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

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NSSC Fall Workshop and Advisory Board Review
October 17-18, 2023

Introduction

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

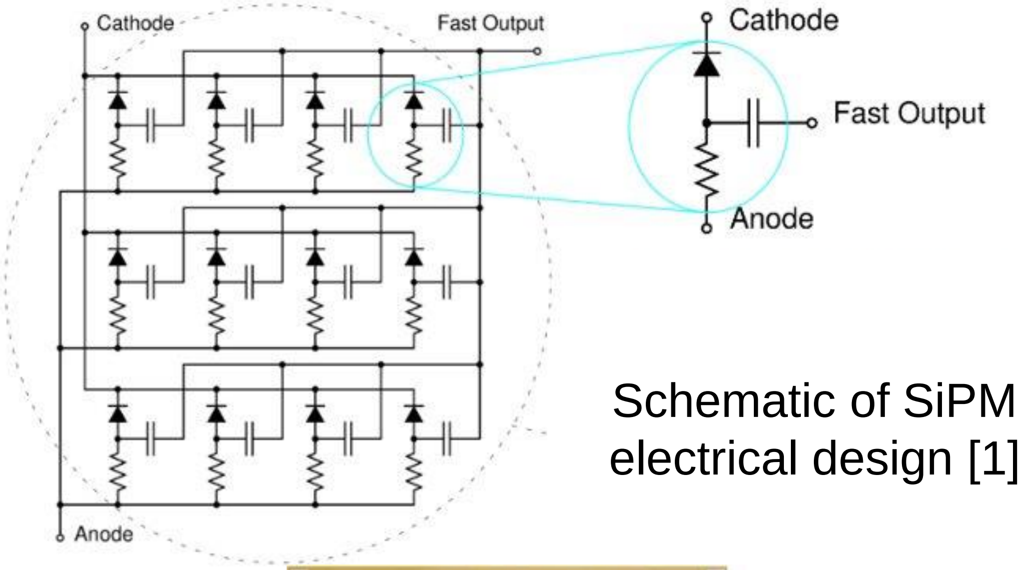
Lab Mentor and Partner National Laboratory: Thomas Weber, Jon Balajthy, and Melinda Sweany at Sandia National Laboratory

Mission Relevance of Research:

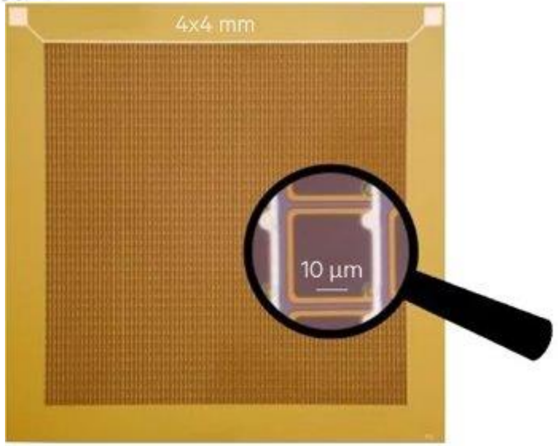
My research focuses on characterizing silicon photomultipliers (SiPMs) to enable their use in harsh environments. This work is highly relevant to the mission of the National Nuclear Security Administration (NNSA), which seeks to deploy radiation detectors in harsh environments to help prevent nuclear 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 support by the UIUC-SNL LDRD project entitled Development of High-Fidelity Radiation Detection Models with SiPM Readout.

Motivation 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 candidates to replaces vacuum photomultiplier tubes (PMTs) in certain radiation detection applications
- Robust models that connect the electrical and optical performance to the radiation detection performance of the SiPM are urgently needed
- Our specific objective is to characterize and reduce the dark counts in SiPMs and develop experimentally validated models



Schematic of SiPM electrical design [1]



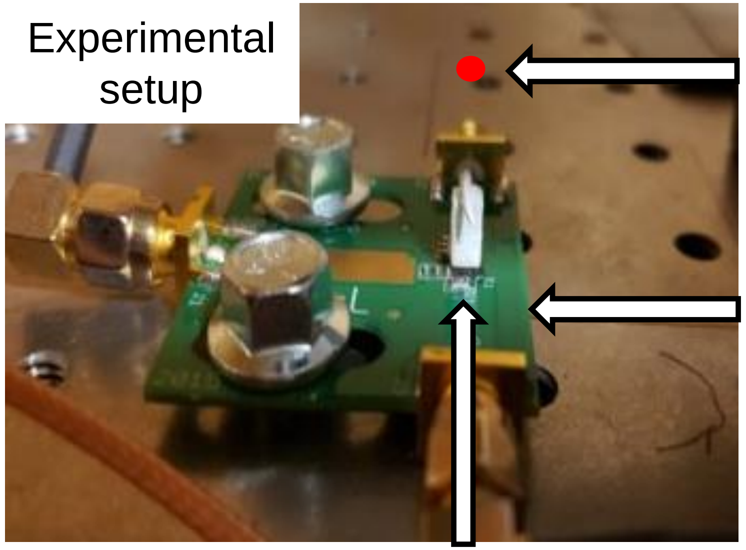
Schematic of SiPM [2]

[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

Overarching challenge that has delayed the deployment of SiPMs in harsh environments is the increase of dark counts and correlated noise with temperature

Experimental setup



Cs-137 source

MicroFJ-SMA evaluation board

EJ-276 scintillator coupled to MicroFJ-30035 SiPM

SiPM characterization workflow

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

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List mode of the scintillation pulses

