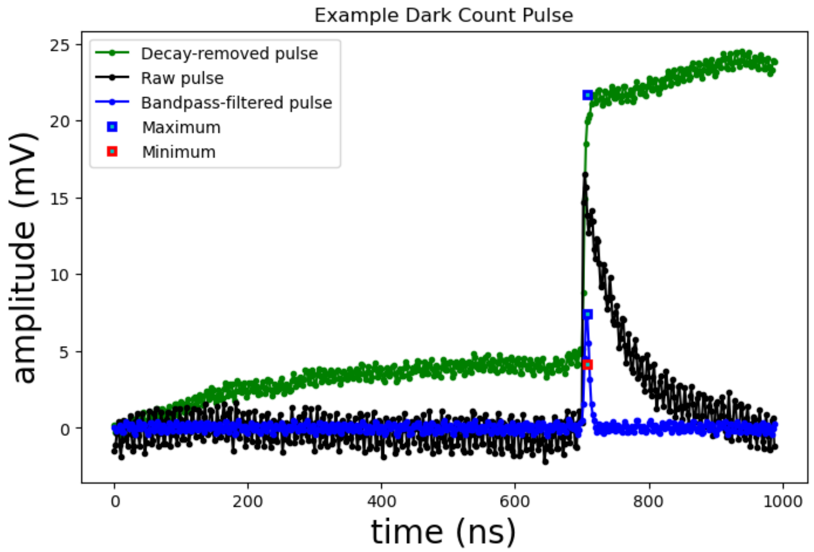
i represents the current sample and *j* represents the previous samples



Raw pulse



Green trace is after applying the equation above to remove the decay of the pulse



Removing the decay and applying a high-pass filter (blue) allows for more accurate pulse height calculation

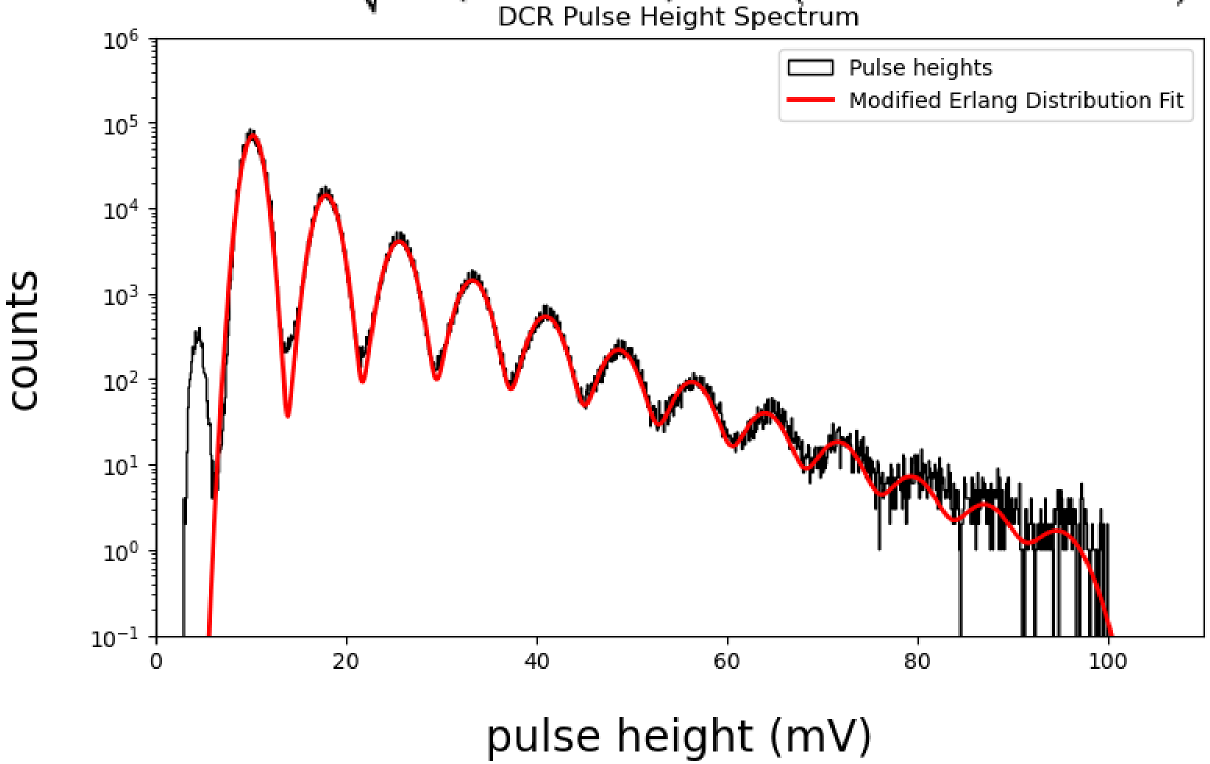
Dark Count Spectrum

- The calculated pulse heights were graphed as a histogram, which was fit with the modified Erlang distribution
- Difference in afterpulsing may be attributed to different manufacturer parameters used to calculate the afterpulses

