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Characterization of Silicon Photomultiplier Photon Detection Efficiency at Liquid Nitrogen Temperature

SiPMs and Rare-Event Searches

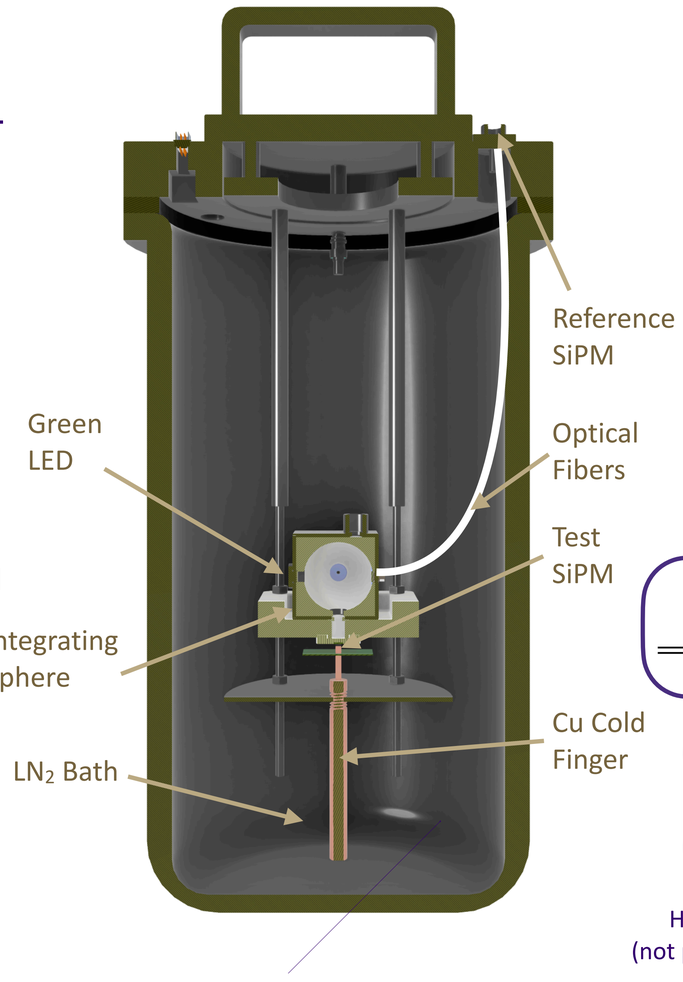
Due to their low cost, low operating voltage, high radio-purity, and high efficiency, silicon photomultipliers (SiPMs) are starting to be used extensively for light readout in rare-event search experiments [1-5].

> LEGEND-200 uses SiPMs in its search for neutrinoless double beta decay to readout its liquid argon (LAr) detector's scintillation light and veto background events
  > Scintillation light is first collected and wavelength shifted to ~ 460 nm - 580 nm by shrouds of optical fibers
> A SiPM is an array of Single Photon Avalanche Diodes (SPADs) connected in parallel, and is reverse-biased in Geiger mode to enable single photon resolution
> The photon detection efficiency (PDE) is a measure of how well a SiPM converts light into a signal

$$PDE = \frac{N_{\gamma,\,detected}}{N_{\gamma,\,incident}}$$

> It is important to measure the PDE in order to understand LEGEND-200's LAr detector response, and to optimize the future ton-scale experiment LEGEND-1000's LAr detector design
> The PDE is well known at room temperature; however, most rare-event search experiments operate SiPMs at cryogenic temperatures

The PDE is not well known at cryogenic temperatures



SiPM Characterization Test Stand

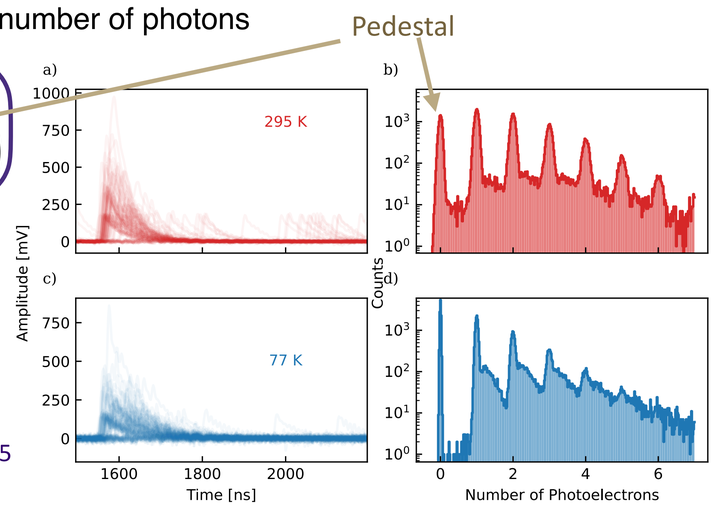
Methods

The UW SiPM characterization test stand enables cryogenic measurements of the PDE [6]

