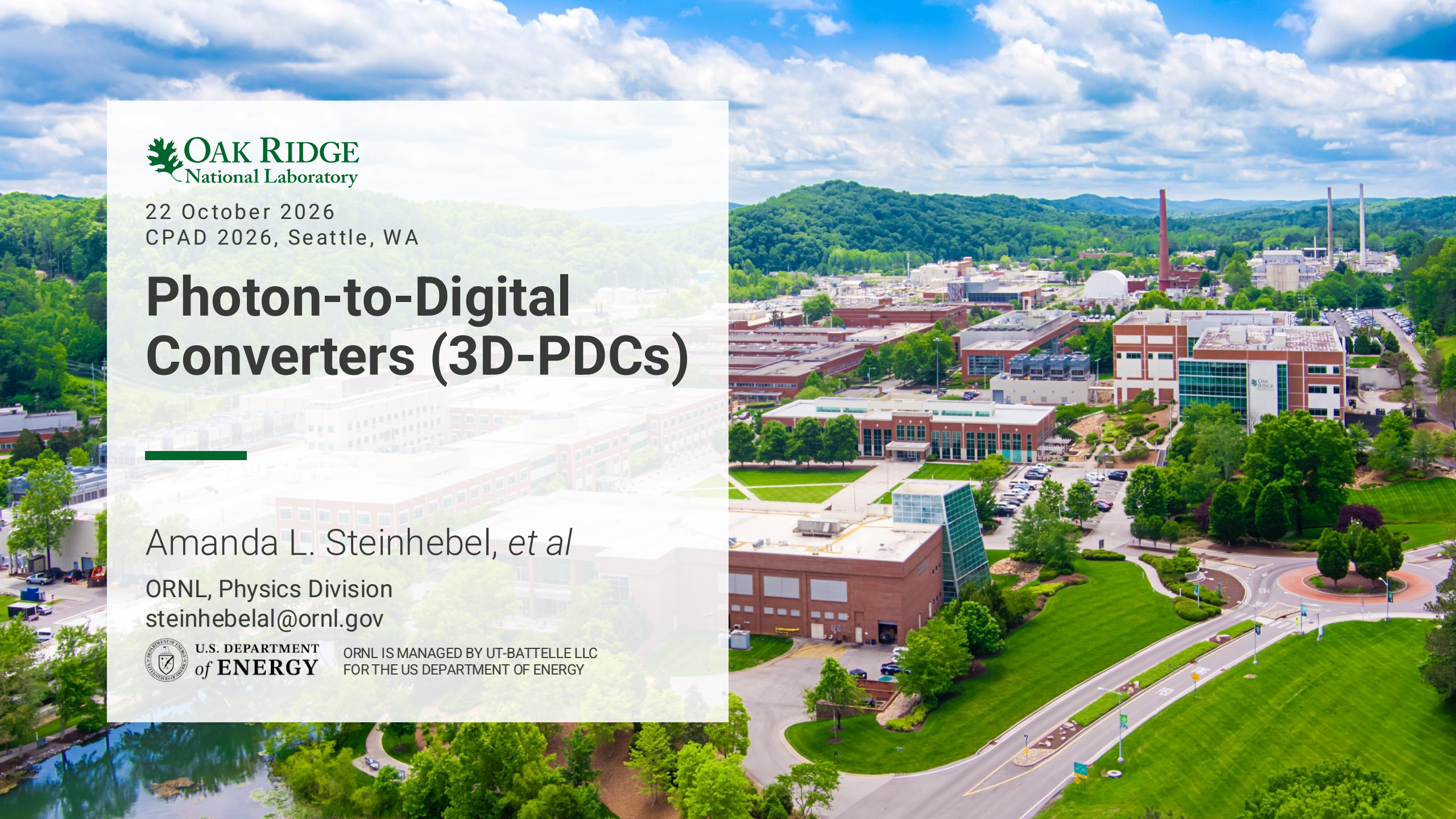


OAK RIDGE National Laboratory

22 October 2026
CPAD 2026, Seattle, WA

Photon-to-Digital Converters (3D-PDCs)

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U.S. DEPARTMENT of ENERGY

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Development is an international effort

Oak Ridge National Laboratory, TN, USA

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*Institution Principal Investigator

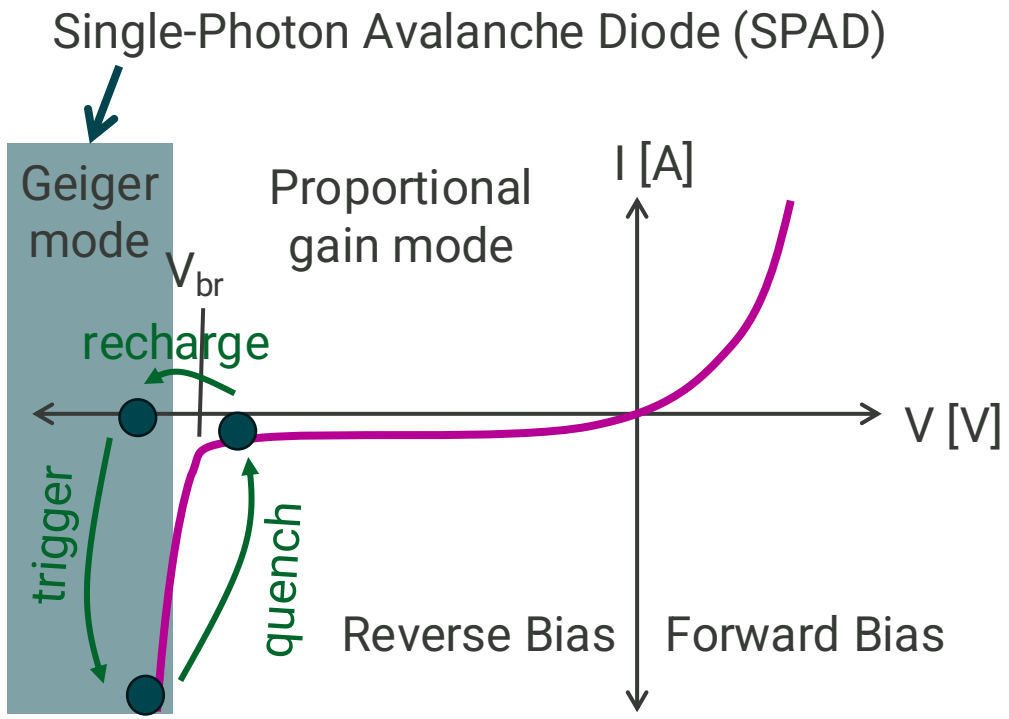


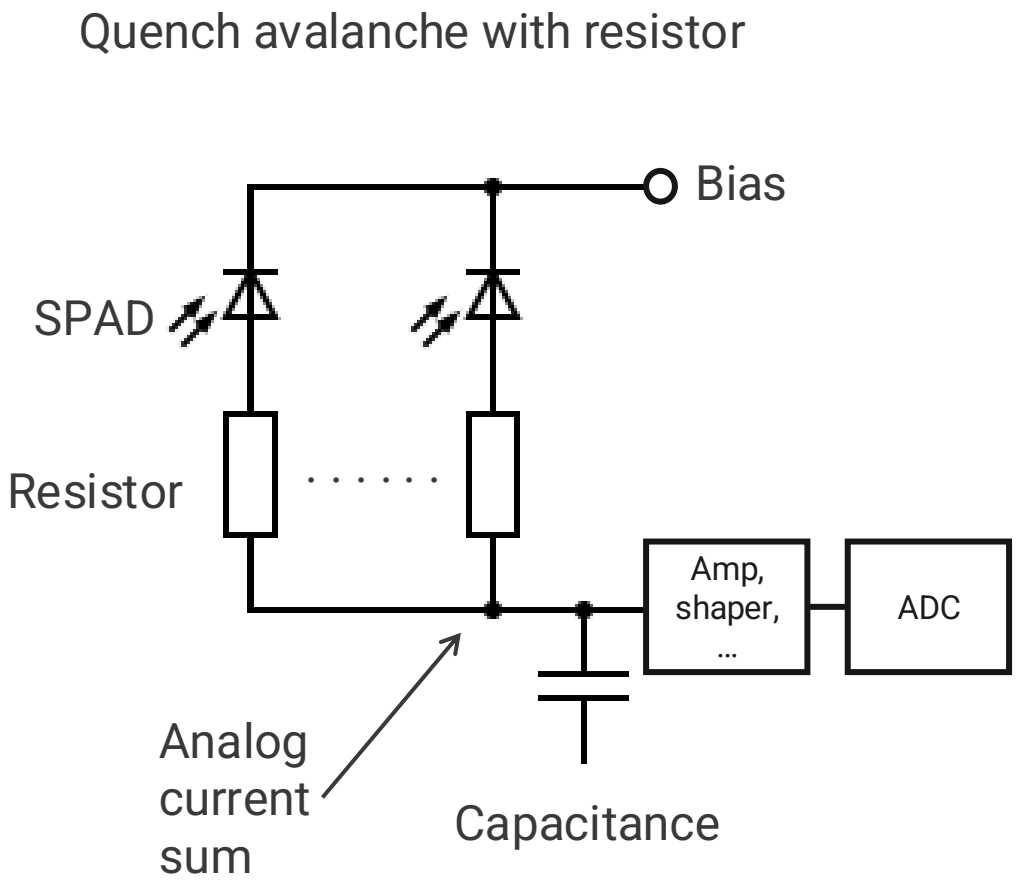




The present work was supported in part by the United States Department of Energy, Office of Defense Nuclear Nonproliferation Research and Development in the National Nuclear Security Administration and by the United States Department of Energy, Office of High Energy Physics.

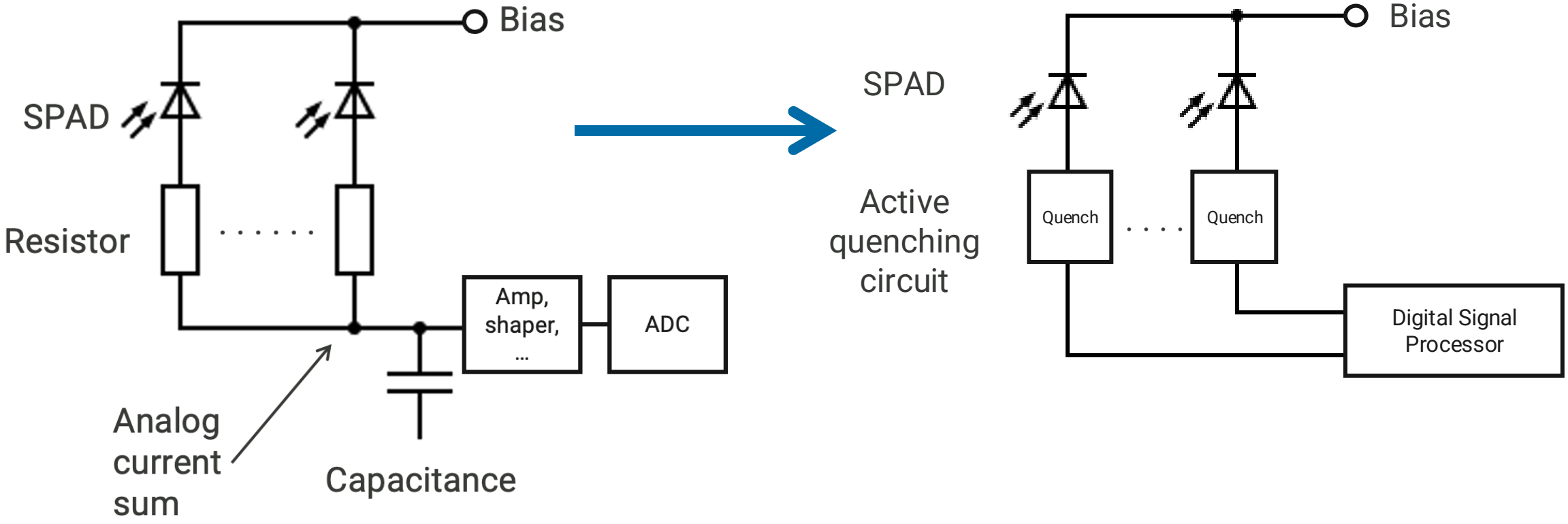
Classical single photon detection with Silicon PhotoMultipliers (SiPMs)





SiPMs return an analog current sum of binary SPAD outputs, converted to digital

Photon-to-Digital Converters (PDCs) are a next-generation SiPM

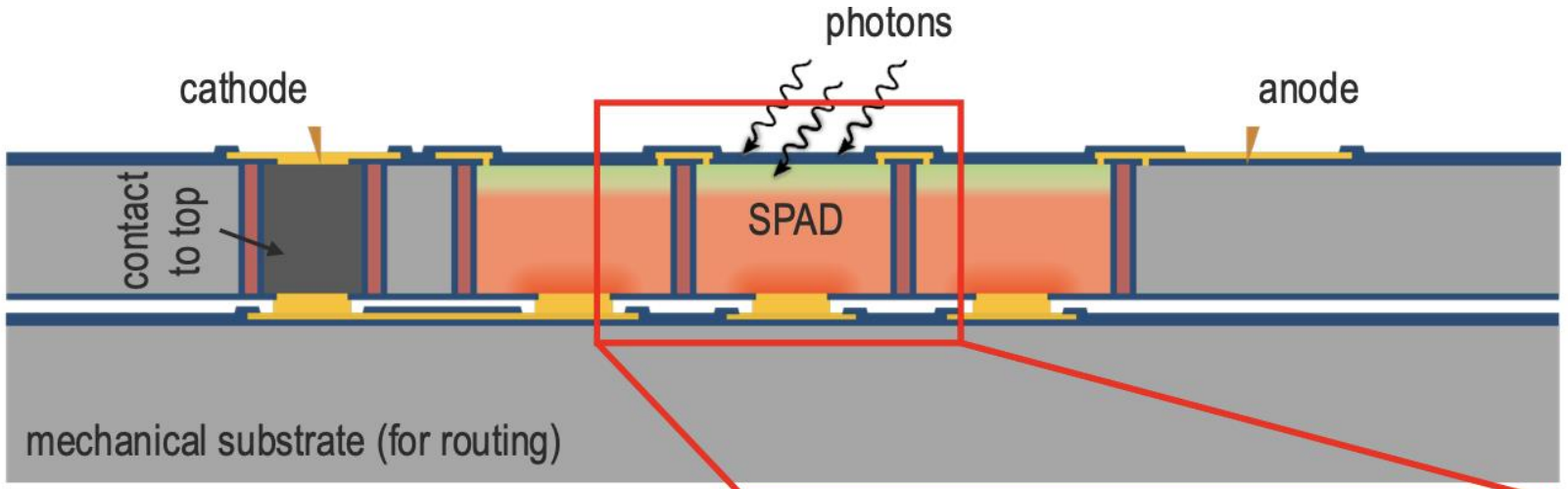


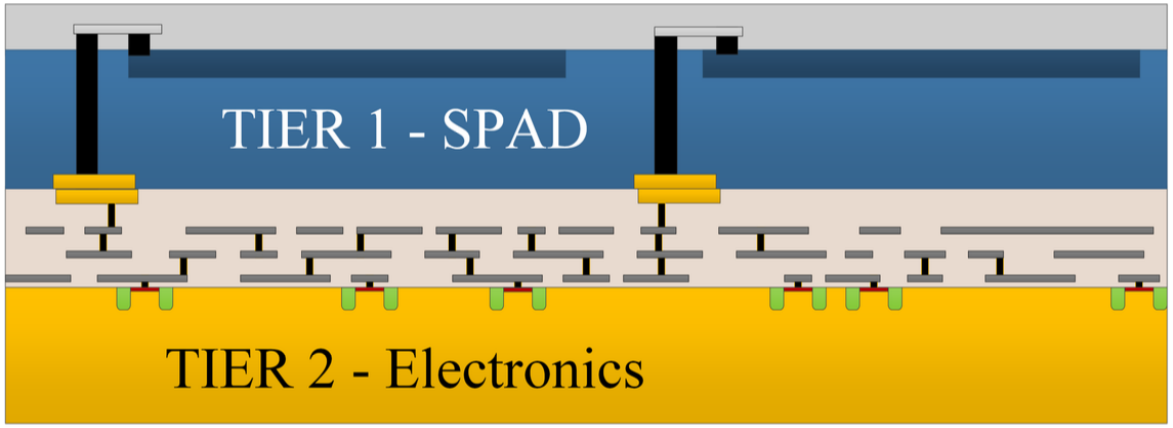
SiPMs return an analog current sum of binary SPAD outputs, converted to digital