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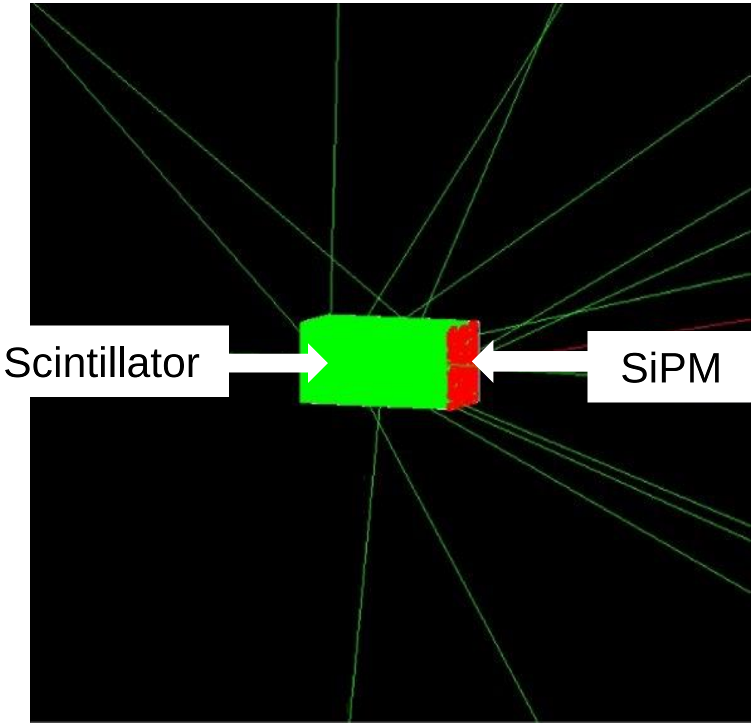
GosSiP [1] simulation of the SiPM electrical response

⇑

Experimentally extract parameters of SiPM response



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

[1] P. Eckert, R. Stamen, H. C. Schultz-Coulon, Study of the response and photon-counting resolution of silicon photomultipliers using a generic simulation framework, Journal of Instrumentation 7 (08) (2012) P08011.
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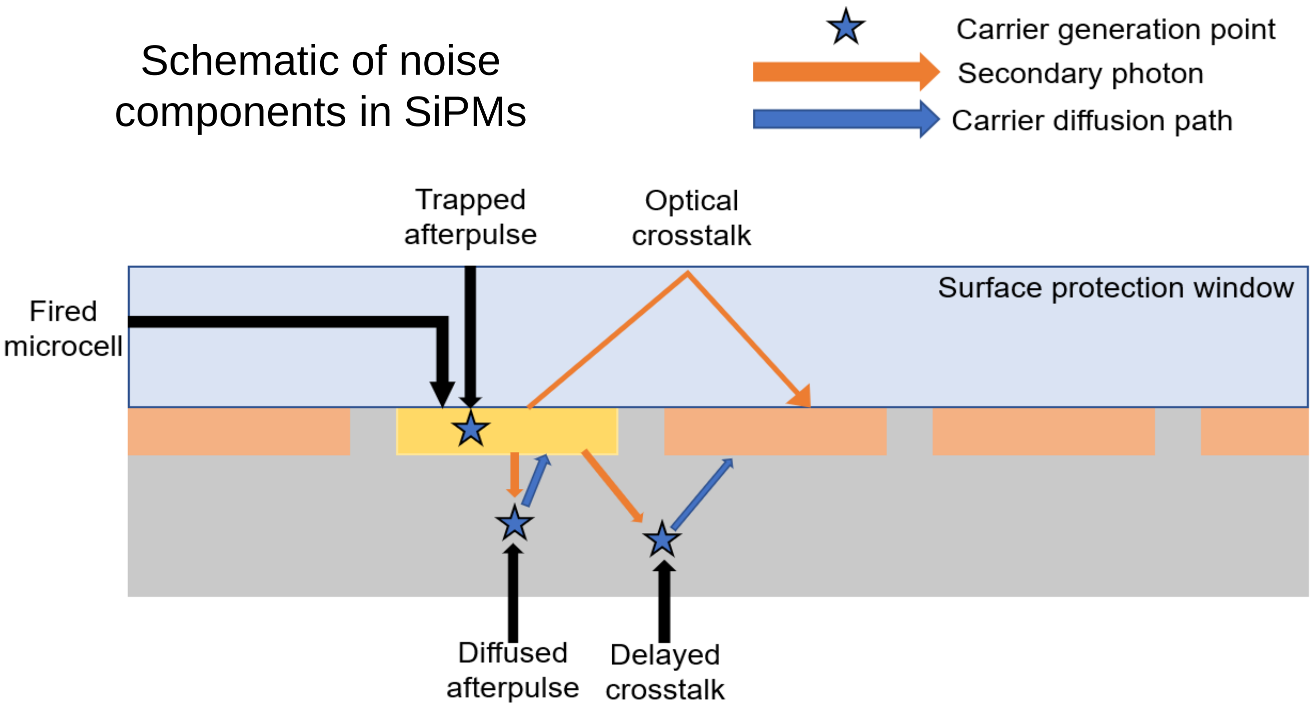
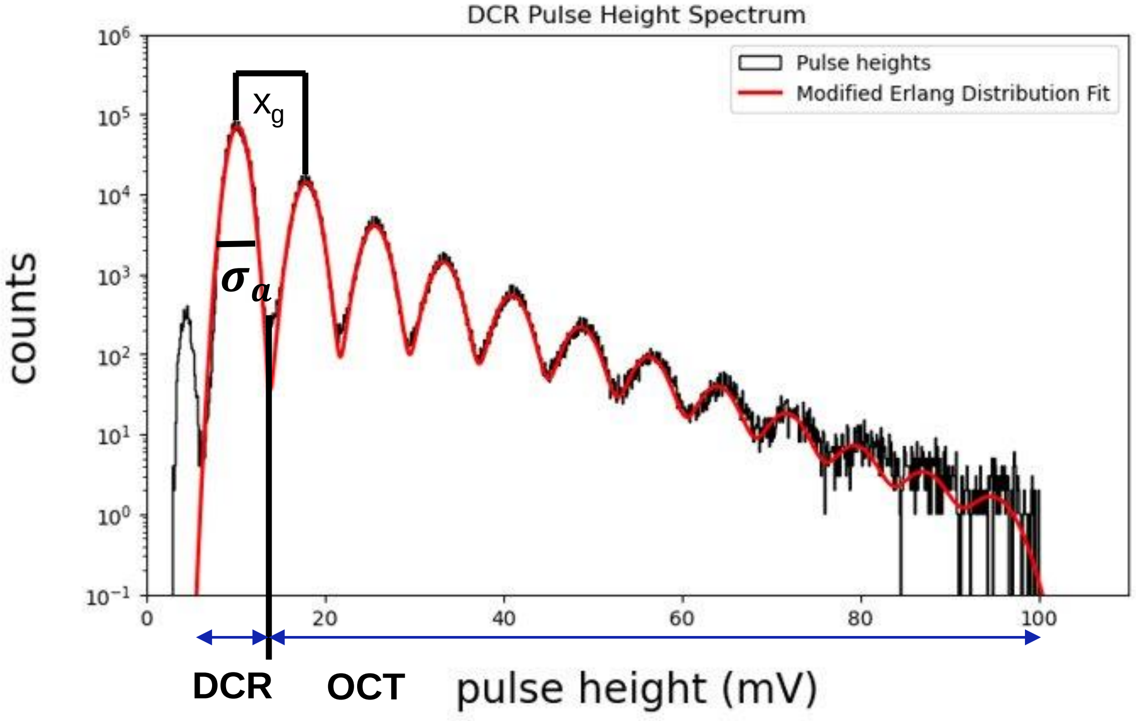
Dark Count Spectrum Analysis