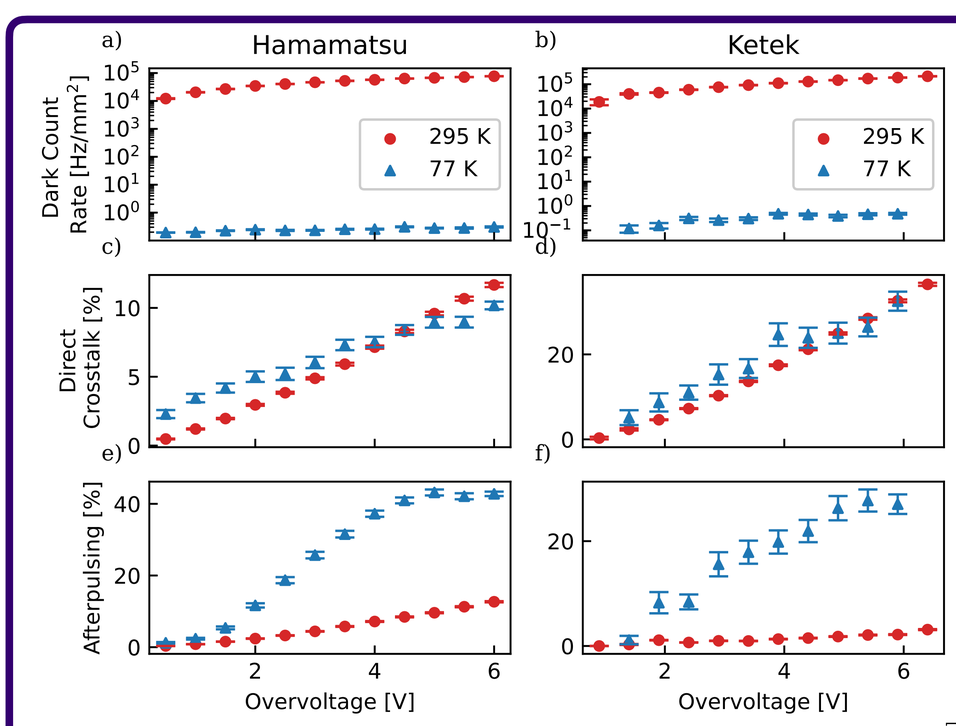
> A pulsed LED sends photons into an integrating sphere (IS) and triggers data acquisition
> One viewing port holds the test SiPM on top of a copper cold finger that is submerged in LN_2: $N_{\gamma,\,detected}$
> An uncalibrated reference SiPM sits on the lid at room temperature, and is coupled to the IS with optical fibers: $N_{\gamma,\,incident}$
  > Transmission of the fibers is measured and divided out
> The number of photons detected is calculated via the Pedestal PDE Measurement [7]
  > The SiPM has some probability of not firing during an LED flash, and this gives an unbiased estimator of the mean number of photons

$$P(N=0) = e^{-\bar{N}_\gamma}$$
$$\implies \bar{N}_\gamma = -\log\left(\frac{n_{N=0}}{n_{total}}\right)$$

Hamamatsu 3050CS
(not pictured) KETEK PM3325



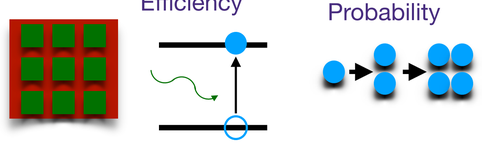
Hamamatsu SiPM data at 2.5 V overvoltage under illumination