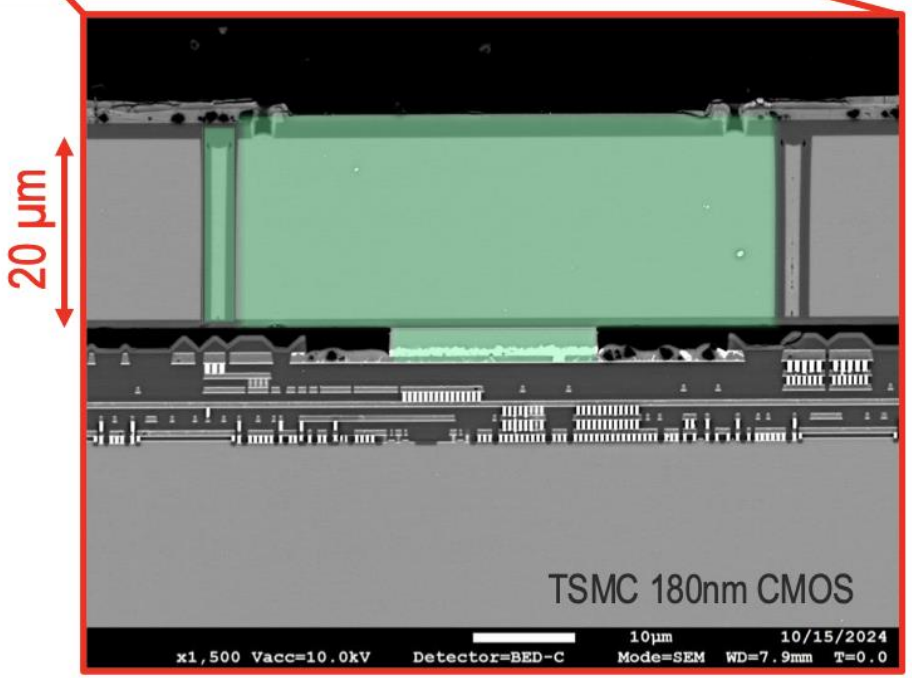
PDCs return a digital sum of binary SPAD outputs, controlled with active quenching

Vertical integration has been developed custom for this project

SPAD properties
- 78 μm pitch
- Thinned to 20 μm
- 64 x 64 SPAD arrays
- 5.85 x 5.25 mm^2 die



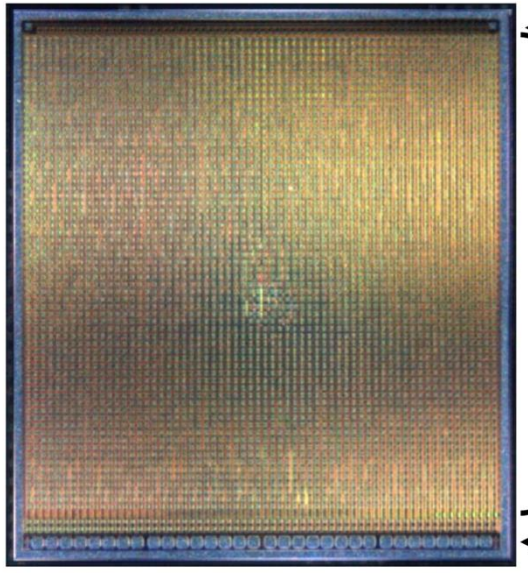


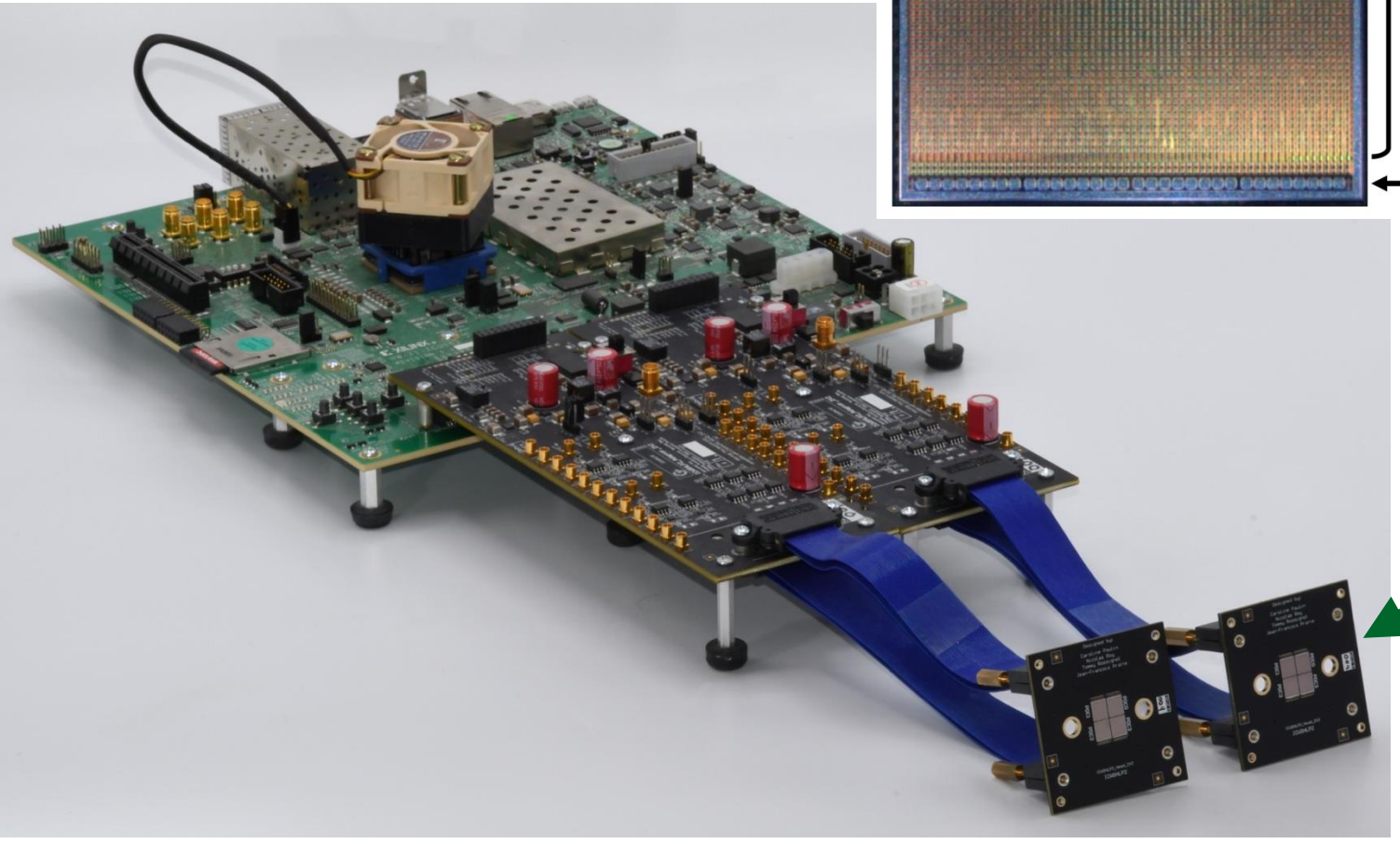


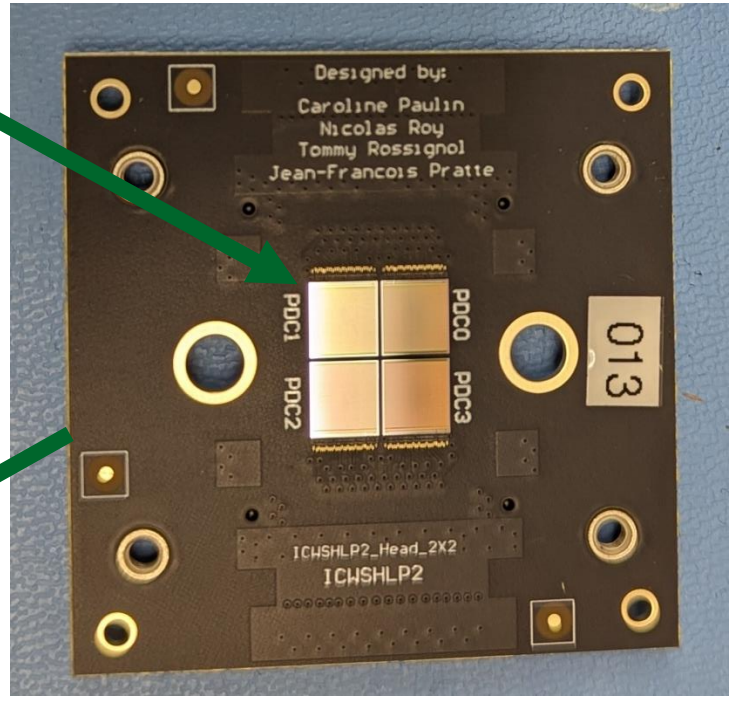
SEM cross section image

Pratte, Jean-Francois *et al*. (2021). 3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works. Sensors. 21. 598. 10.3390/s21020598.

PDC_v2 is currently being tested in the lab







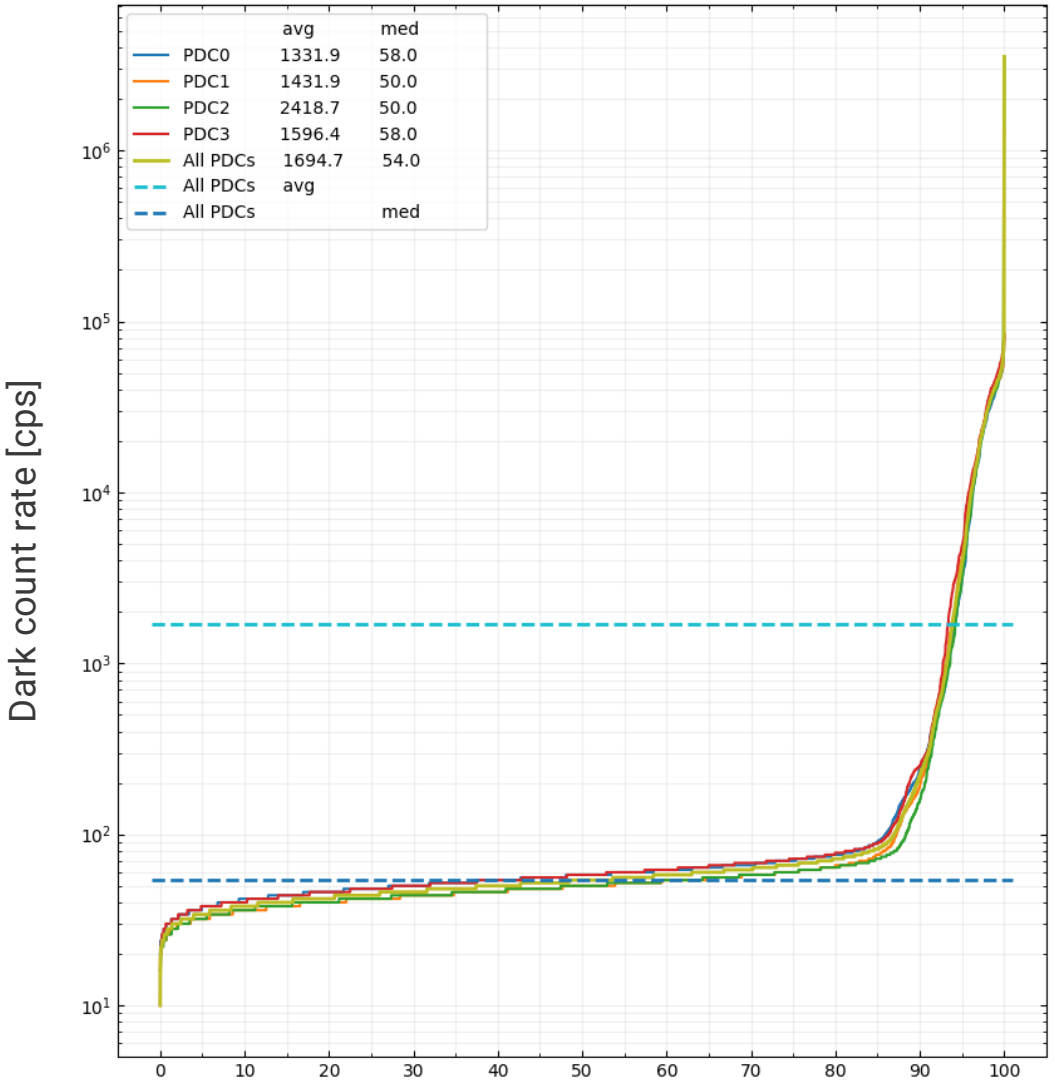
T. Rossignol *et al,* (2024). A 3D photon-to-digital converter readout for low-power and large-area applications. JINST. 19. P09017.

Performance is promising

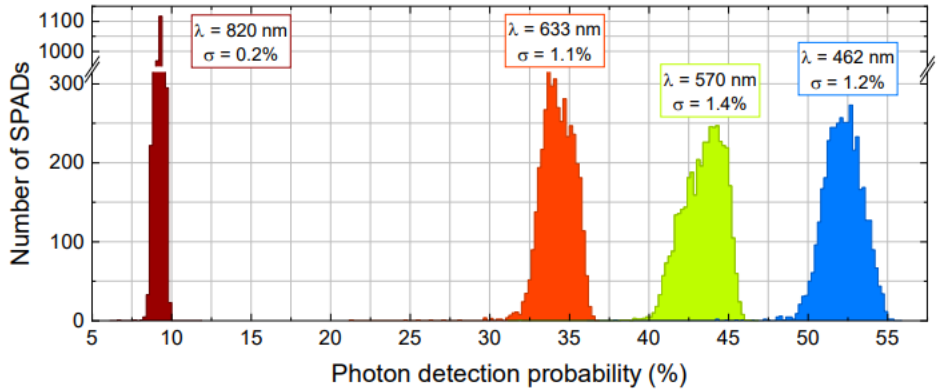
Photodetection (SPAD)		Readout (PDC)	
Single photon timing resolution	160 ps @ 410 nm 110 ps @ 820 nm	Sampling resolution	10 ns
Photon detection efficiency	50% @ 410 nm	Memory depth	128 bits
Dark count rate median at STP	100 cps/SPAD = 0.03 cps/μm^2	Holdoff configuration	10 ns – 10 µs
Pitch	78 µm	Recharge configuration	2 – 60 ns
		Power consumption	< 600 $\mu W/cm^2$

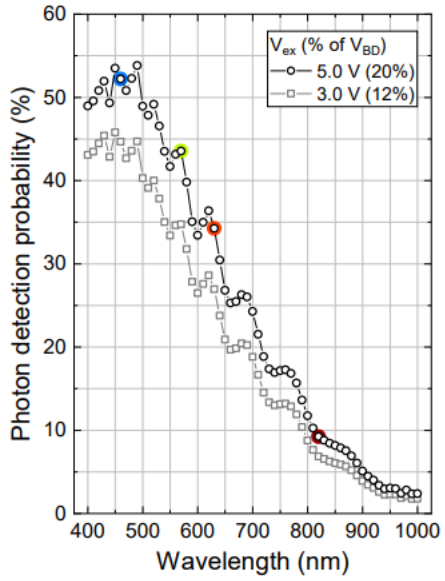
Full-array array characterization shows expected response