	Onsemi Board	Onsemi data sheet value
Dark count rate	85 kHz/mm^2	150 kHz/mm^2
OCT probability	21.9%	25%
Afterpulse probability	21.2%	5%
Gain	5.12×10^7 electrons	6.3×10^6 electrons

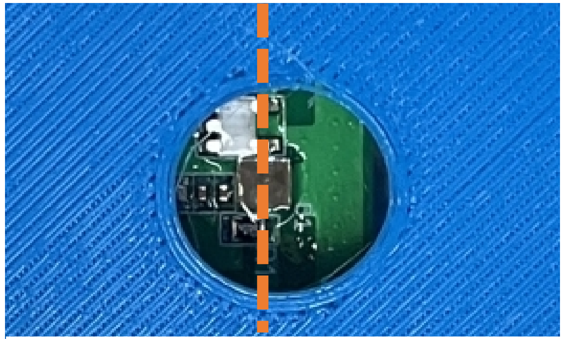
Model function

$$Y(x) = A\sum_{n=1}^{\infty} \frac{p_n}{\sqrt{2\pi(\sigma_e^2 + n\sigma_a^2)}} \exp\left(\frac{-\left(x - nx_g - x_o\right)^2}{2(\sigma_e^2 + n\sigma_a^2)}\right)$$

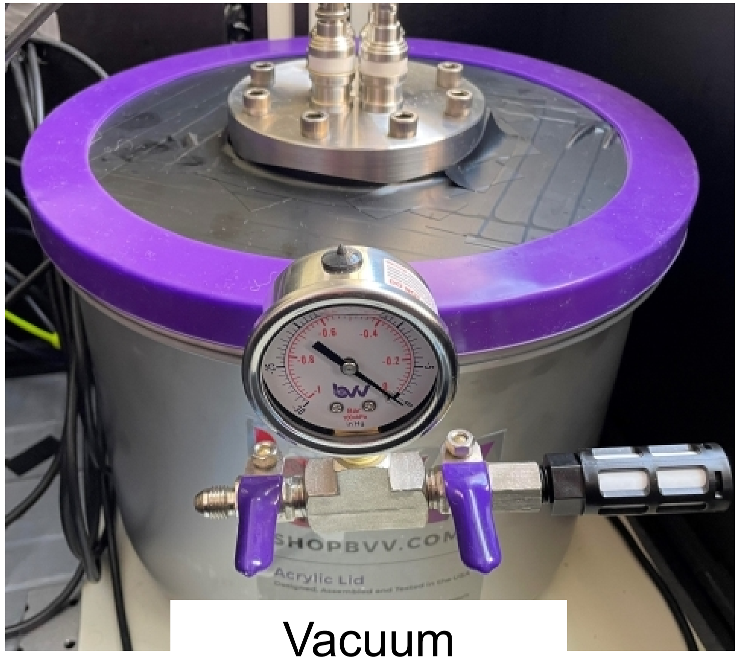


p_n = crosstalk probability
σ_a = avalanche noise
x_g = gain
σ_e = electronic noise
x_0 = baseline offset

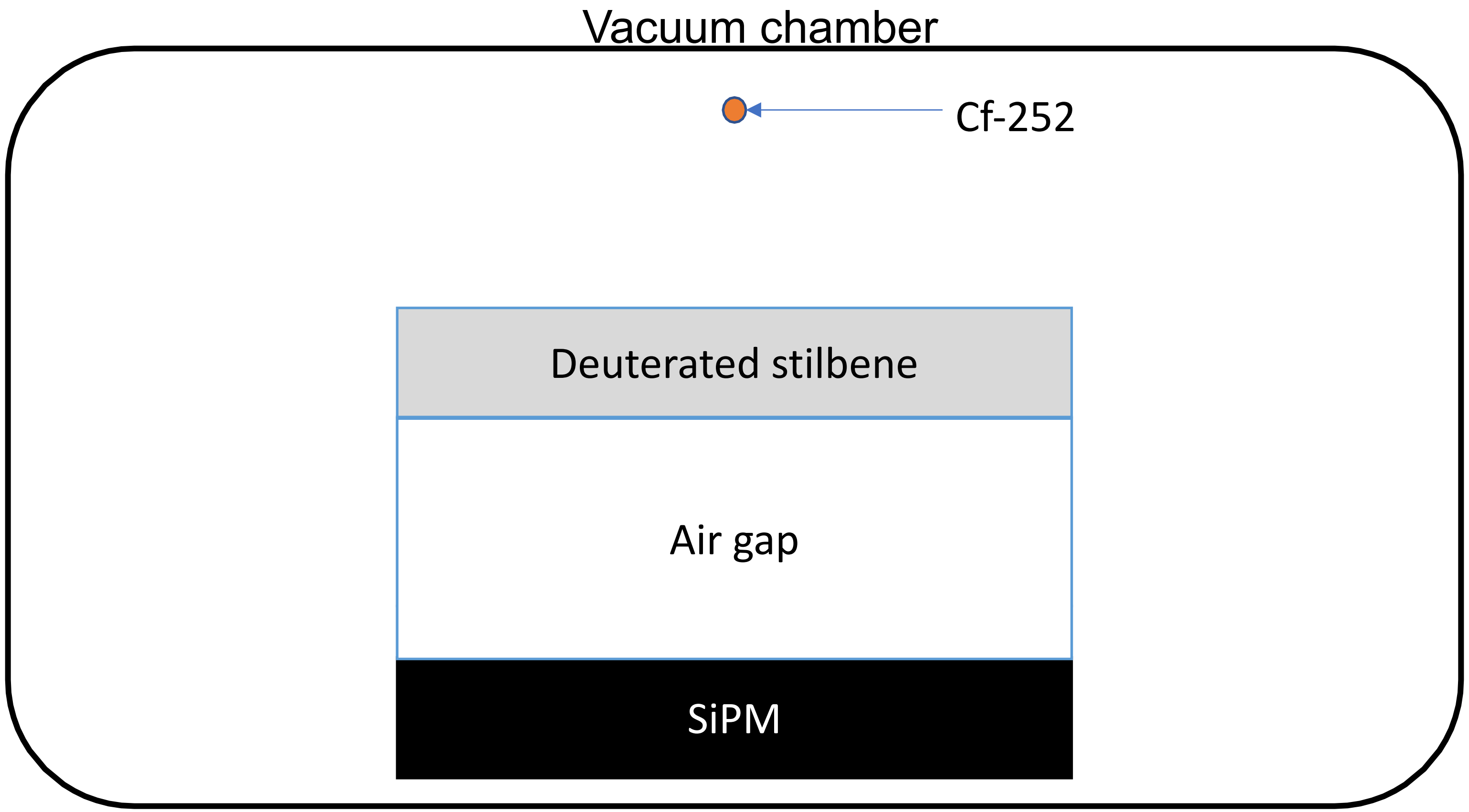
Optical Crosstalk (OCT) Measurement Setup