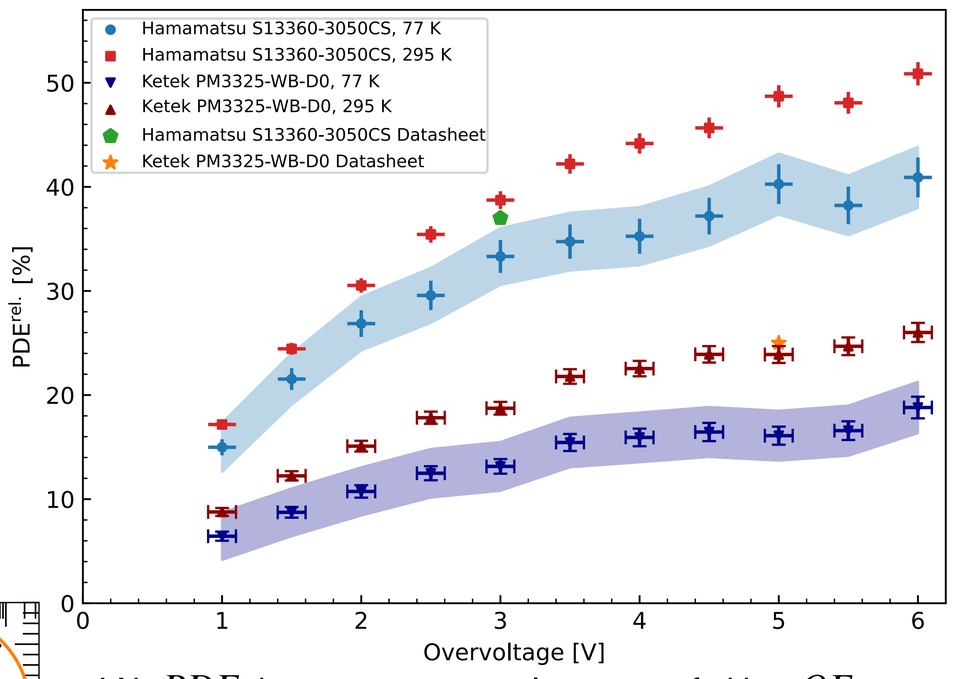
> Dark condition data and illuminated PDE data are processed automatically with open-source SiPM_STUDIO software [8]
> Substantially increased afterpulsing rate at liquid nitrogen temperatures could be explained by newly activated charge traps or increased diffusion afterpulsing
> Direct crosstalk seems to be largely temperature independent

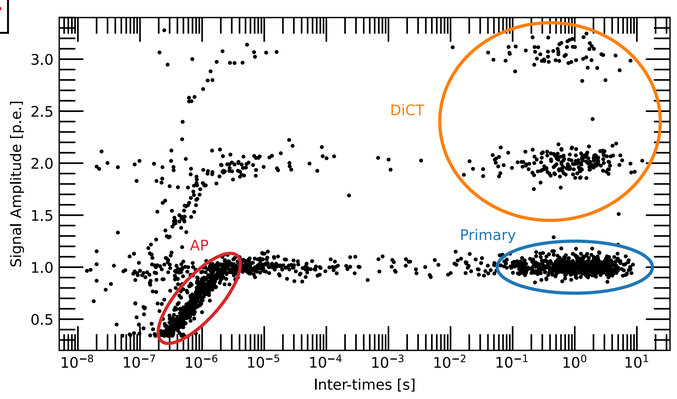
Results

$$PDE(V_{bias}, \lambda) = \underbrace{FF}_{\text{Fill Factor}} \cdot \underbrace{QE(\lambda, T)}_{\text{Quantum Efficiency}} \cdot \underbrace{P_{Geiger}(V_{bias}, \lambda, T)}_{\text{Geiger Discharge Probability}}$$



> Fill Factor: ratio of active area to total
> QE: probability to create charge carrier
> P_{Geiger}: probability to trigger avalanche





LN_2 Dark condition data for KETEK SiPM at 4 V overvoltage

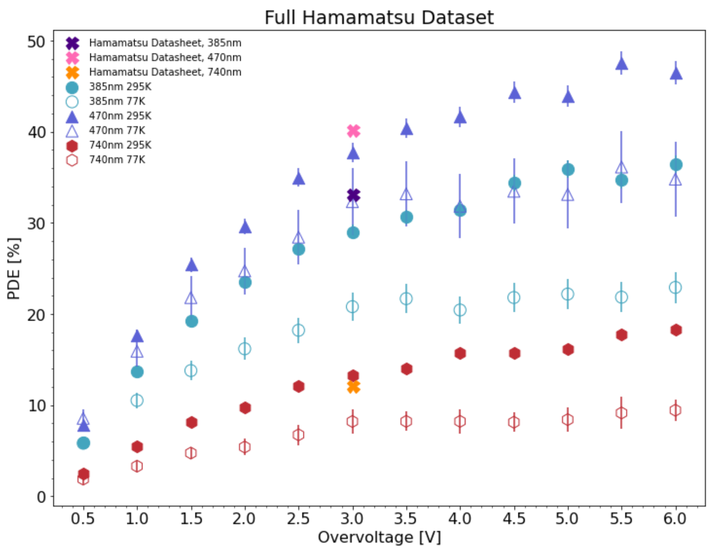
> LN_2 PDE decrease means at least one of either QE or P_{Geiger} must decrease
> QE depends on the photon absorption length in silicon, so this potentially is what is decreasing at LN_2 temperatures
> Charge carrier freeze out occurs around 100 K in silicon $\implies$ $QE \downarrow$? [9]

Work In Progress

The behavior of the quantum efficiency and Geiger triggering probabilities at LN_2 temperatures needs to be studied in further detail

> Characterizing $PDE(T)$ for several LED wavelengths could reveal if the QE is dropping, and the mechanism behind its shift at LN temperatures
> This wavelength dependence is being studied by UW undergraduate researcher Ian Wang

Ian Wang
UW Undergrad Researcher



Acknowledgements & References

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