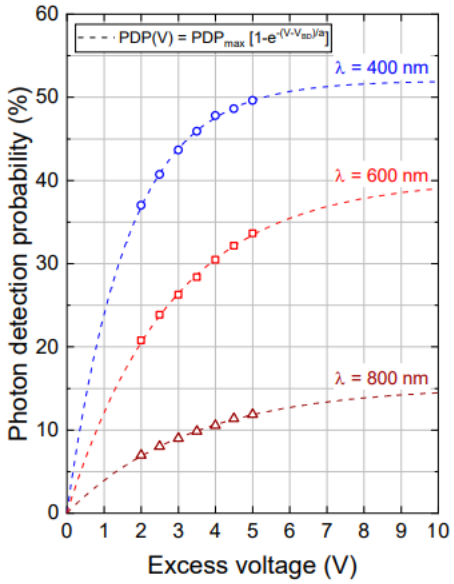
Dark count rate



Photon detection probability







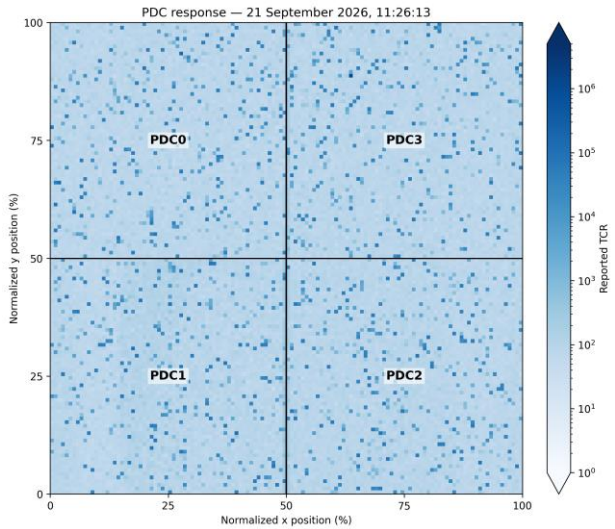
Uniformity between SPADs <1.5% at all wavelengths

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Scintillation measurement procedure

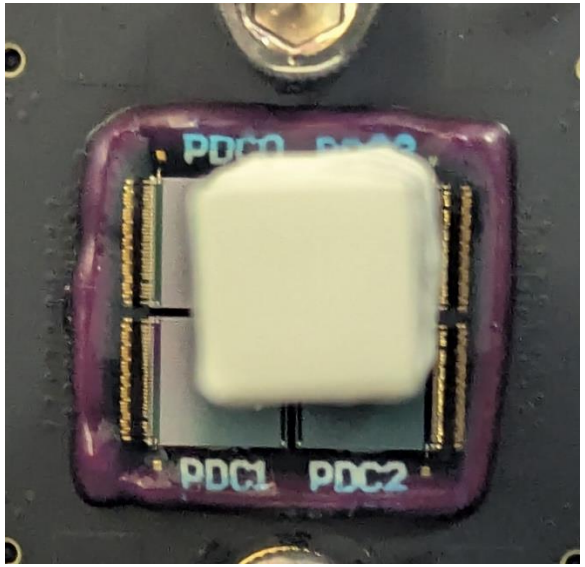
Measure TCR

Scan through individual SPADs, measure total count rate (TCR)



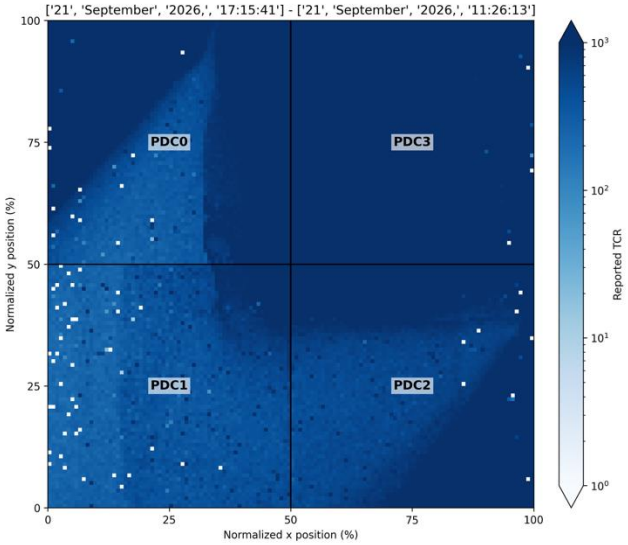
Couple Scintillator

As shown on previous slide, using extra caution to not damage vertical integration



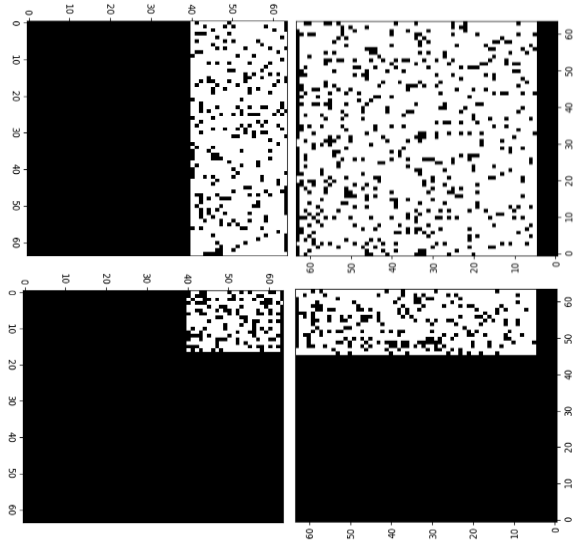
Measure TCR again

Scan through individual SPADs, measure total count rate (TCR) with faint backlight, identify exposed pixels

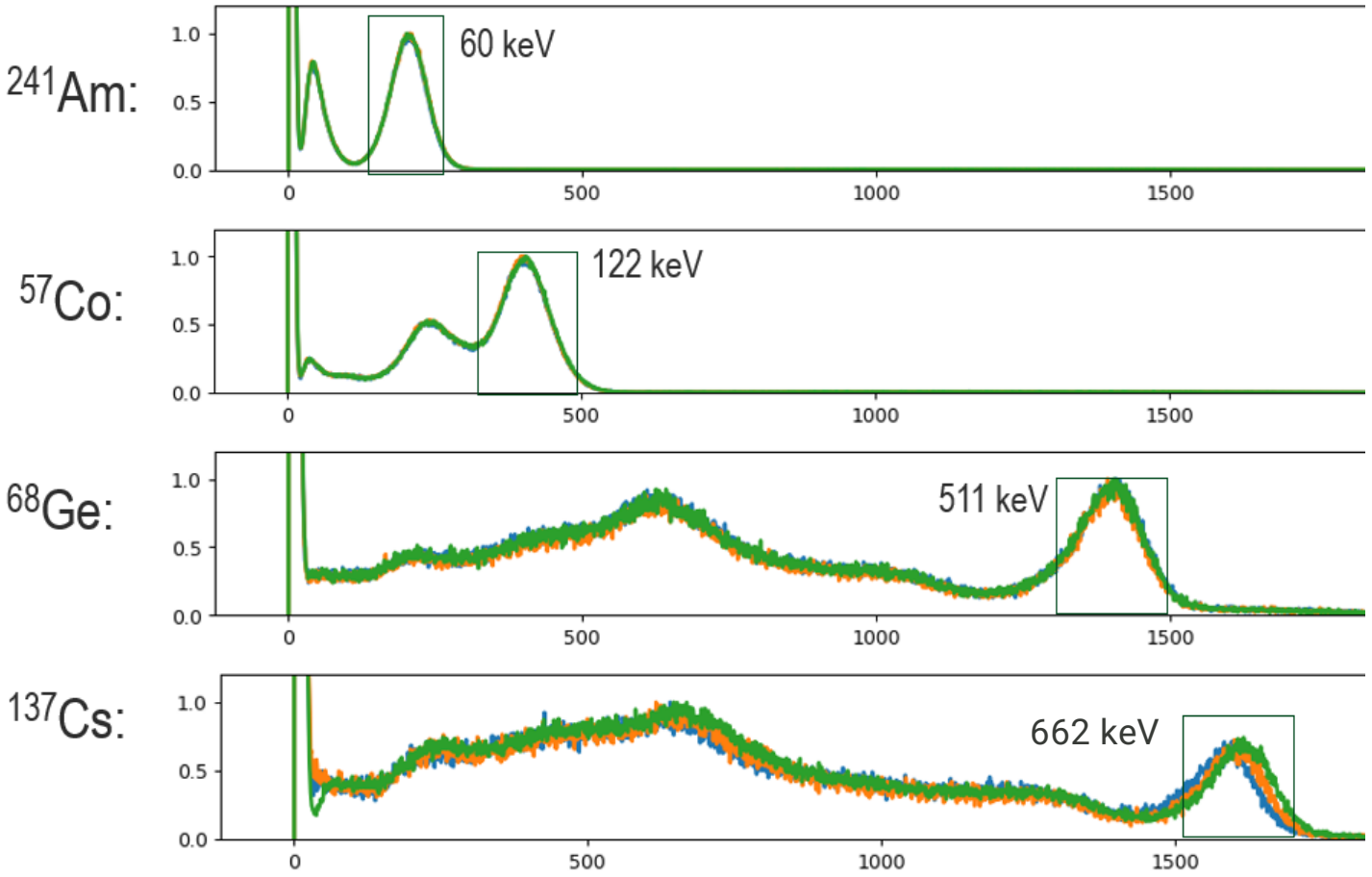


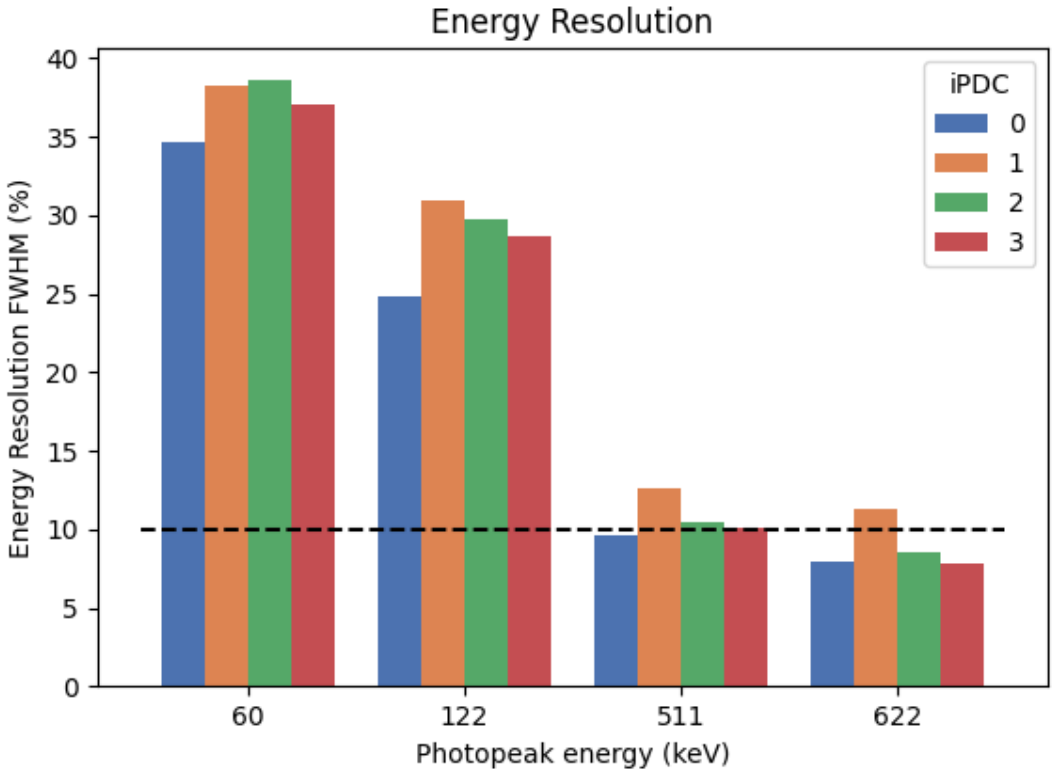
Mask exposed Pixels

Define pixel mask to disable exposed and noisy (>100cps) pixels



Energy response with LYSO scintillator





Showing only PDC0
Different colors = repeated runs

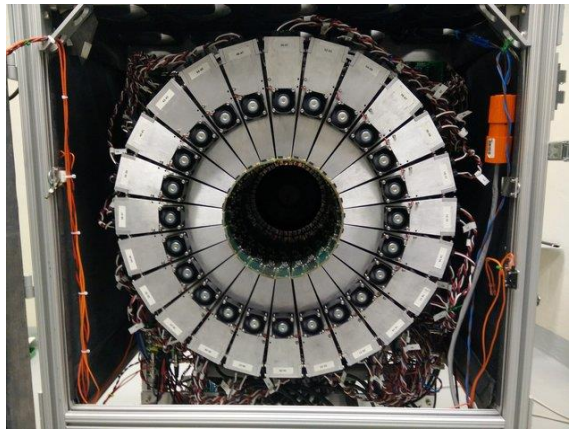
Applications are wide and not field-specific

National Security



M. R. Heath *et al*., "Development of a Portable Pixelated Fast-Neutron Imaging Panel," in *IEEE Transactions on Nuclear Science*, vol. 69, no. 6, pp. 1352-1356, June 2022, doi: 10.1109/TNS.2021.3136344

Medical Imaging



https://www.usherbrooke.ca/grams/domaines-interets/monde-medical/labpet-tdm

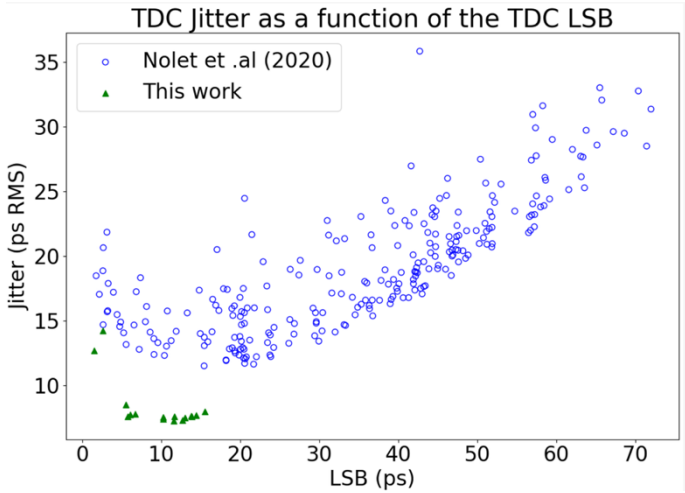
Fundamental Physics

ePIC

nEXO

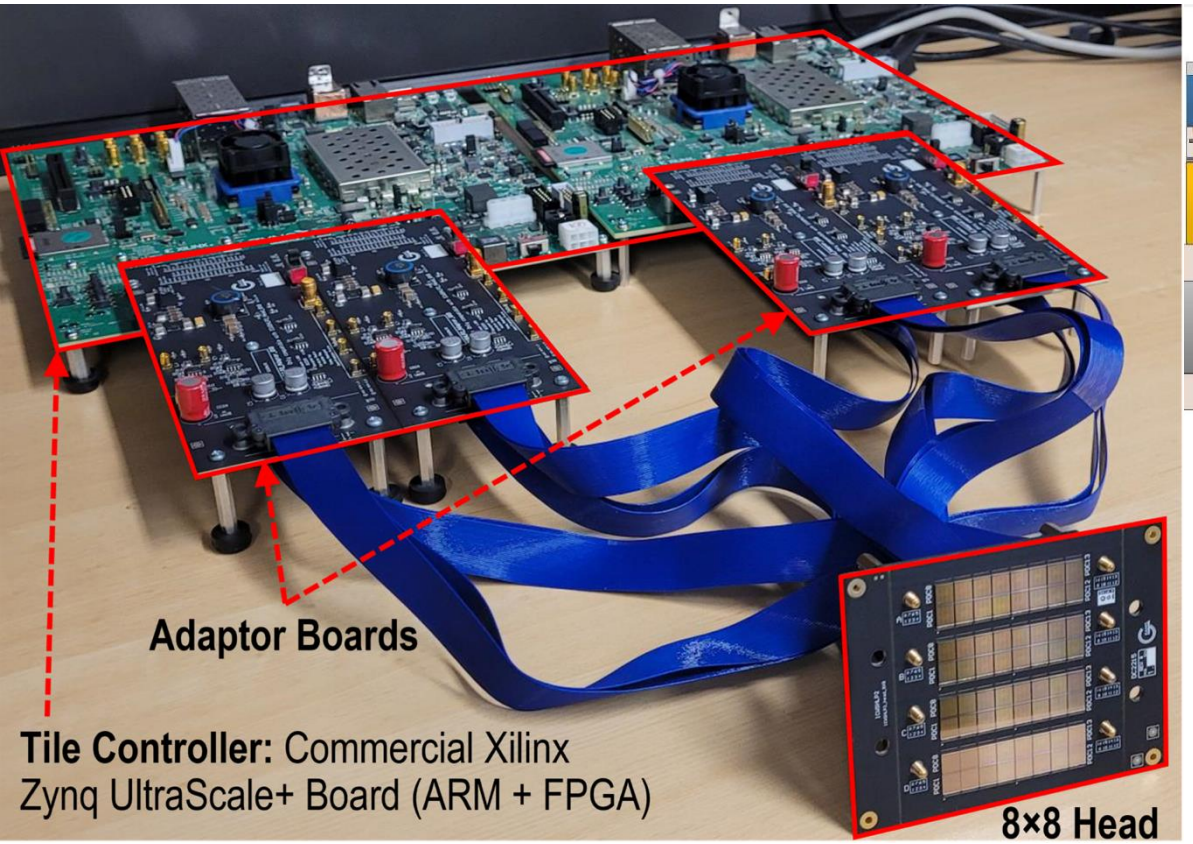
Pratte, Jean-Francois *et al*. (2021). 3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works. Sensors. 21. 598. 10.3390/s21020598.