- 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





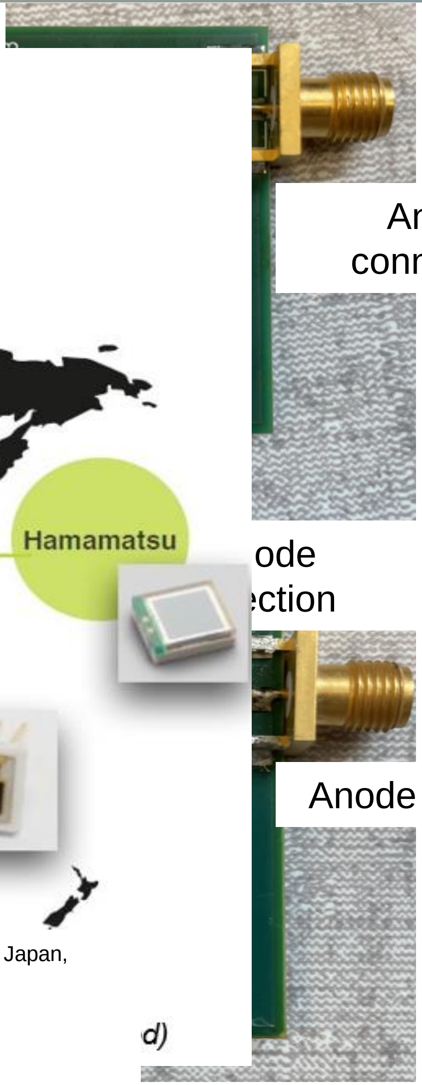
DCR = dark count rate
OCT = optical crosstalk
σ_a = avalanche noise
x_g = gain

Printed Circuit Board (PCB) Design

Onsemi

6Vdc OV

Acerbi, Fabio. “SiPM overview: status and trends.” 5th International Workshop of New Photon-Detectors, University of Tokyo, Tokyo, Japan, November 27-29, 2018