SiPM beneath holder



Vacuum chamber



Schematic showing cross section along dashed line of measurement setup
Note: schematic not to scale

OCT Results

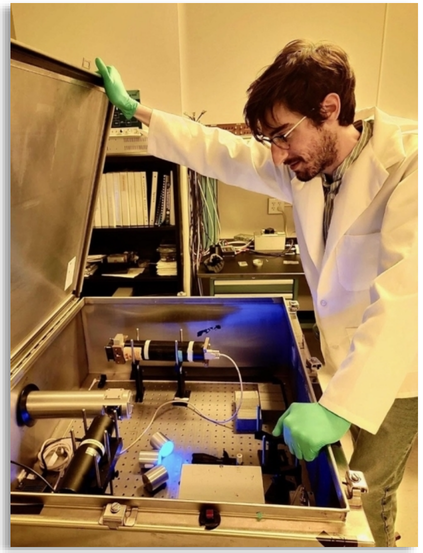
	Filter name	Wavelength Selection	OCT probability
No filter			21.4%
Interference filter	Semrock BrightLine FF01-520/70-25	Transmittance band: 485nm-555nm	23.7%
Bandpass filters	UG5	400nm-600nm	17.8%
	BG39	700nm-1000nm	17.6%
	BG40	700nm-1000nm	17.6%
	KG2	800nm-1200nm	18.1%
Longpass filters	N-WG280	200nm-250nm	18.7%
	OG590	200nm-550nm	18.9%
	RG695	200nm-650nm	18.6%
	RG850	200nm-700nm	18.1%
	RG1000	200nm-700nm	17.8%

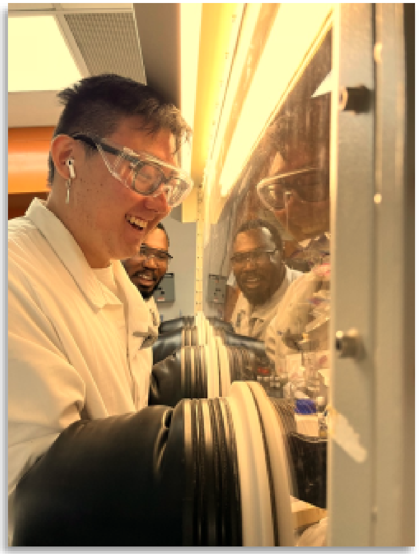
Table listing results of OCT filter study

Conclusions and Current Work

- SiPMs do not benefit from decades of R&D which have matured PMT technology; therefore, robust and high-fidelity models are needed for their optimum deployment, especially in harsh environments
- We have characterized first-principle parameters of SiPM response through new dark count rate experimental setups
- Our estimated parameters are in good agreement with the manufacturer's parameters
- The developed procedures will enable comparison between different technologies solely based on their micro-electronic SiPM configuration
- The extracted parameters will be used for first-principle simulations that generate electrical SiPM response (GosSiP) from radiation transport simulation (GEANT4)
- Finally, the characterization and control of specific parameters, such as OCT, are expected to reduce the noise associated with the signal and improve detection metrics such as energy and time resolution and pulse-shaped discrimination

Acknowledgements





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Thank you for your attention! Questions?