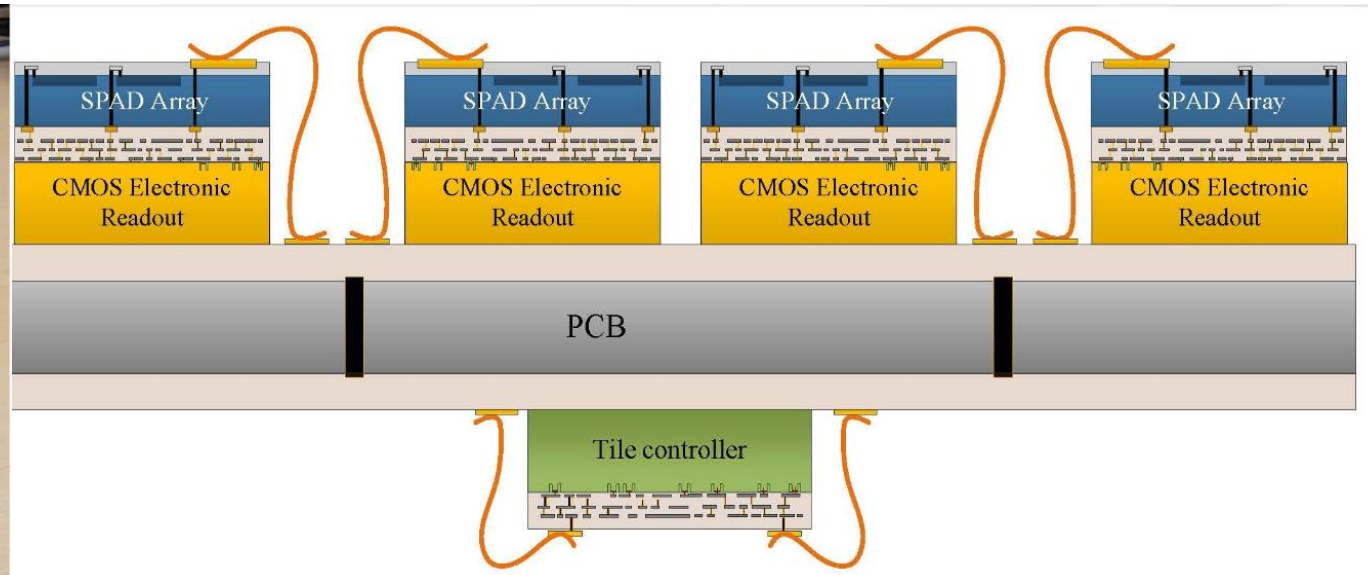
Quantum Key Distribution



Carrier, Simon *et al*. "Towards a Multi-Pixel Photon-to-Digital Converter for Time-Bin Quantum Key Distribution." *Sensors (Basel, Switzerland)* vol. 23,7 3376. 23 Mar. 2023, doi:10.3390/s23073376

Future work includes large-format demonstration



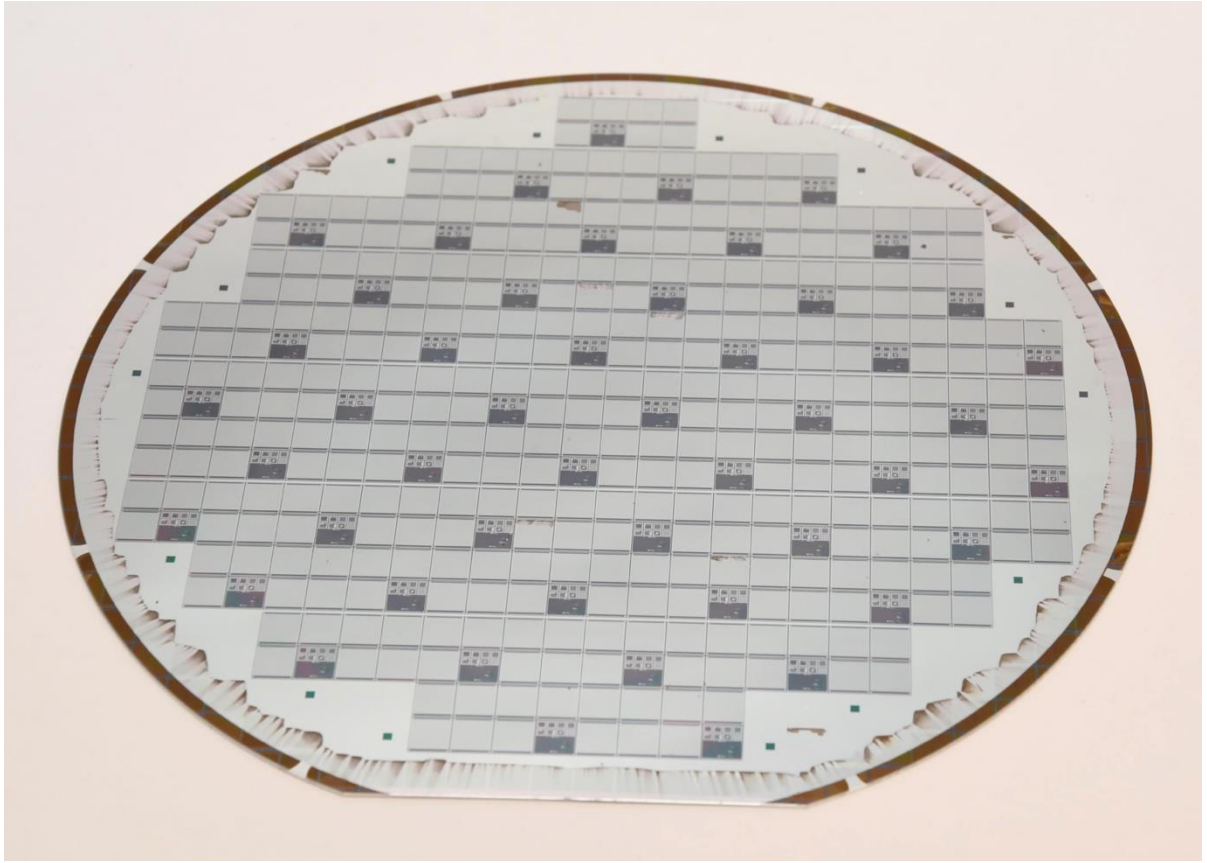


Additional studies in progress:

- Characterization studies with scintillators
- Temperature testing, including cryo
- Irradiation studies
- In-house fabrication
- Simulations

Even more features under development with PDC65

- Individual SPAD ID
- Precision timing with >500 TDCs on
  - No multi-TDCs in the DAQ modules
- Digital sum for subsets of SPADs
- Analog circuit protections (closed layout transistors)
- Operate in additional modes
  - Timestamp-driven mode
  - Camera mode
  - External trigger mode



https://indico.global/event/442/contributions/124510/attachments/59674/114905/202506%20Sherbrooke%20CAP%20PDC-quantum.pdf

R. A. Giampaolo *et al.*, "Photon-to-Digital Converter in 65 nm CMOS Technology with SPTR Below 15 ps FWHM," *2025 IEEE NSS, MIC, and RTSD Conference (RTSD)*, Yokohama, Japan, 2025, pp. 1-1, doi: 10.1109/NSS/MIC/RTSD57106.2025.11286524.

All-digital 3D-PDCs will be a low-noise, low-power, high-timing precision SiPM alternative

Interested in joining the development effort or US Users Group?

Contact Lorenzo Fabris (fabrisl@ornl.gov) and Amanda Steinhebel (steinhebelal@ornl.gov)





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Backup

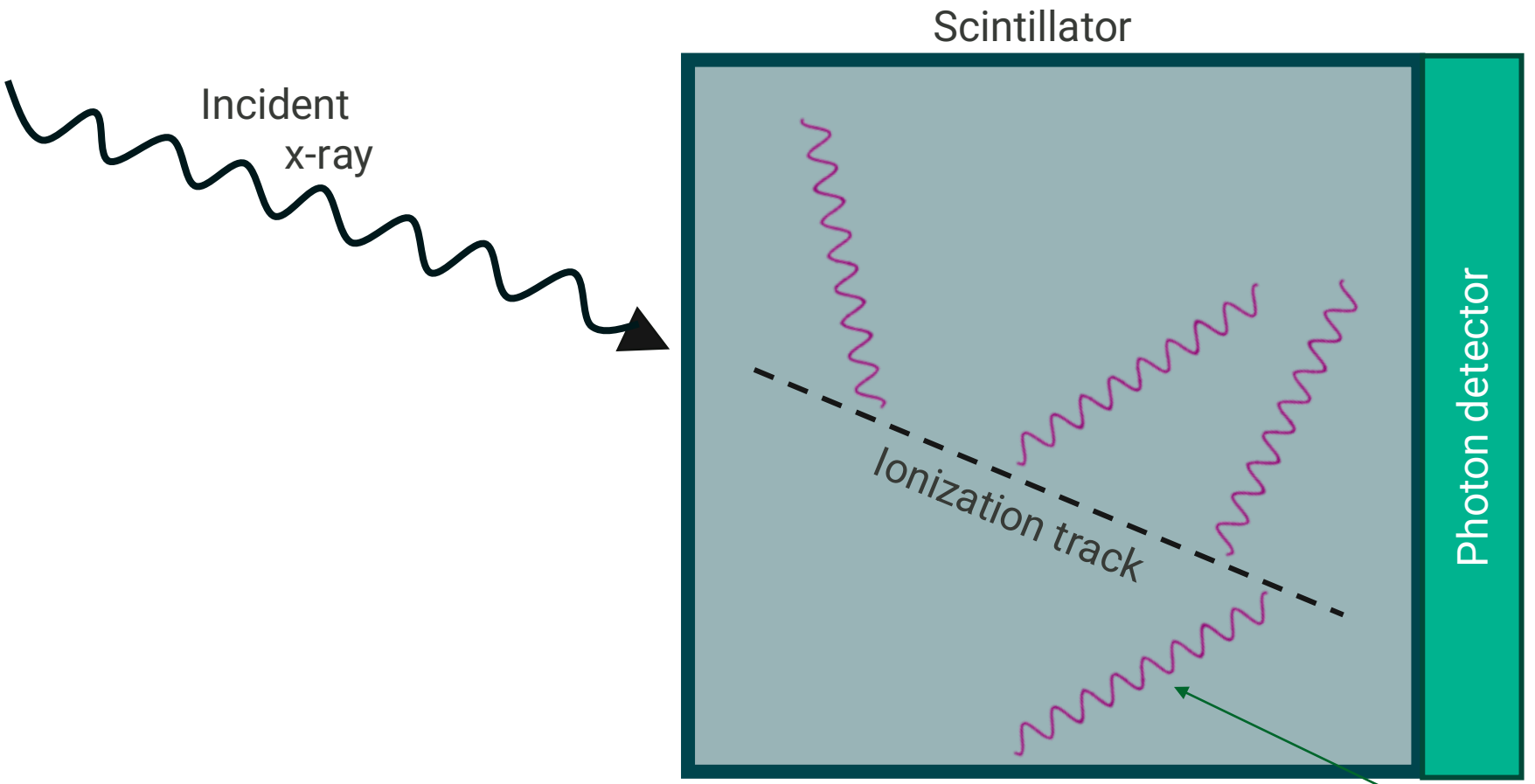
Abstract

Photon to Digital Converters (3D-PDCs) are next-generation digital silicon photomultipliers (SiPMs) that vertically integrate a sensing layer of Single Photon Avalanche Diodes (SPADs) with a custom CMOS active quenching circuit and processing electronics. This design enables individual-SPAD control, reducing system noise and offering ~100 ps single-photon timing resolution. The 'fully digital' philosophy avoids the analog-to-digital conversions used in SiPMs, decreasing power consumption while supporting customizability. The project aims to be a drop-in replacement for SiPMs in a wide range of applications from quantum measurements to radiation detection, fundamental nuclear and high-energy physics, and medical devices. This talk will cover 3D-PDC design, current performance status, the outlook for future systems utilizing the device, and remaining R&D challenges.

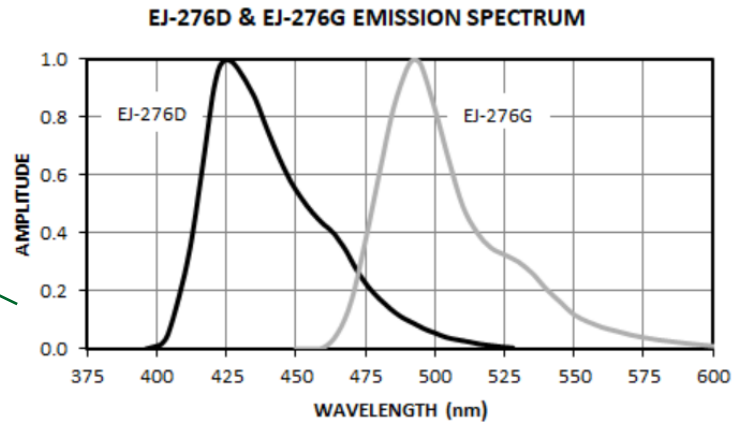
References

- T. Rossignol *et al,* (2024). A 3D photon-to-digital converter readout for low-power and large-area applications. JINST. 19. P09017.
- Pratte, Jean-Francois *et al*. (2021). 3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works. Sensors. 21. 598. 10.3390/s21020598.
- Pratte, Jean-Francois *et al*. (2023). Fast neutron radiography-based on single-photon digital photosensor: concept and demonstration. Proceedings Volume 12696, Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XXV; 1269606 https://doi.org/10.1117/12.2682610.
- Carrier, Simon *et al*. “Towards a Multi-Pixel Photon-to-Digital Converter for Time-Bin Quantum Key Distribution.” *Sensors (Basel, Switzerland)* vol. 23,7 3376. 23 Mar. 2023, doi:10.3390/s23073376
- M. R. Heath *et al*., "Development of a Portable Pixelated Fast-Neutron Imaging Panel," in *IEEE Transactions on Nuclear Science*, vol. 69, no. 6, pp. 1352-1356, June 2022, doi: 10.1109/TNS.2021.3136344.
- S. Parent *et al*., “Wafer-level characterization and monitoring platform for single-photon avalanche diodes,” IEEE Journal of the Electron Devices Society, vol. 12, pp. 127–137, 2024.
- Vachon, F *et al*., “Measuring count rates free from correlated noise in digital silicon photomultipliers”, *Measurement Science and Technology,* vol. 32, no. 2, Art. no. 025105, IOP, 2021. doi:10.1088/1361-6501/abba4b.
- R. A. Giampaolo *et al*., "Photon-to-Digital Converter in 65 nm CMOS Technology with SPTR Below 15 ps FWHM," *2025 IEEE Nuclear Science Symposium (NSS), Medical Imaging Conference (MIC) and Room Temperature Semiconductor Detector Conference (RTSD)*, Yokohama, Japan, 2025, pp. 1-1, doi: 10.1109/NSS/MIC/RTSD57106.2025.11286524.