Anode connection

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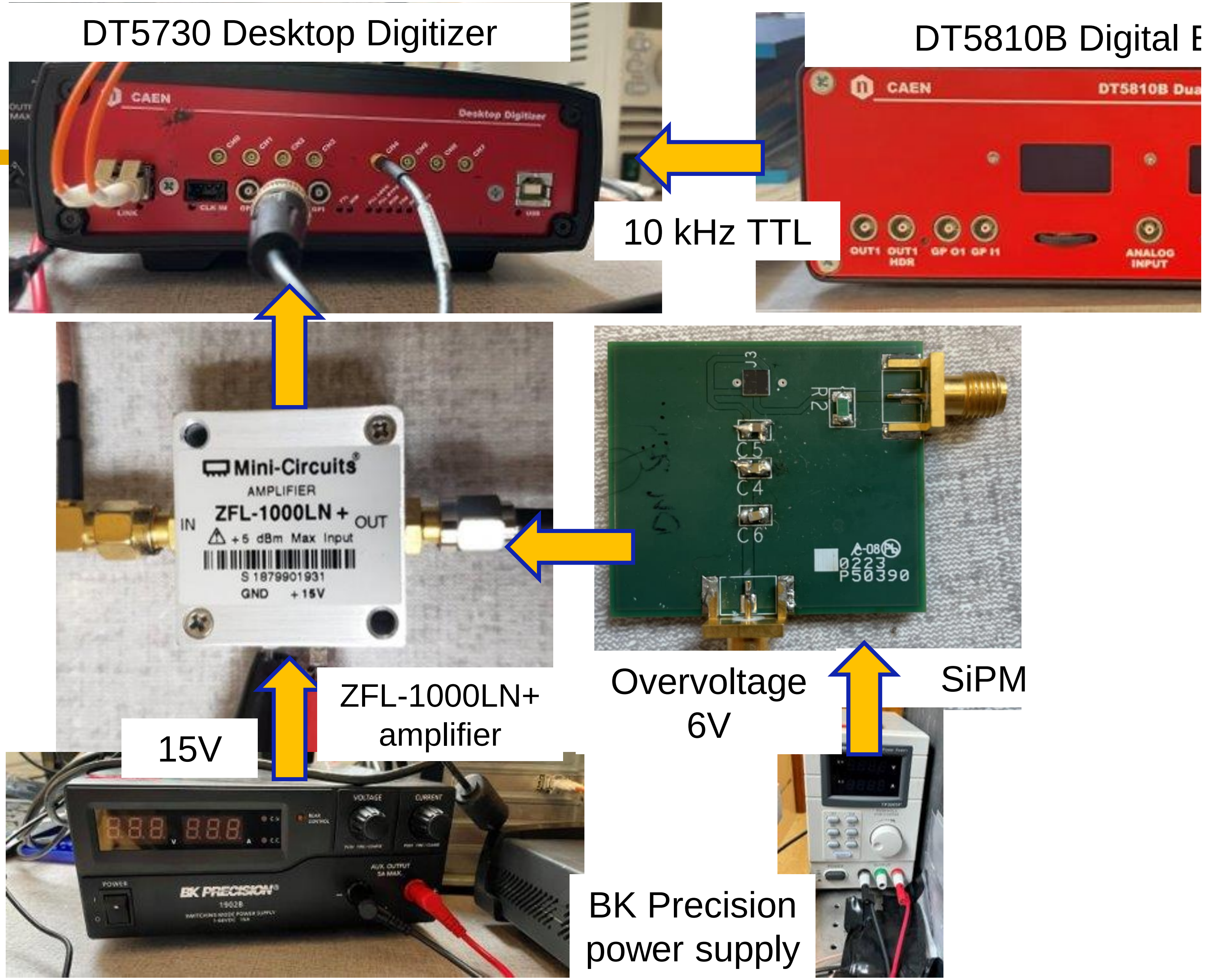
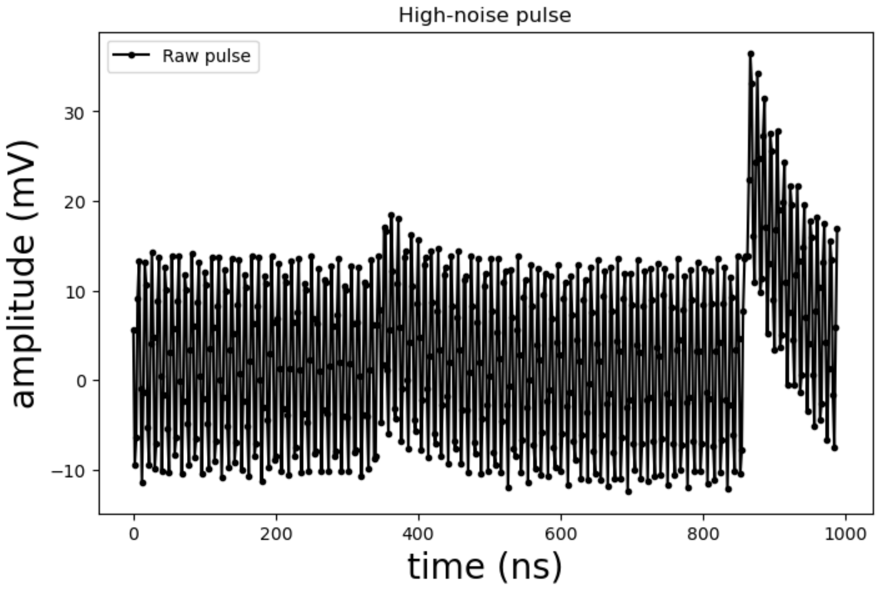
Anode connection

d)

Cathode connection


DT5730 Desktop Digitizer
DT5810B Digital E
10 kHz TTL
CAEN
Desktop Digitizer
DT5810B Dua
OUT1
OUT1 HDR
GP O1
GP I1
ANALOG INPUT
Mini-Circuits
AMPLIFIER
ZFL-1000LN+
IN
OUT
+5 dBm Max Input
GND +15V
ZFL-1000LN+
amplifier
15V
Overvoltage
6V
SiPM
BK PRECISION
BK Precision
power supply


High-noise pulse
Raw pulse
amplitude (mV)
time (ns)
−10
0
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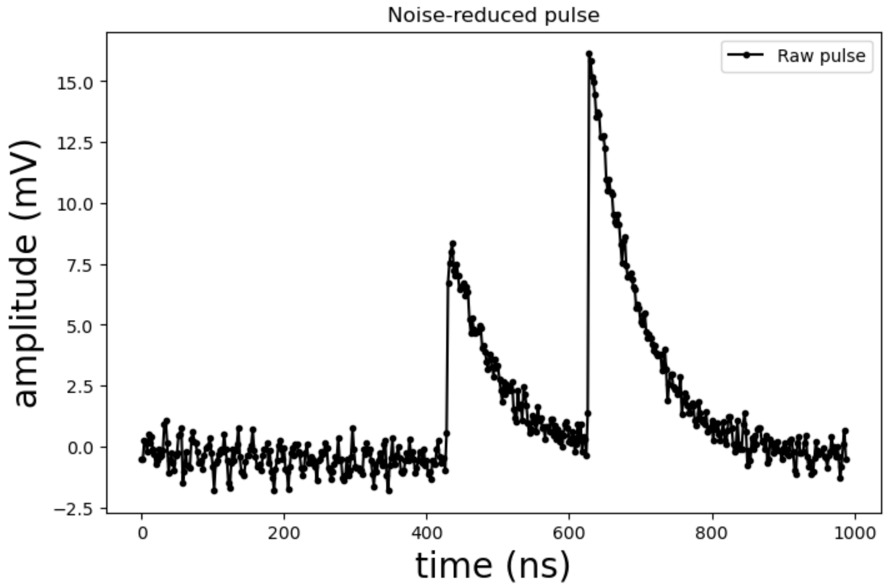
20
30
0
200
400
600
800
1000


Noise-reduced pulse
Raw pulse
amplitude (mV)
time (ns)
−2.5
0.0
2.5
5.0
7.5
10.0
12.5
15.0
0
200
400
600
800
1000