Radiation detection requires single-photon accuracy

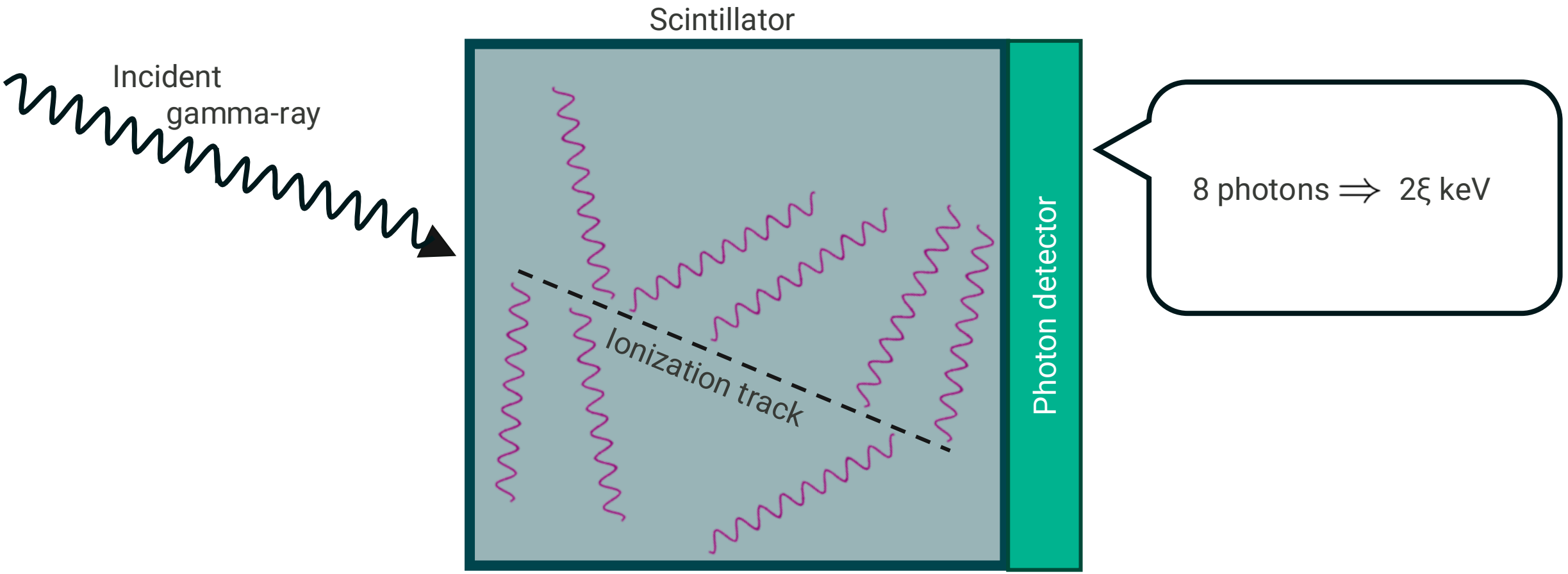


4 photons $\Rightarrow$ ξ keV



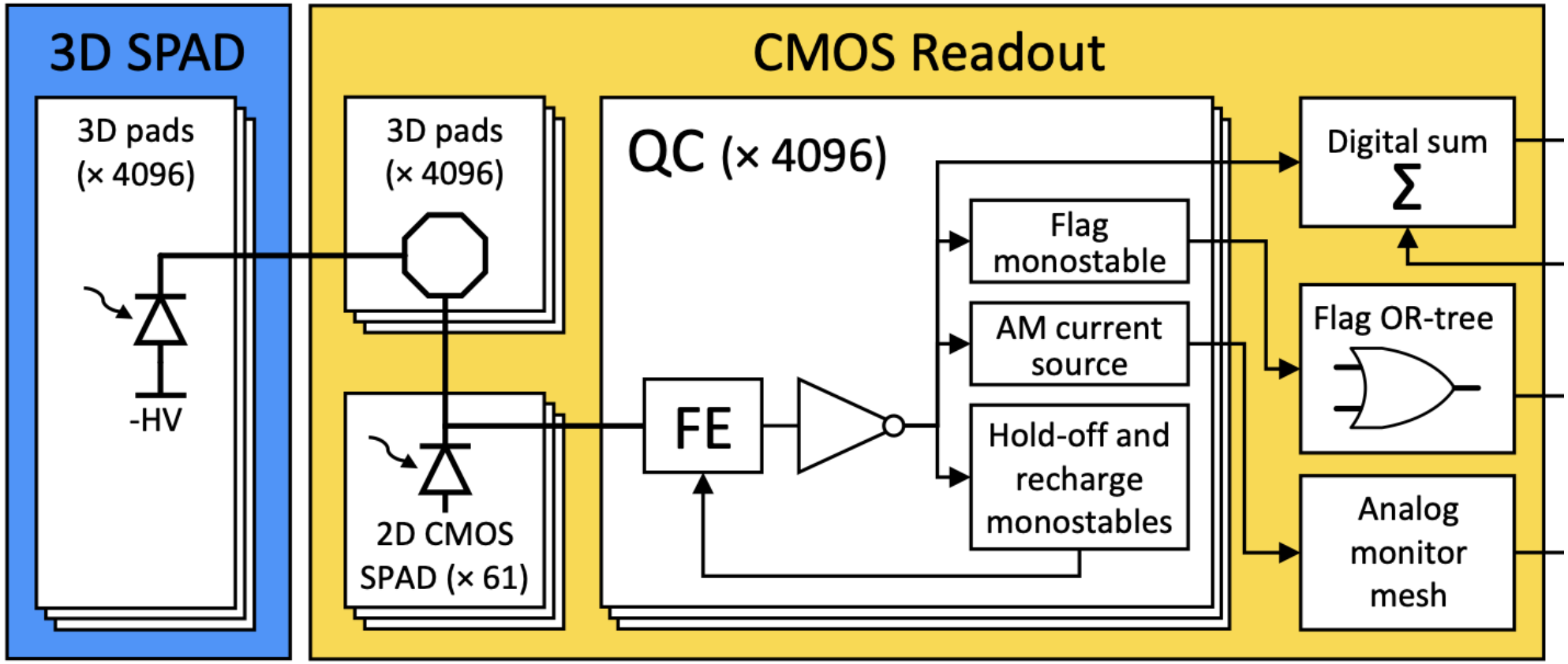
https://eljentechnology.com/products/plastic-scintillators/ej-276

Radiation detection requires single-photon accuracy



CMOS active quenching circuit enables extra features

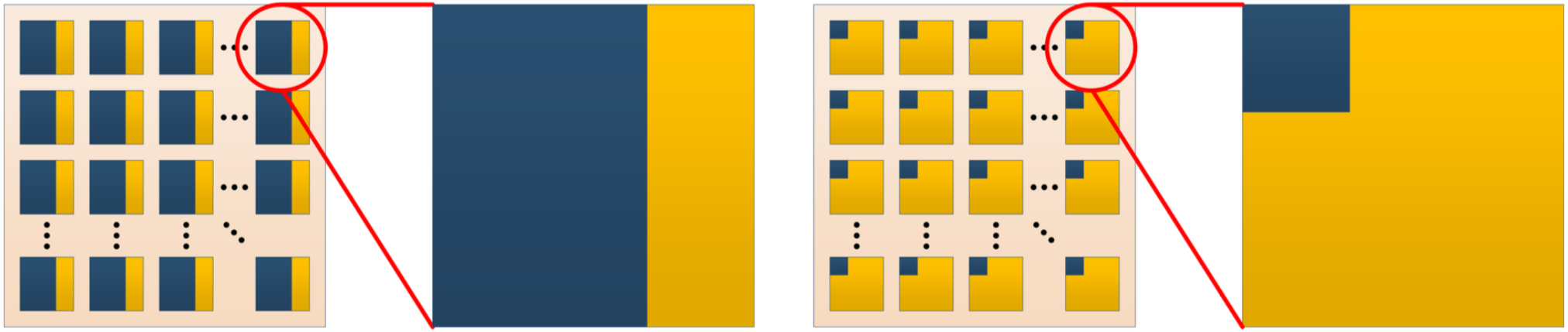
Quenching Circuit (QC) main function = lower bias after trigger and return SPAD to bias above breakdown



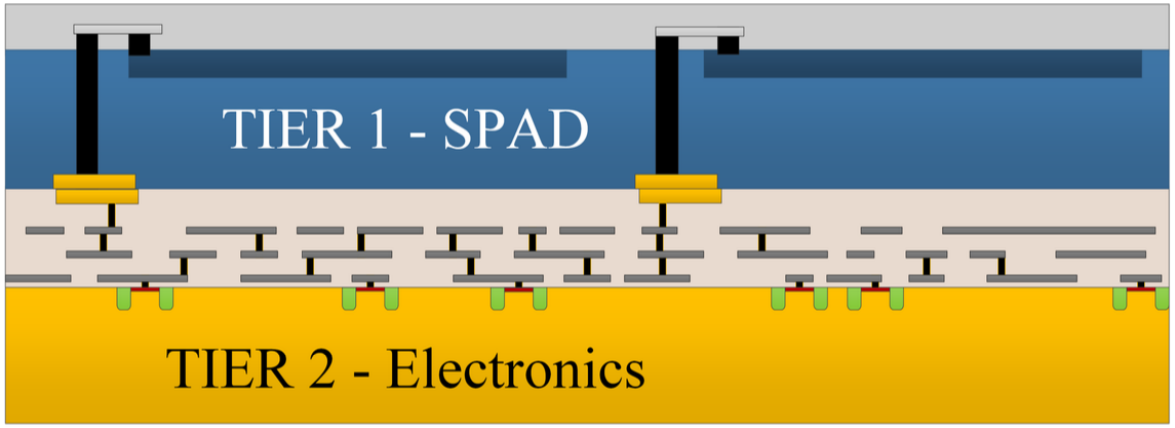
T. Rossignol *et al,* (2024). A 3D photon-to-digital converter readout for low-power and large-area applications. JINST. 19. P09017.

High fill factor achieved through vertical integration

2D dSiPMs balance sensitive area with functionality/features

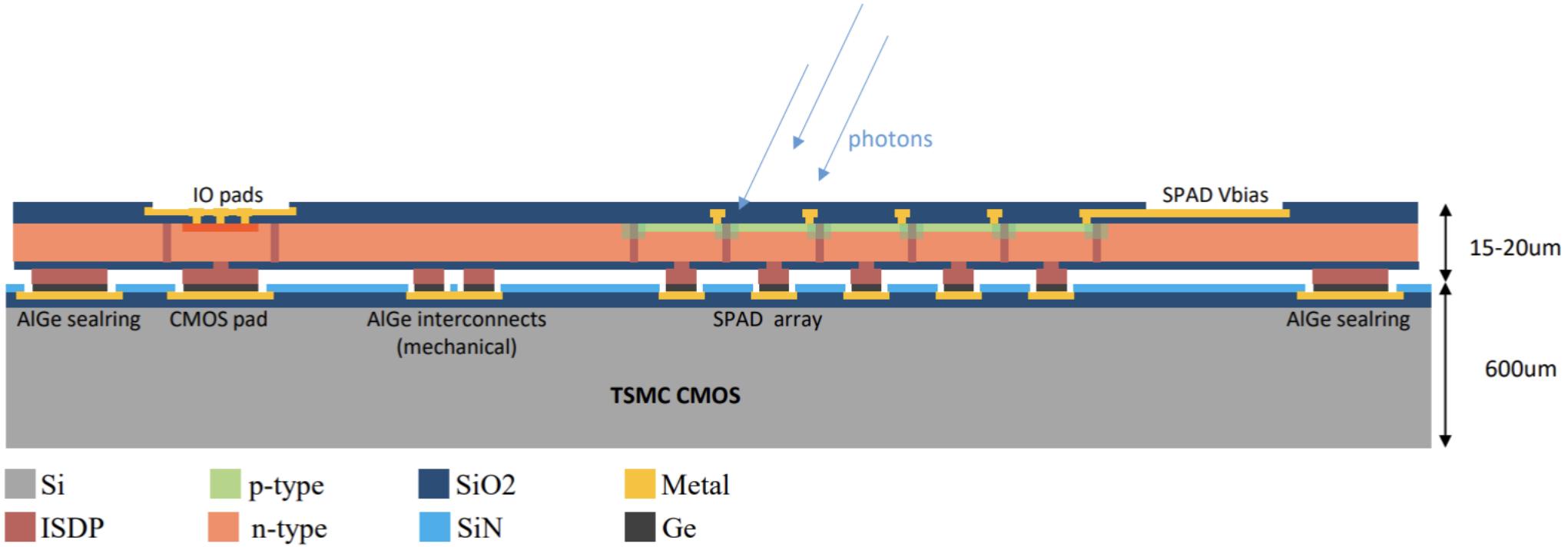


Vertical integration allows 3D PDCs to optimize both (in area and fabrication)

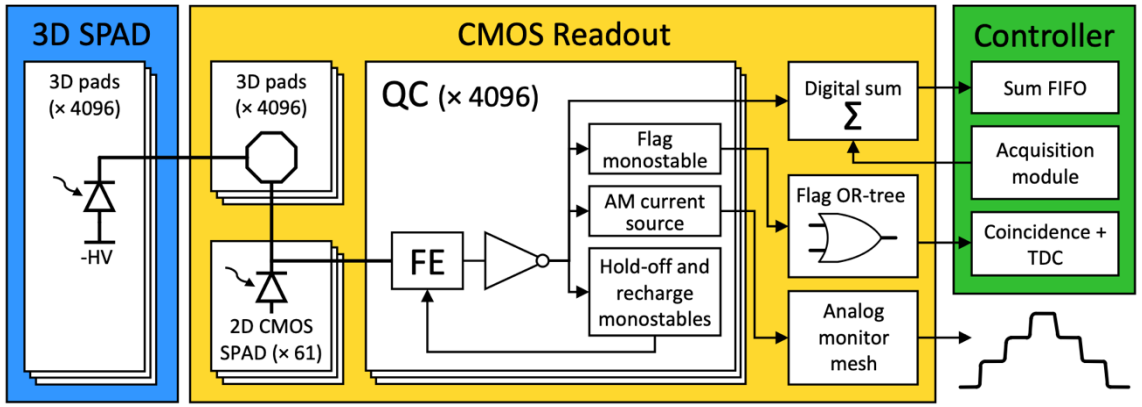


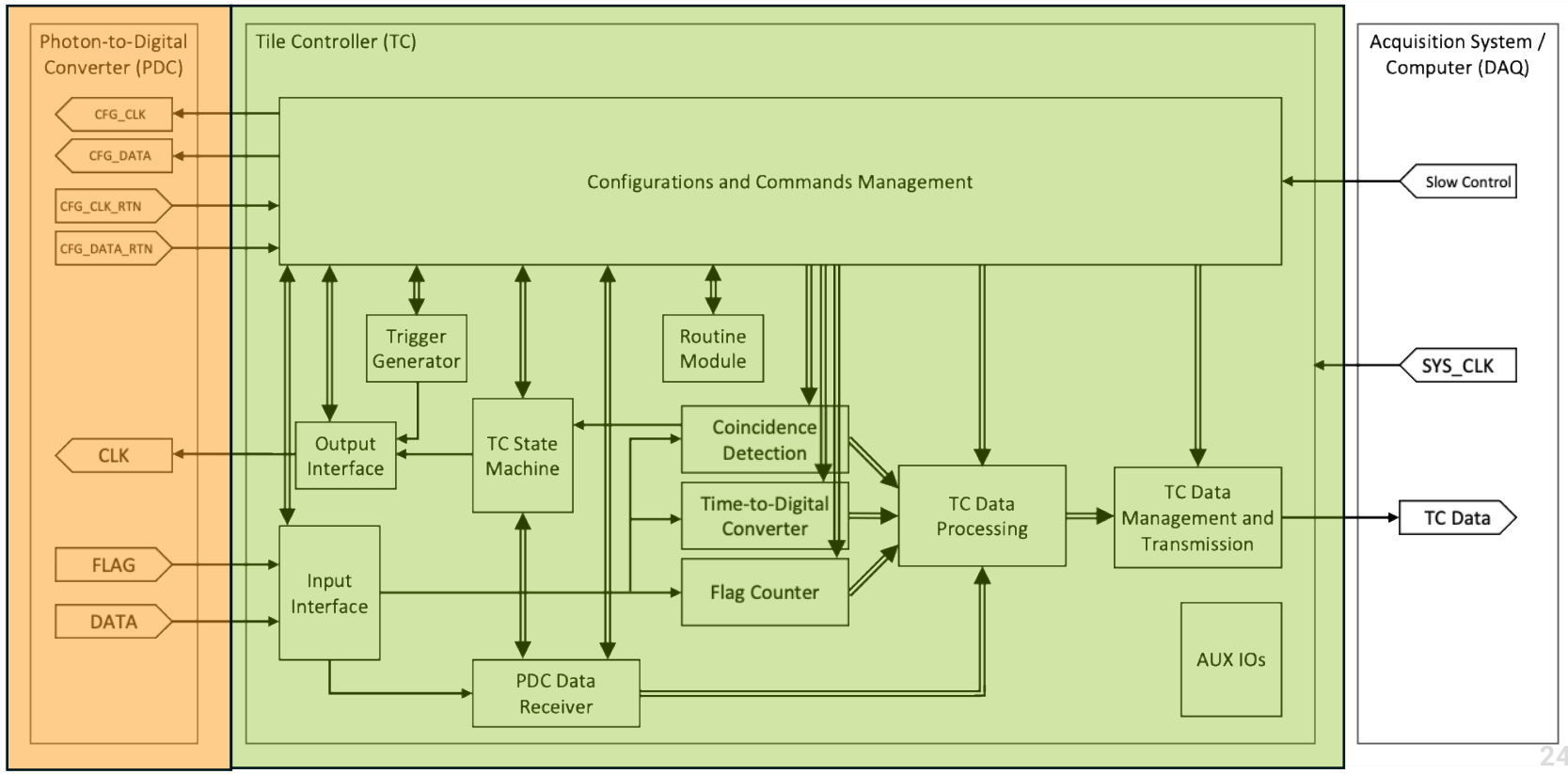
Pratte, Jean-Francois *et al*. (2021). 3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works. Sensors. 21. 598. 10.3390/s21020598.

PDC Cross-section

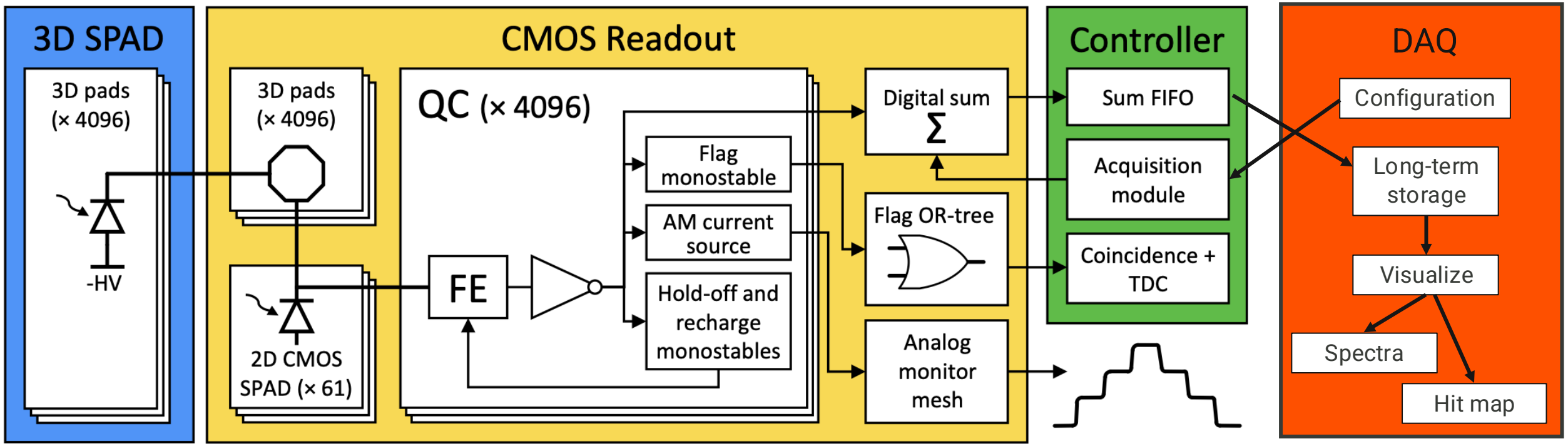


Tile Controller Functionality



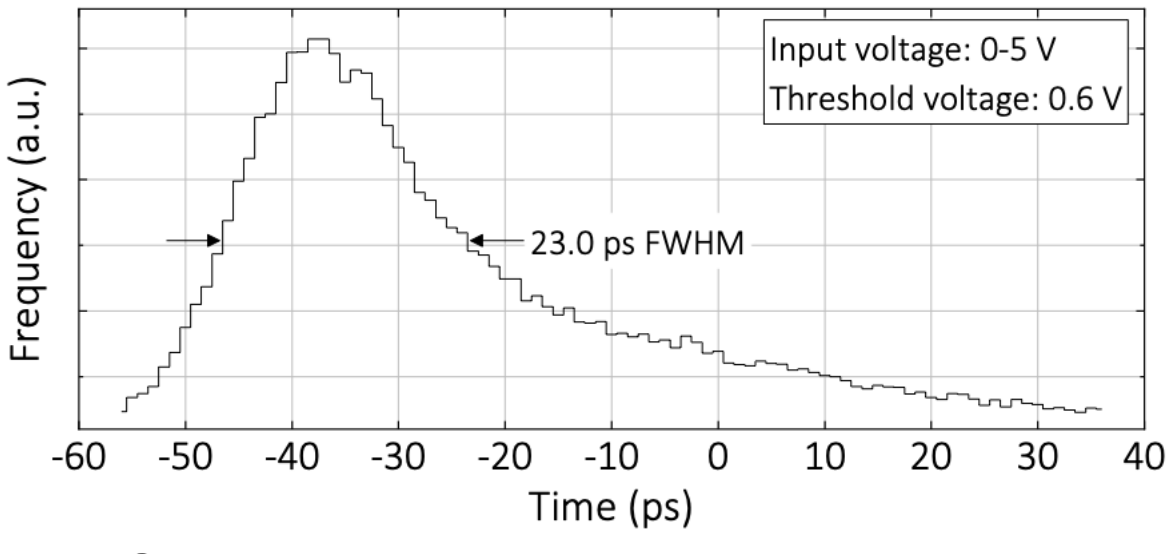


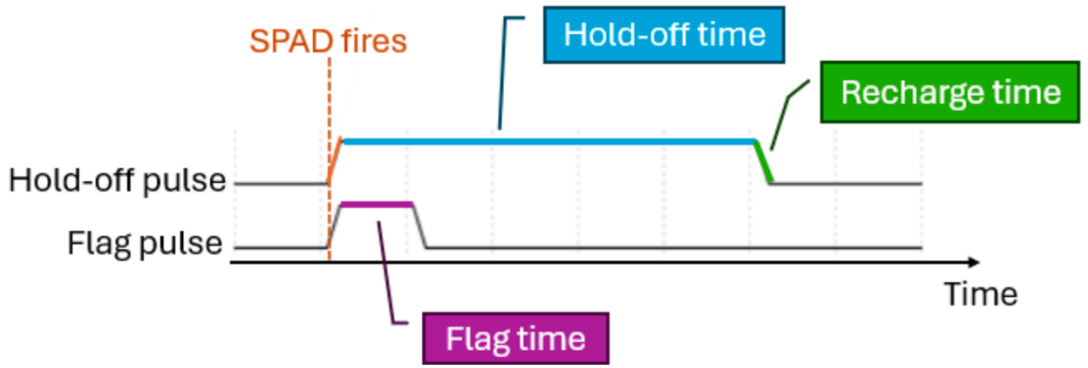
PDC_v2 operation is possible with provided Controller, DAQ, and analysis tools

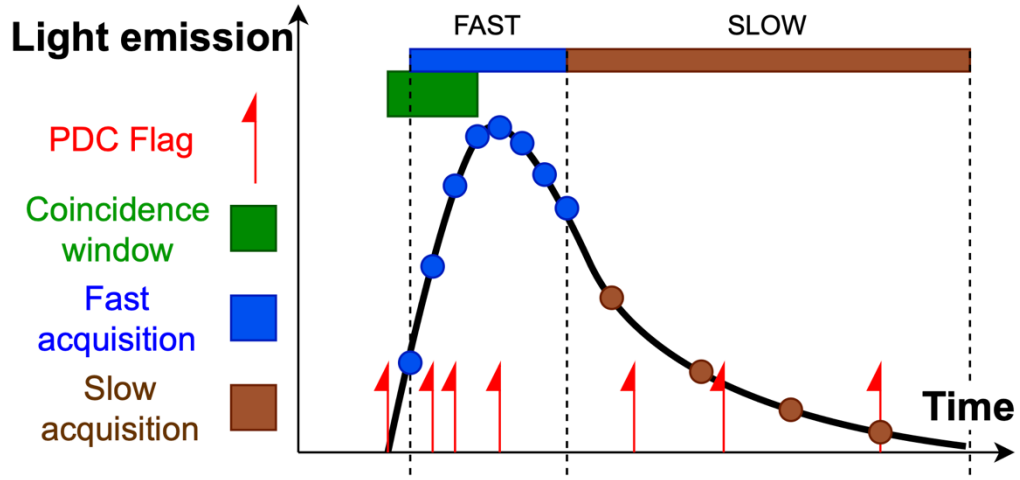


https://github.com/UdeS-PDC/PDCv2-Public

Precision timing is a design priority







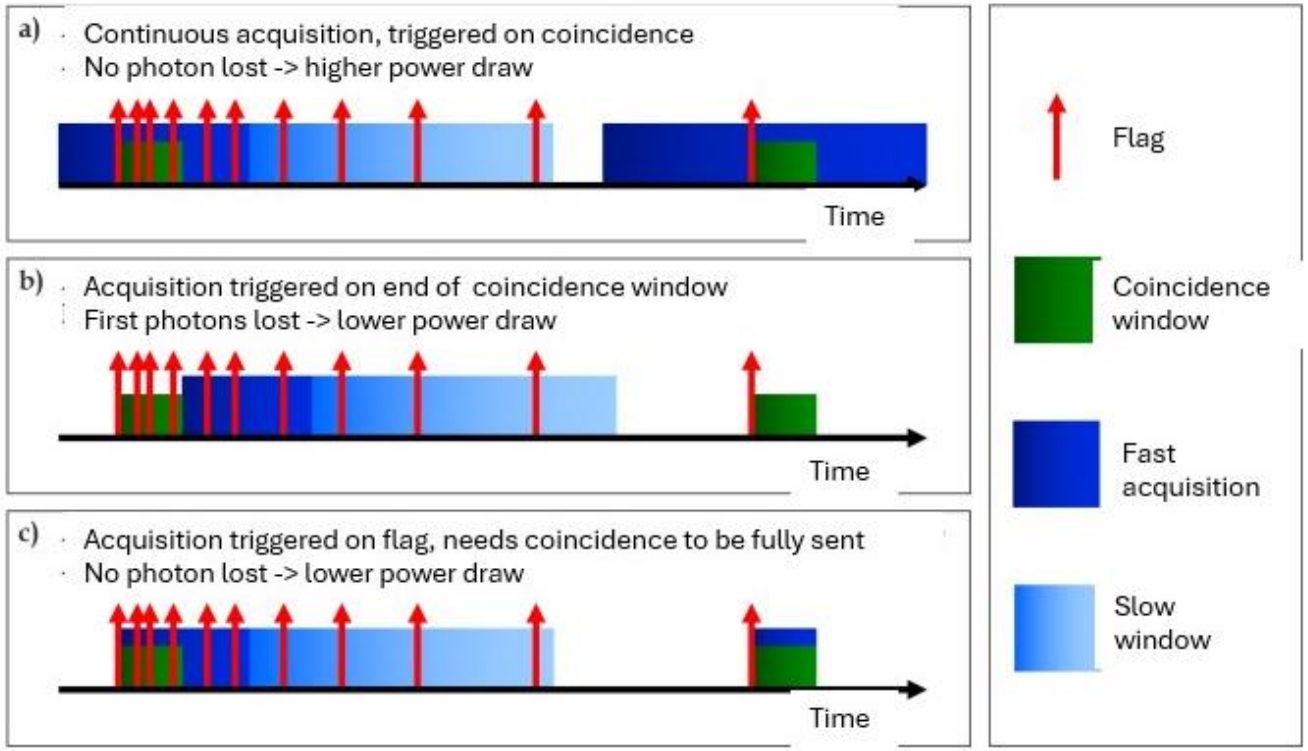
Each flag = fired SPAD

User defines coincidence window conditions

S. Parent et al., "Wafer-level characterization and monitoring platform for single-photon avalanche diodes," IEEE Journal of the Electron Devices Society, vol. 12, pp. 127–137, 2024.

Data acquisition options

- In (a), clock is continuous (high power consumption). When a coincidence is met acquisition is completed. The FIFO keeps the history of what happened before.
- In (b), when an event of interest is detected, the clock is sent to each ASIC and the acquisition starts. However, a delay exist between arrival of first photon and the start of acquisition.
- In c), the controller waits for a flag before acqusition. For each flag, clock and acquisition are sent to the ASIC. If the coincidence requirement is met, the data are saved and transmitted. Otherwise, data are overwritten.

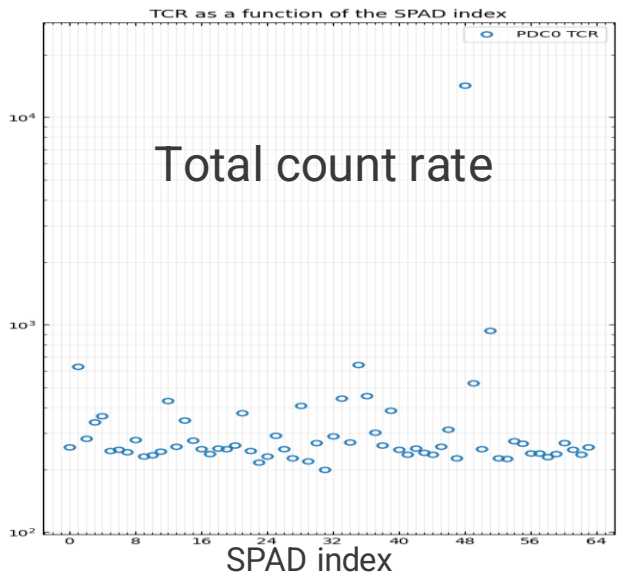


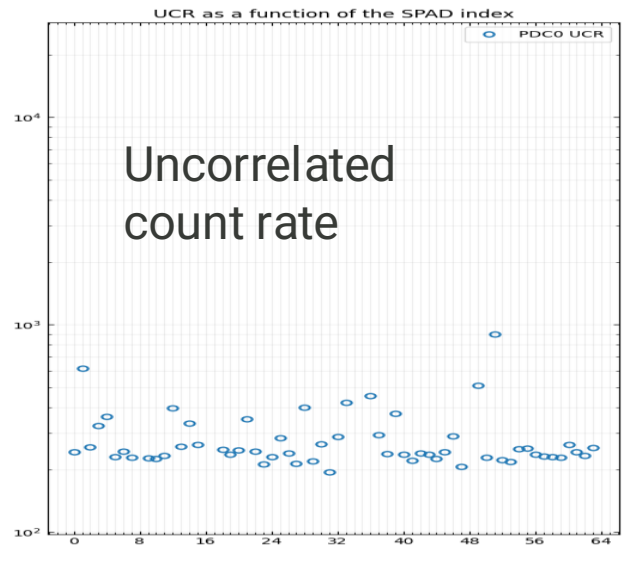
Coincidence modes for pulse shape discrimination