Dark Count Pulses and Data Processing

ILLINOIS

Decay removal model

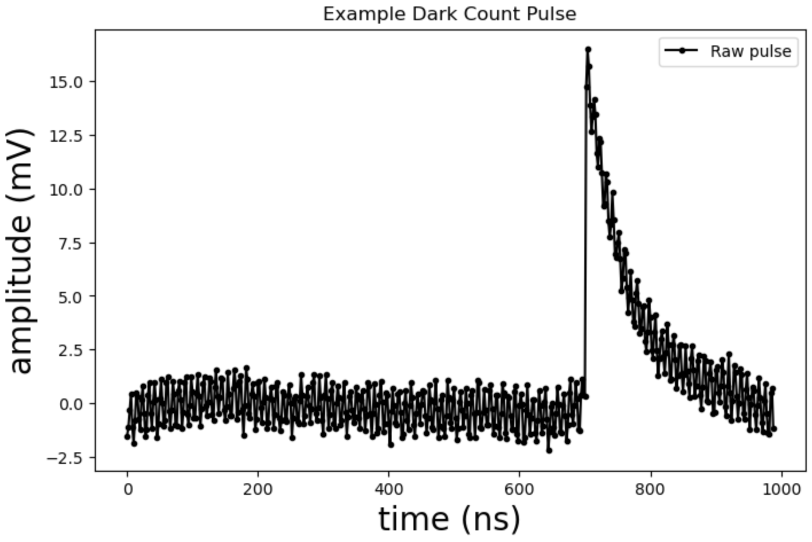
$$V_i = V_{0_i} + \frac{1}{\tau}\sum_{j=1}^{i} V_{o_j} \times (t_j - t_{j-1})$$

where $t_{j-1} = 0$

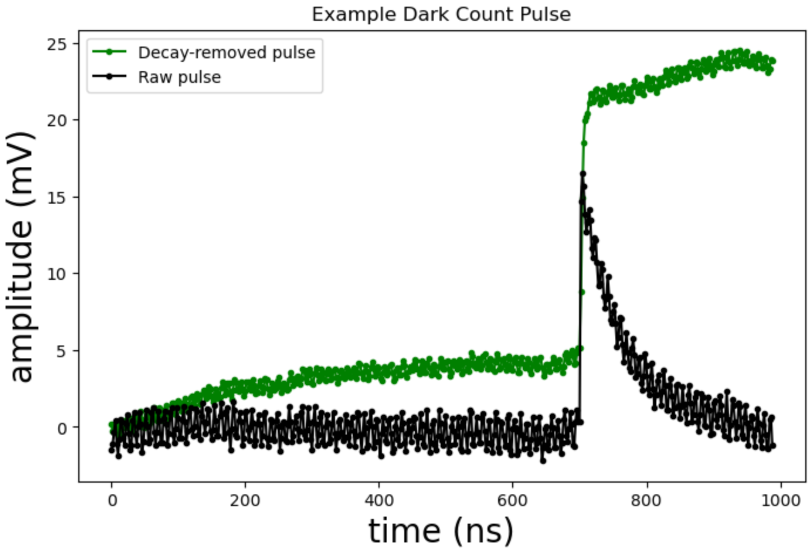
and $V_0 = V - V_{min}$

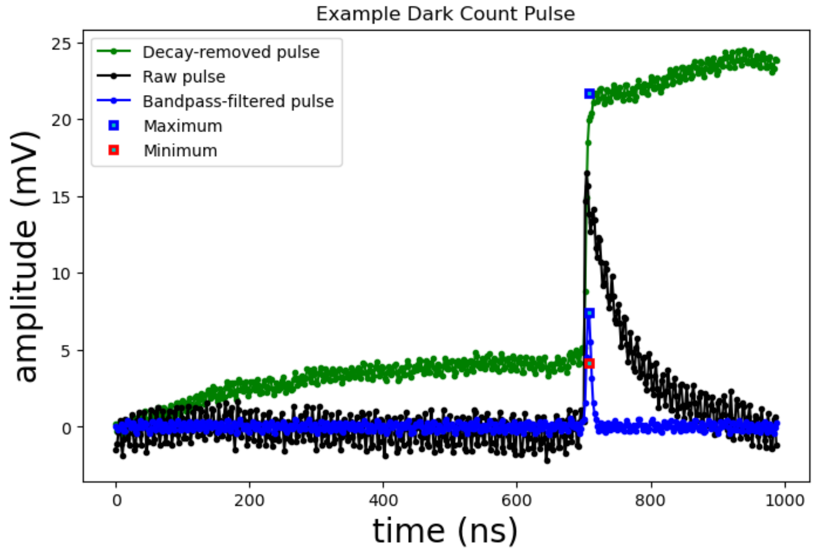
t=time in nanoseconds   V= volts in millivolts τ= microcell recharge time