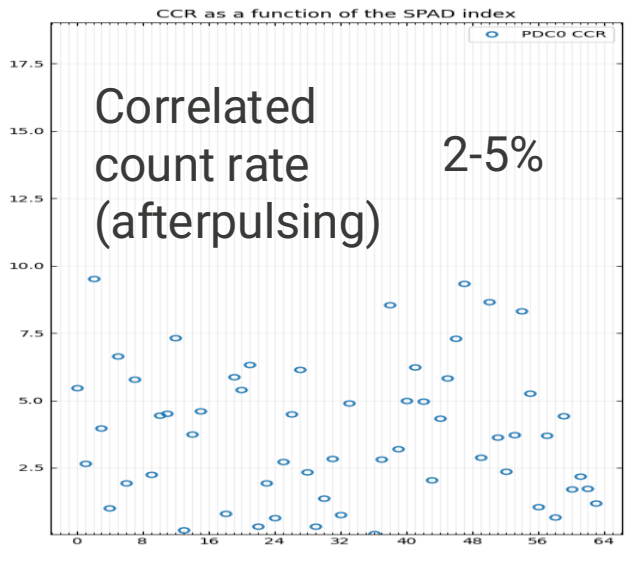
Test structures show promising results

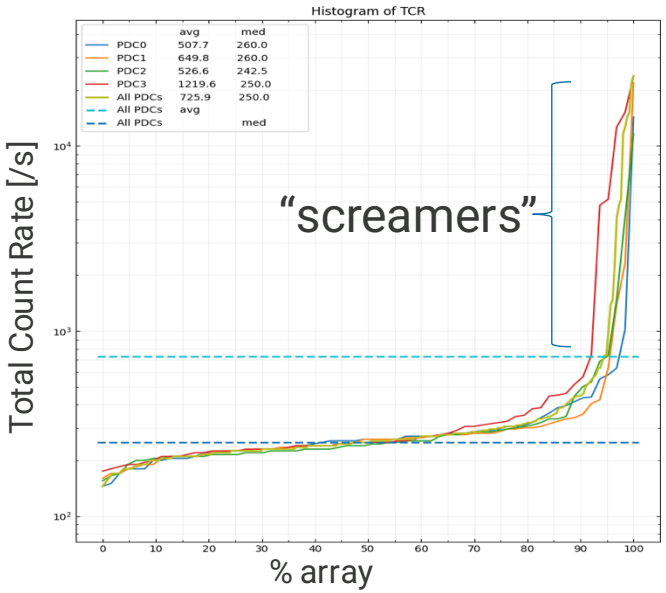
Integrated logic to separate and study (un)correlated hits

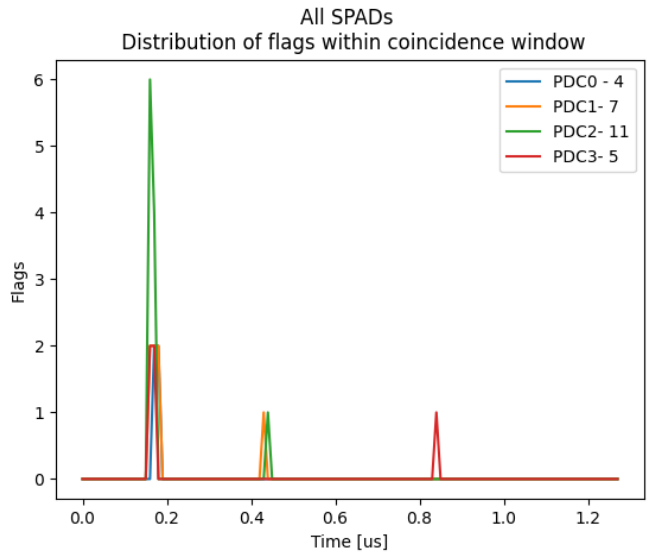
Ability to identify and disable noisy SPADs

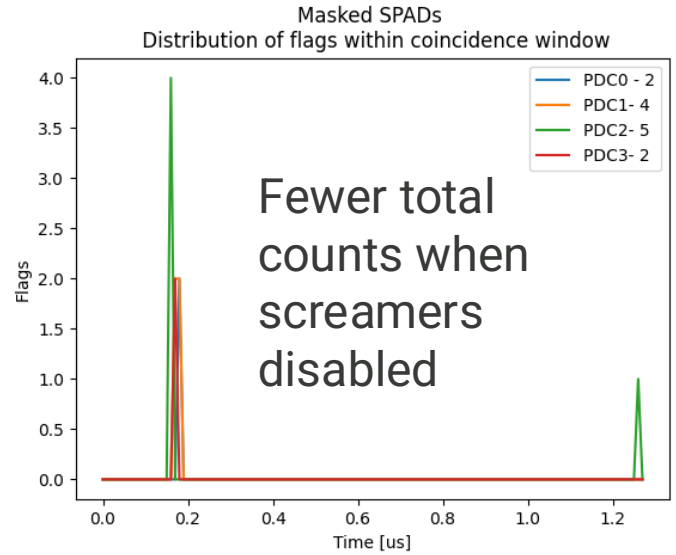












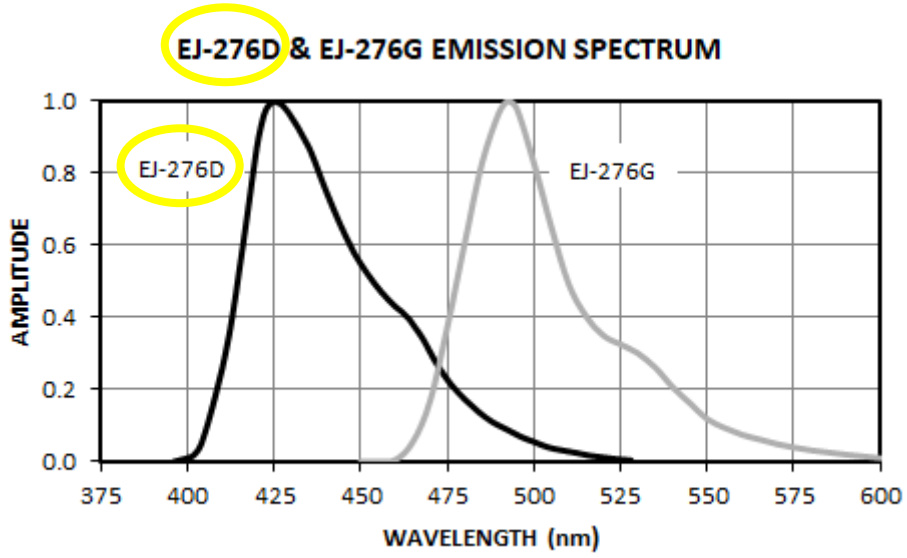
Vachon, F *et al.*, "Measuring count rates free from correlated noise in digital silicon photomultipliers", *Measurement Science and Technology*, vol. 32, no. 2, Art. no. 025105, IOP, 2021. doi:10.1088/1361-6501/abba4b.

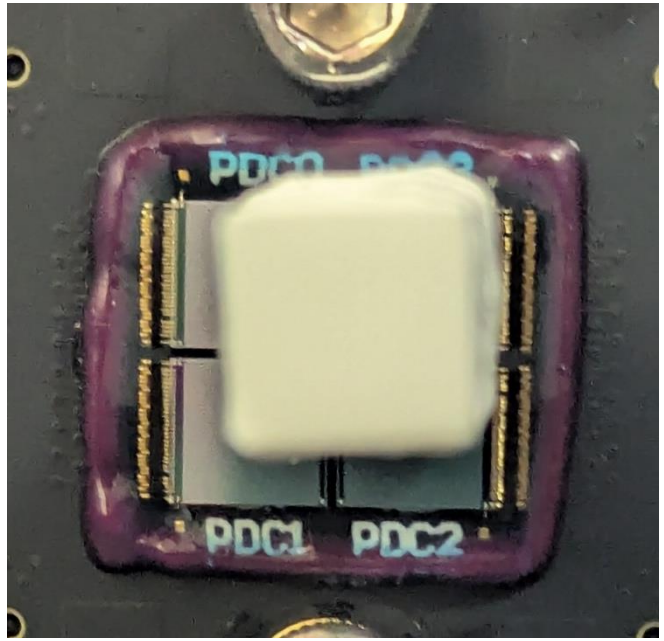
Scintillator measurements - EJ276D

- Organic plastic scintillator produced by Eljen
- Pulse discriminating between gammas and neutrons
- Used for neutron devices, esp. for nuclear security

Preparation

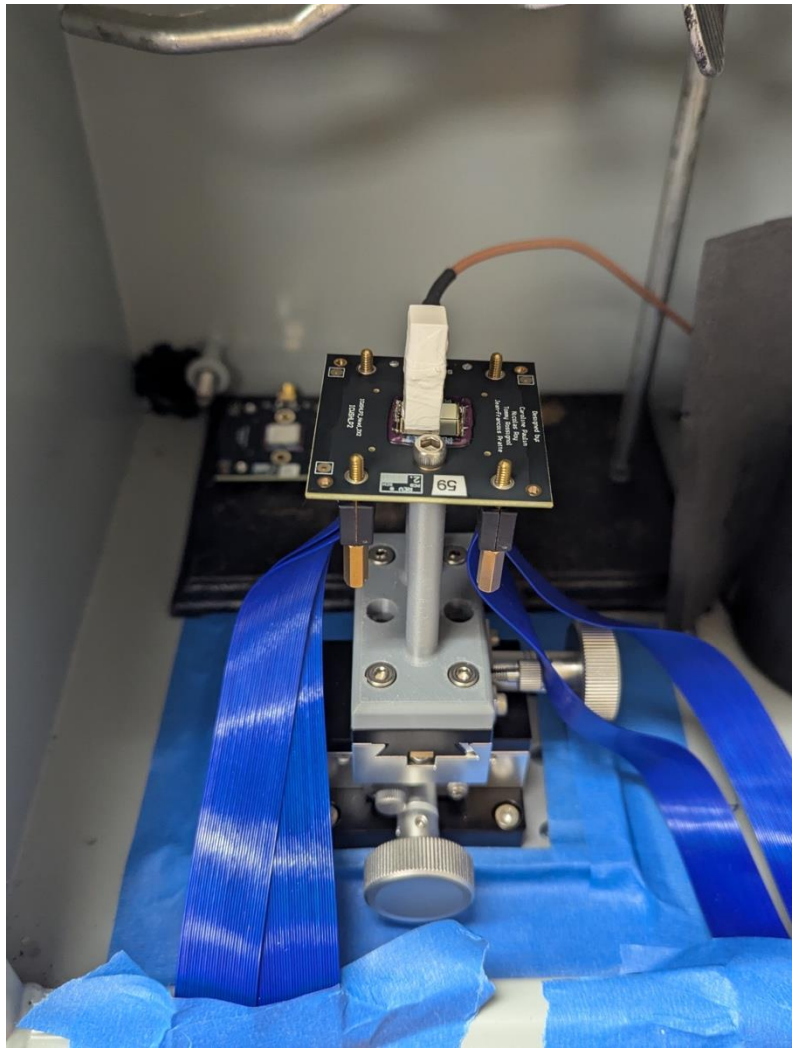
- Wrapped in PTFE (Teflon) as a reflective layer
- Coupled to PDC with 1mm thick silicone optical coupling pad





Chip in dark box on stand, shown coupled to scintillator

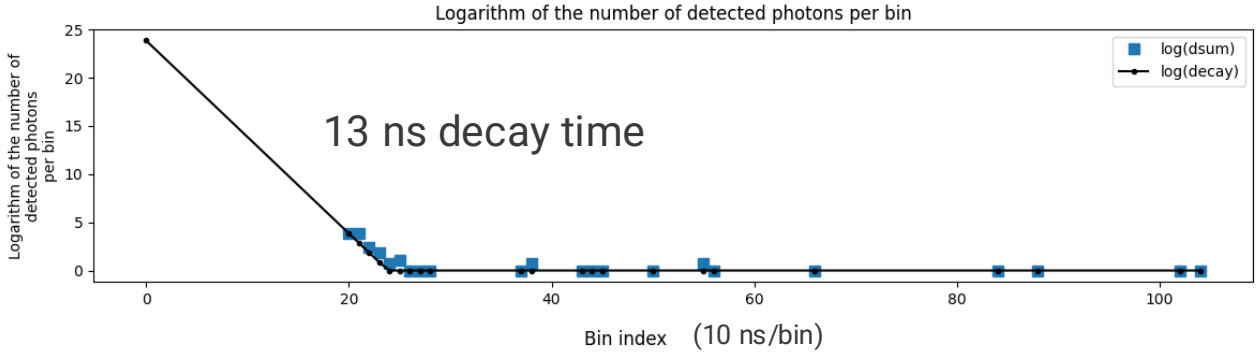
- PDC active area ~ 10x10mm2
- Scintillator size ~ 7x7x25 mm3



First scintillation results

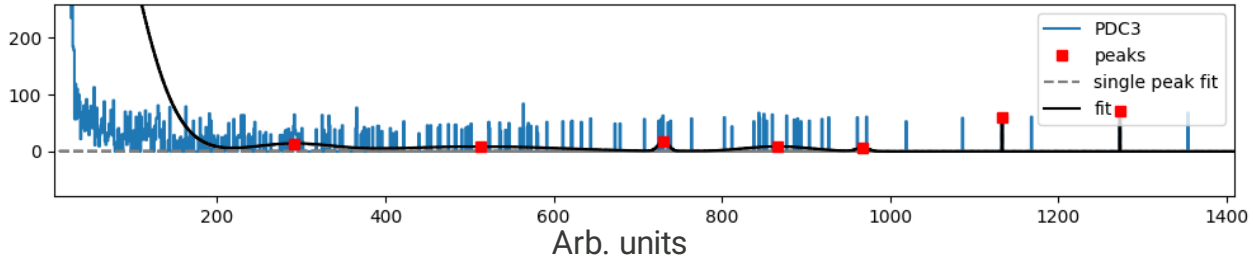
- 22Na, 2.7E-8 Ci
  - Beta+ decay, expect 511 keV annihilation gammas
- Placed <1mm away from scintillator face
- 30 min total data collection
- Average 21.9 events / s passing data quality checks