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



Raw pulse

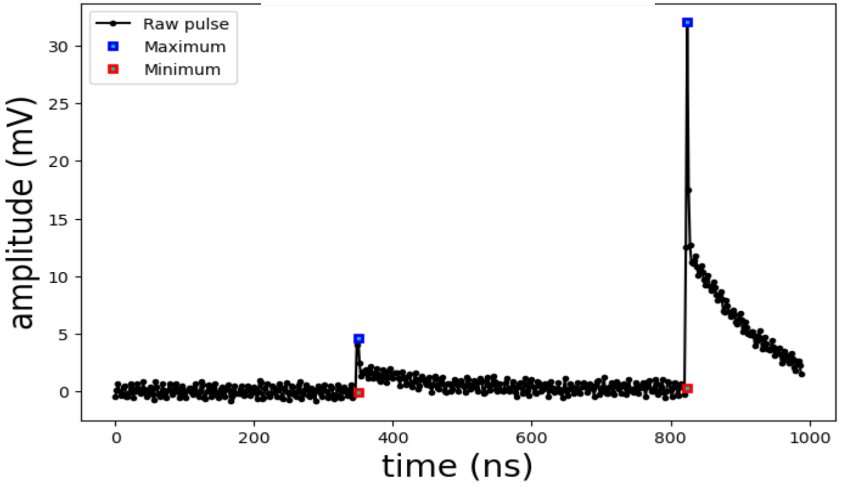


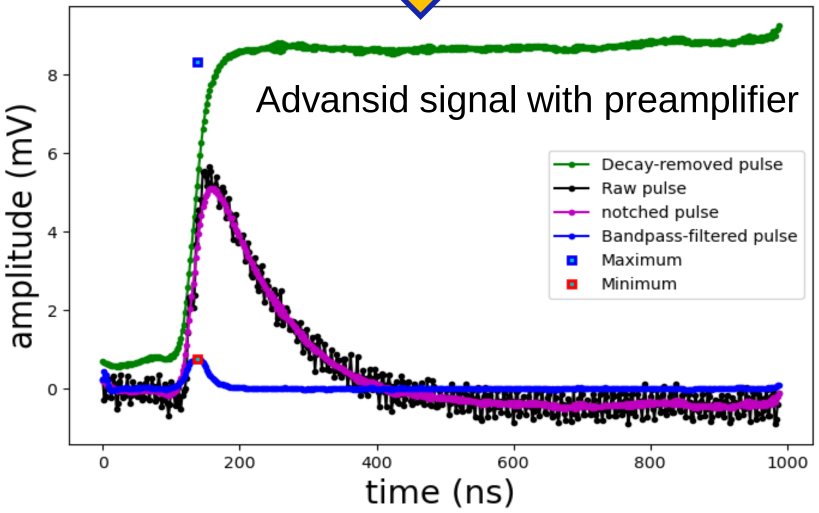


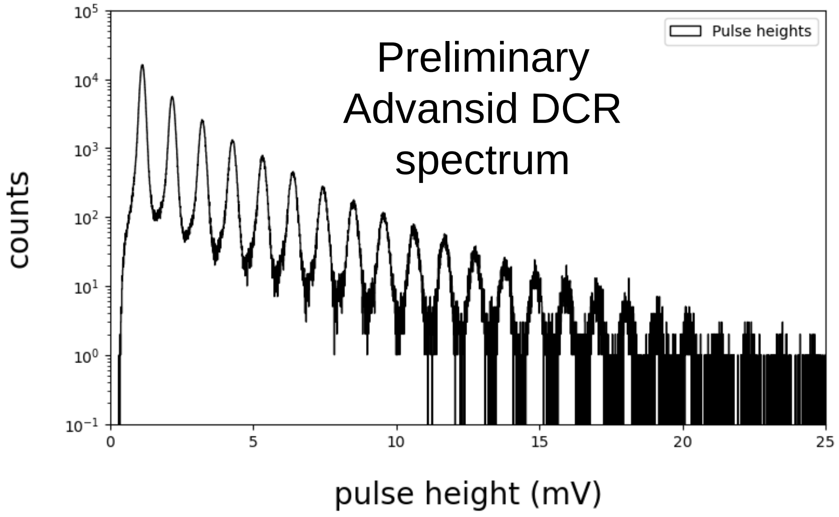
Removing the decay and applying a high-pass filter (blue) allows for more accurate pulse height calculation

Advansid Analysis

Advansid signal





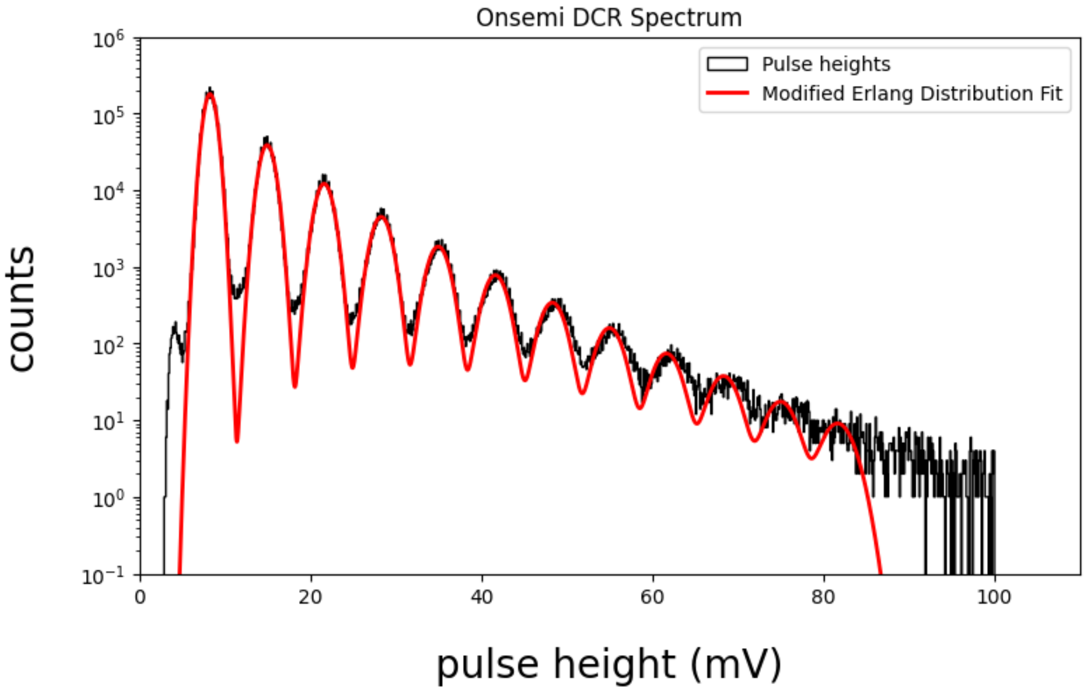


Dark Count Spectrum

	Onsemi meas.	Onsemi data sheet value	Advansid meas.	Advansid data sheet value
Dark count rate (kHz/mm^2)	164	150	75	<100
Breakdown voltage (V)	24.7	24.4-24.7	26.6	~26
OCT probability (%)	23.3	25	14.9	N/A
Gain	4.45×10^7 electrons	6.3×10^6 electrons	6.9×10^6 electrons	3.6×10^6 electrons

Model function

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



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

Optical Crosstalk (OCT) Measurement Setup

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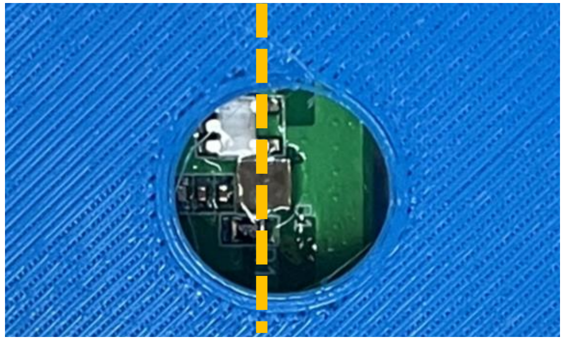
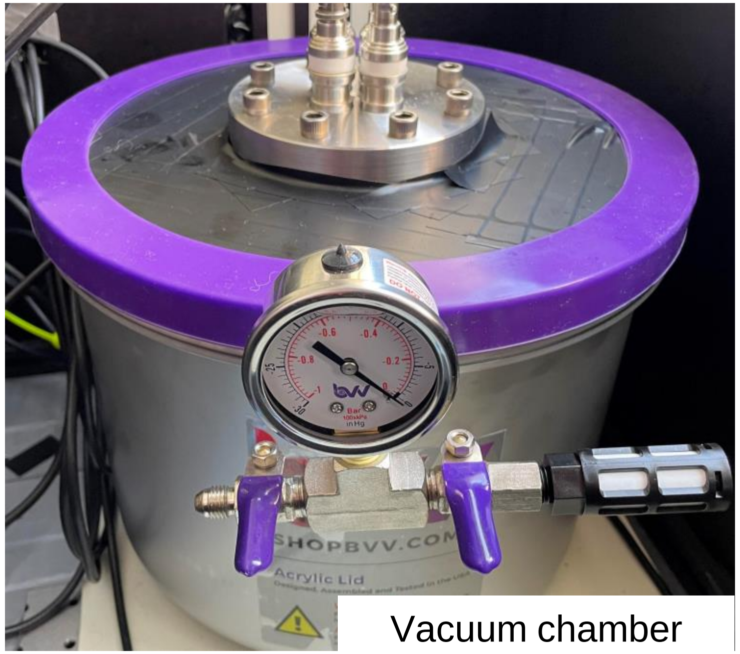


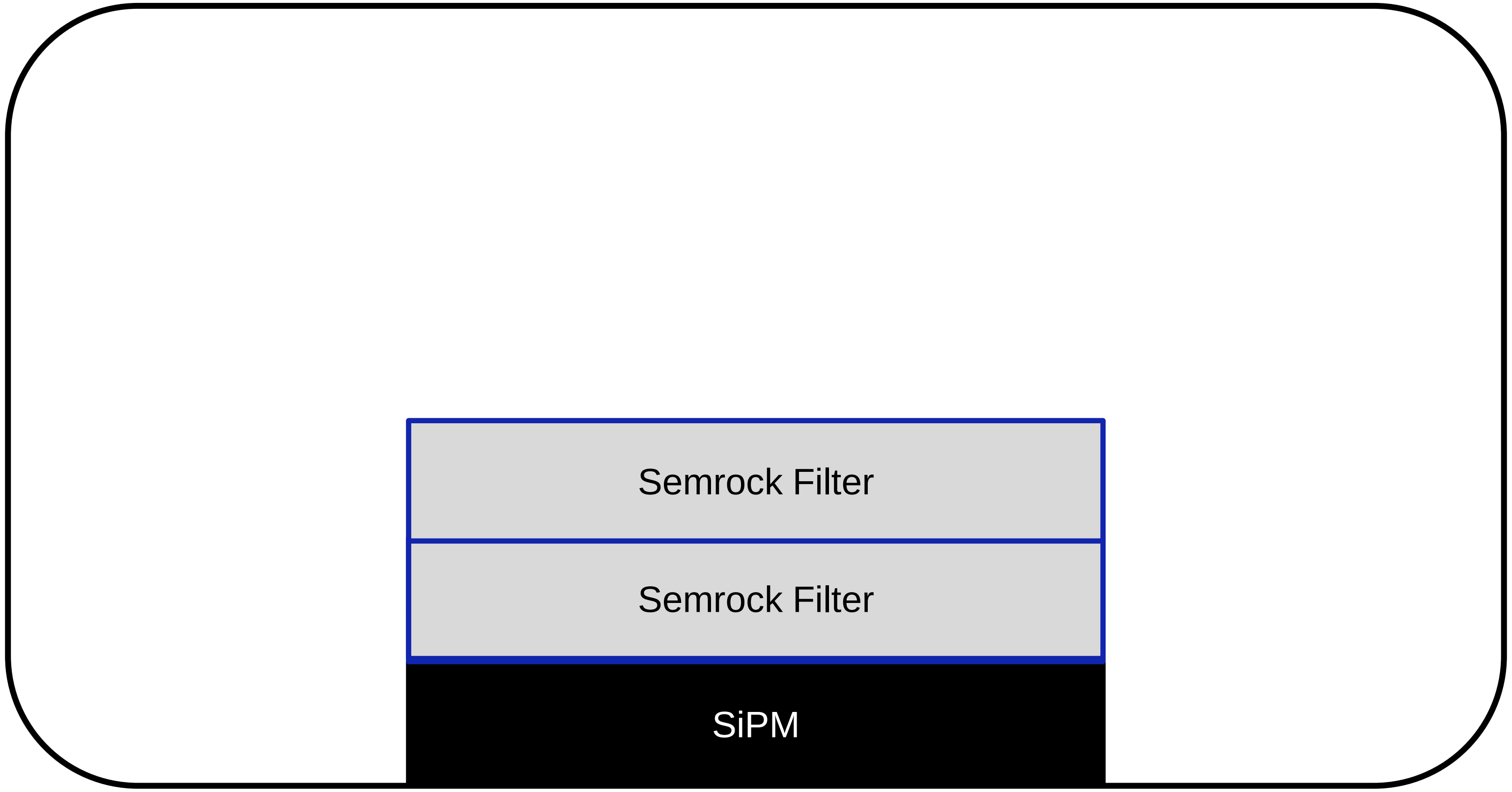
SiPM beneath holder



Vacuum chamber

Filter testing schematic on cross-section along dashed line in the top left image.

Vacuum chamber



OCT Results

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	Filter name	Wavelength Selection	OCT probability and STD (%)
No filter			22.8
Interference filter	Semrock BrightLine FF01-520/70-25	Transmittance band: 485nm-555nm	24.3
Bandpass filters	UG5	400nm-600nm	18.56 ± 0.05
	BG39	700nm-1000nm	18.04 ± 0.05
	BG40	700nm-1000nm	18.44 ± 0.05
	KG2	800nm-1200nm	19.04 ± 0.05
Longpass filters	N-WG280	200nm-250nm	20.98 ± 0.04
	OG590	200nm-550nm	19.10 ± 0.00
	RG695	200nm-650nm	17.26 ± 0.12
	RG850	200nm-700nm	19.70 ± 0.09
	RG1000	200nm-700nm	19.00 ± 0.06

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 low-noise dark count rate experimental setup
    - We have compared two technologies based solely on their micro-electronic SiPM configuration. We found that Advansid has a lower DCR compared to the Onsemi by a factor of **0.457**
    - Advansid has a lower OCT probability by a factor of **0.639**

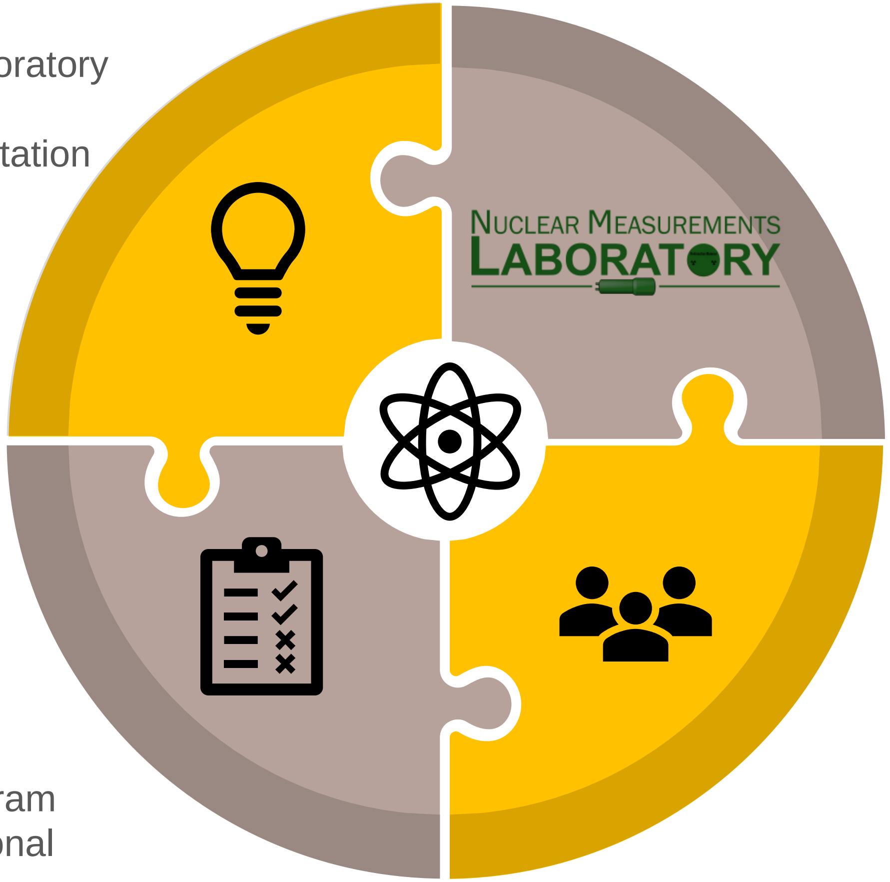
- The extracted parameters will be used for first-principle simulations that generate electrical SiPM response (GosSiP) from radiation transport simulation (GEANT4)

- 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

The NSSC Experience

LEARN

- Advance Radiological Laboratory
- Nuclear Policy Issues and Deterrence Keepin Presentation



EXPERIENCE

- NSSC-LANL Keepin Fellowship Summer Program
- Internship at Sandia National Laboratory

RESEARCH

- IEEE Presentation: First-principle SiPM Characterization to Enable Radiation Detection in Harsh Environments
- First Principle of SiPM Response (paper to be submitted)
- INMM Presentation: "Effect of Silicon Photomultiplier Optical Crosstalk on Pulse-shape Discrimination and Energy Resolution"

NETWORK

- Network with fellow students and DOE lab researchers

Acknowledgements

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number **DE-NA0003996.**

Breakdown Voltage Measurement

- The breakdown voltage was determined by locating the nearest data point to the sharp increase in current
  - This procedure was suggested by Broadcom on their website
- The experiment measured the voltage every ~0.5V, which can be decreased if we need better sensitivity for the breakdown voltage
- The measured breakdown voltages measured are within the expected region quoted in the SiPMs' datasheet
- Having a more precise measurement will allow us to compare the SiPMs' response at the exact same overvoltage