Example event
Linearized energy, considering holdoff time and SPAD availability

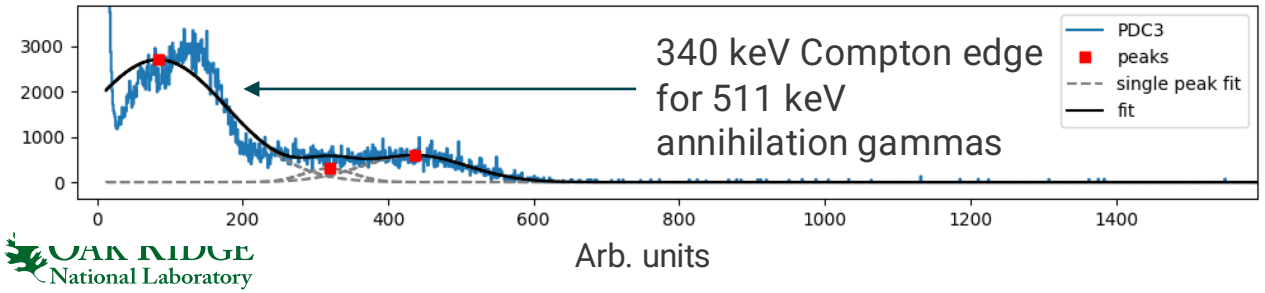


PDC3 Only Energy Spectrum

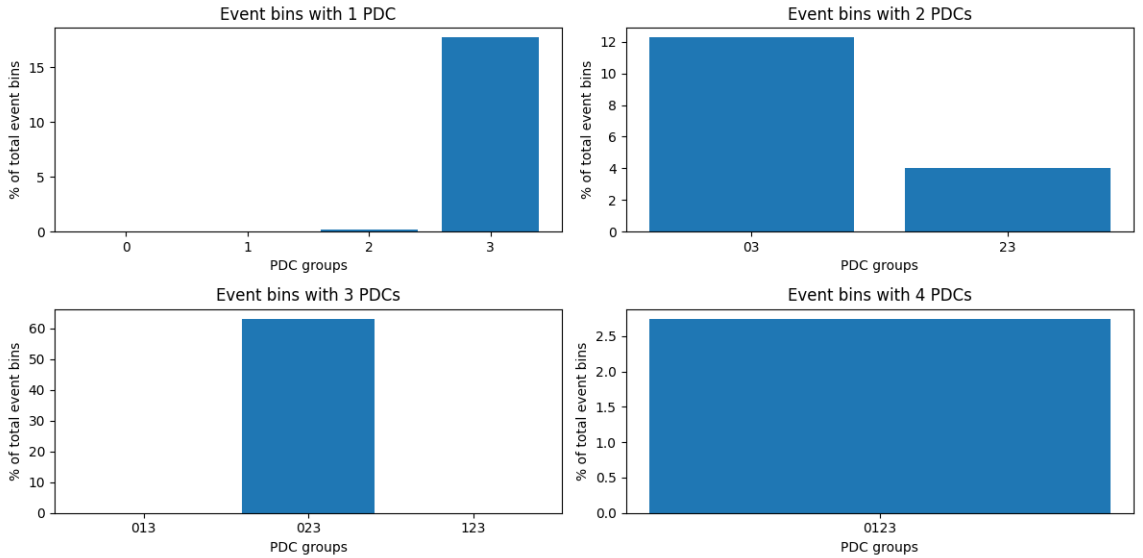
Background



22Na

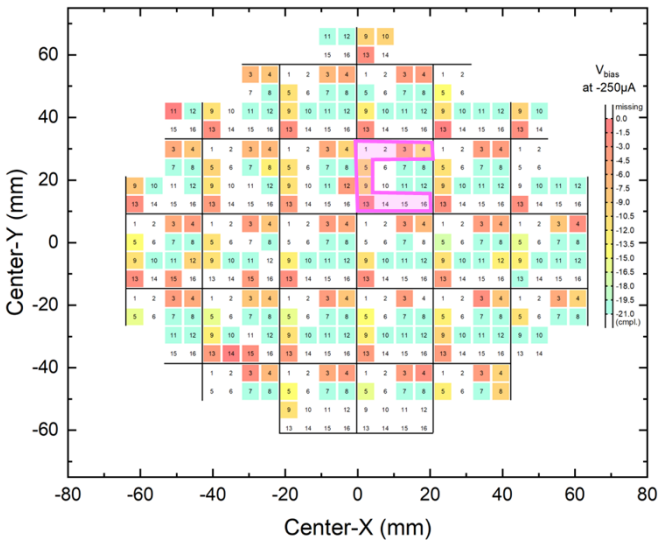


Triggered PDCs per event

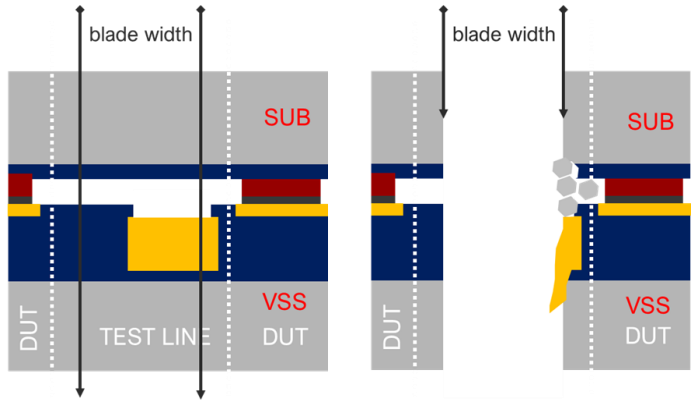


Novel processing has led to important lessons learned

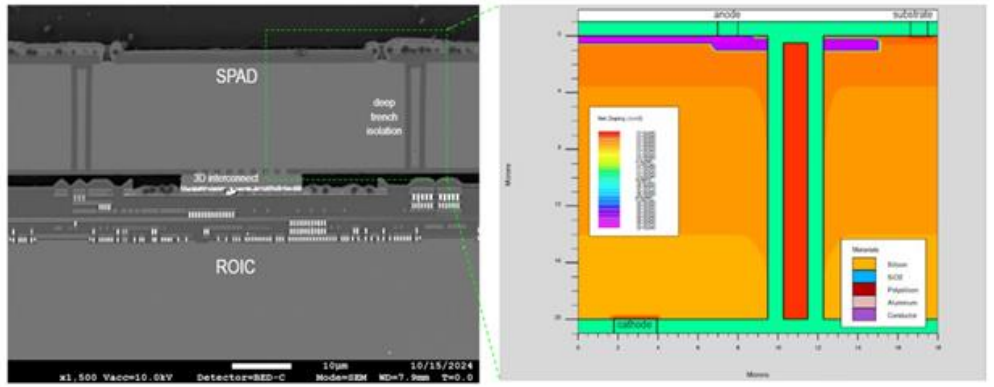
Layer Shorting

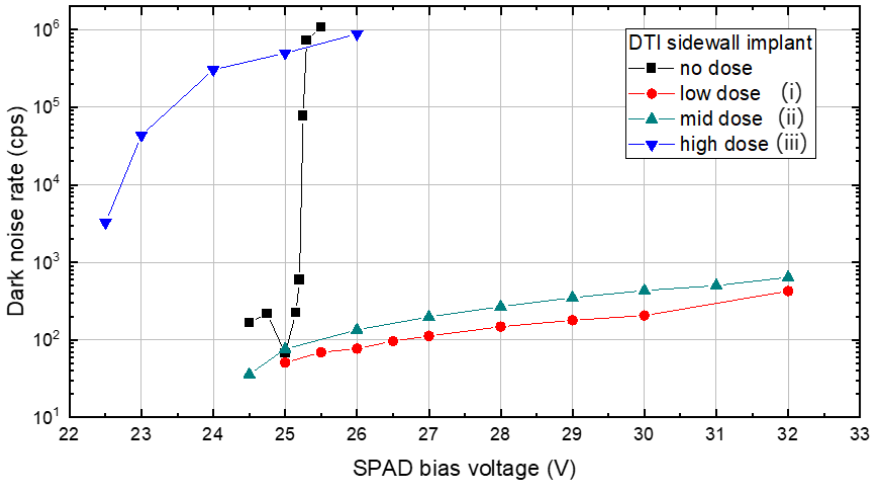


- PDCs on the wafer worked on the probe station but stopped after dicing
- Failures followed a geometrical pattern
- Due to foundry-introduced structures in dicing lane



Deep trench isolation sidewall implant

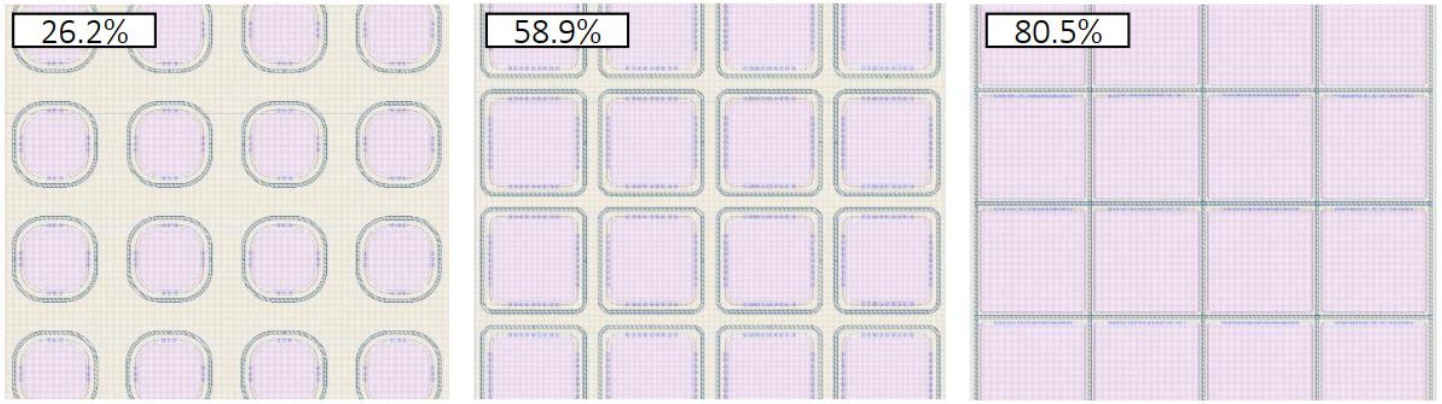




Dope trench sidewalls to overcome charge injection induced by crystal defects

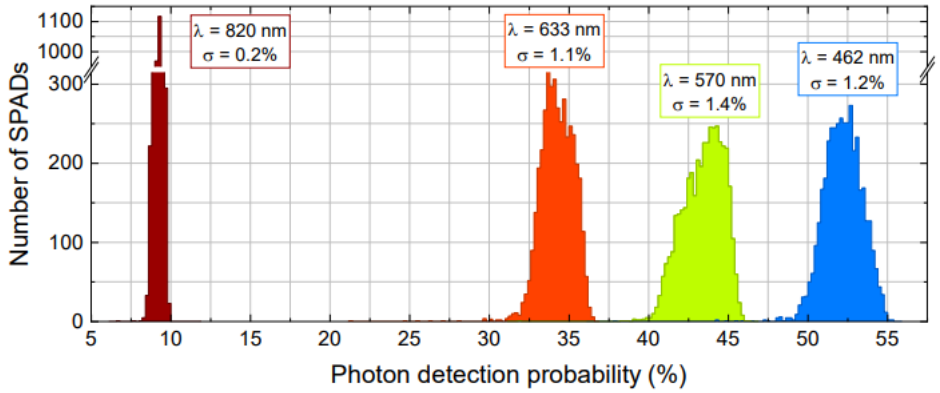
Additional R&D Challenges

SPAD fill factor

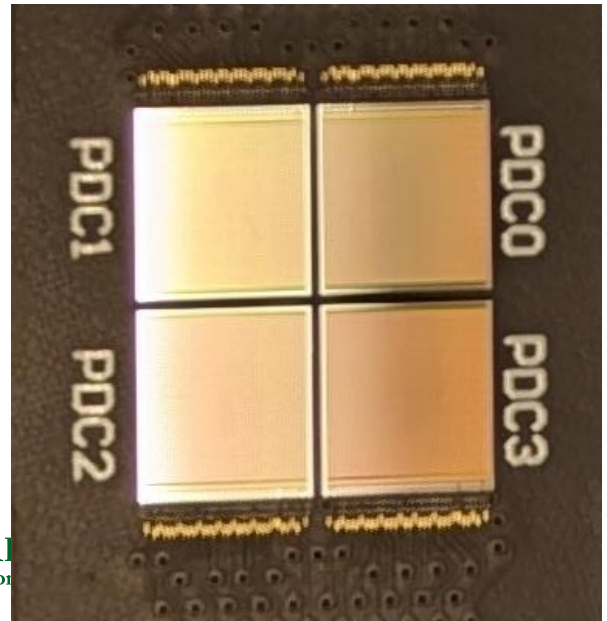


Current design (conservative) | All design rules respected | Pushing design rules

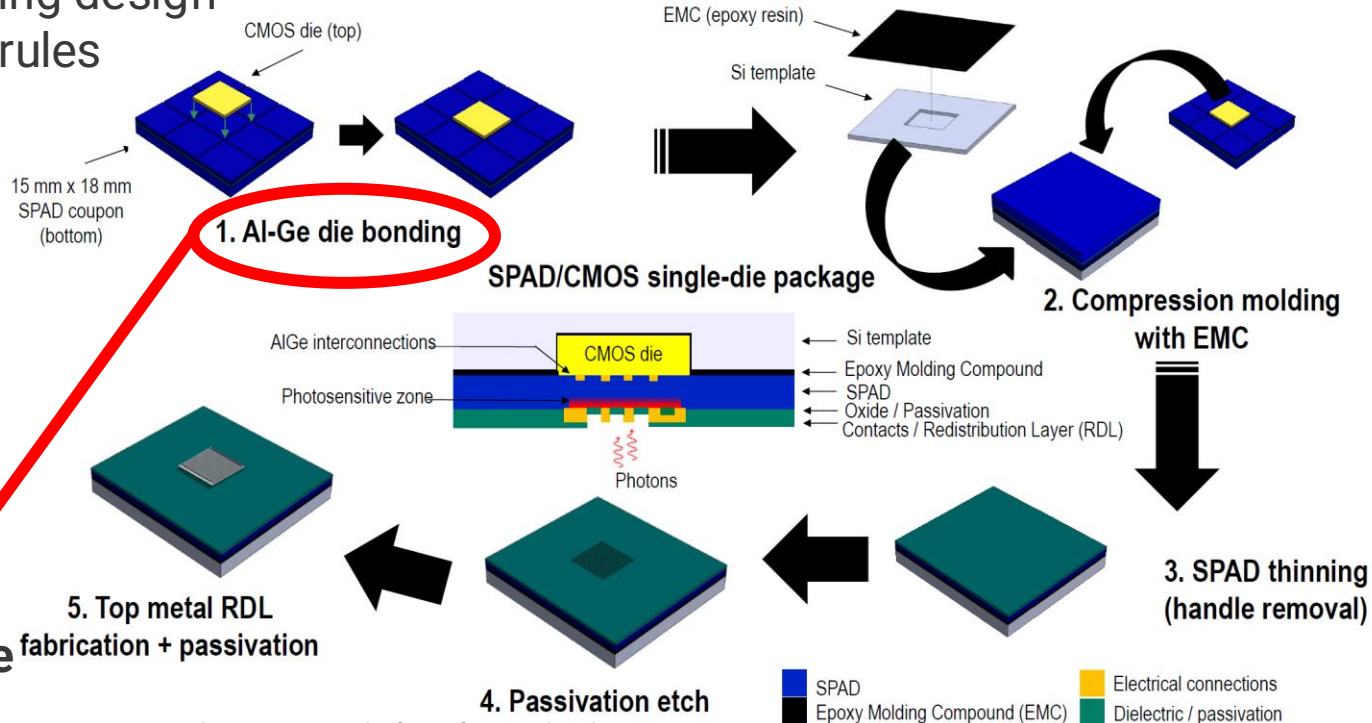
PDE, esp. at long wavelengths



4-side buttable



Single-die bonding



Bonding technique

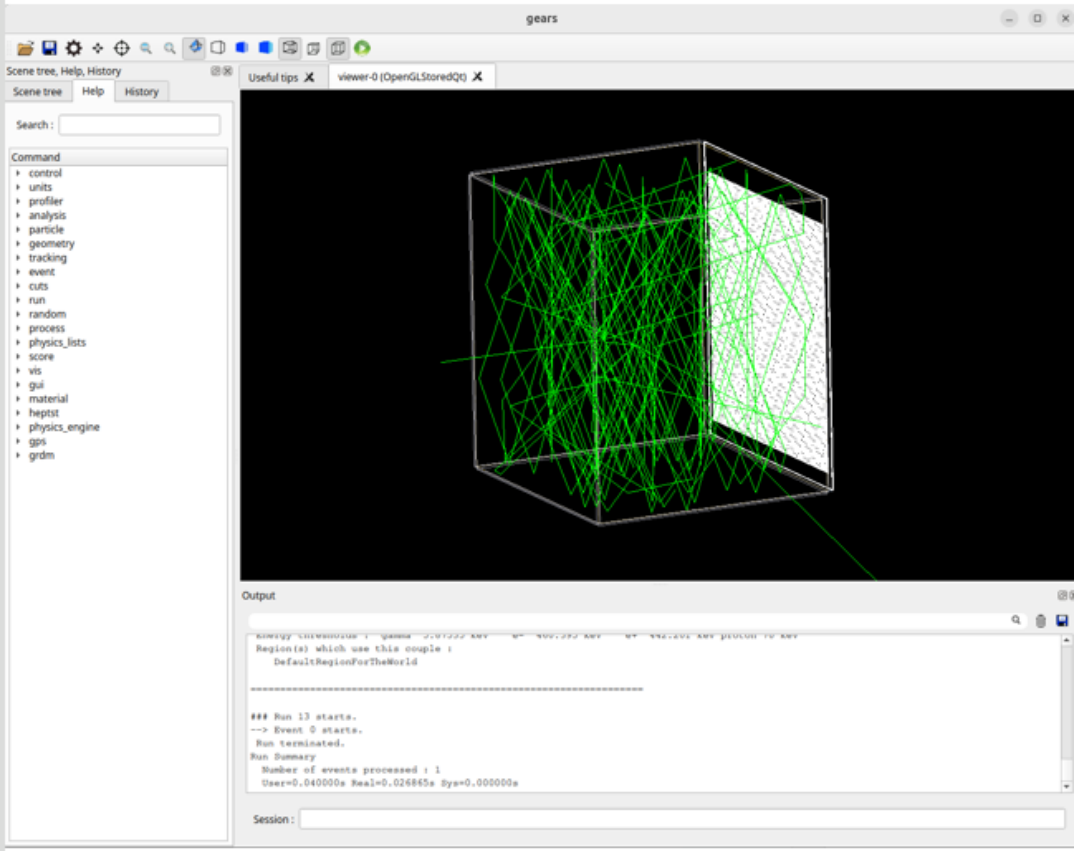
S. Parent *et al.*, "Wafer-level characterization and monitoring platform for single-photon avalanche diodes," IEEE Journal of the Electron Devices Society, vol. 12, pp. 127–137, 2024.

Simulation suite in development

Goal = provide Geant4-based simulation models with realistic geometry for PDC and tile controller simulation (analysis system including detector response function, quantum efficiency, data packaging, etc)

Quick Example Simulation – Block of Scintillator on PDC

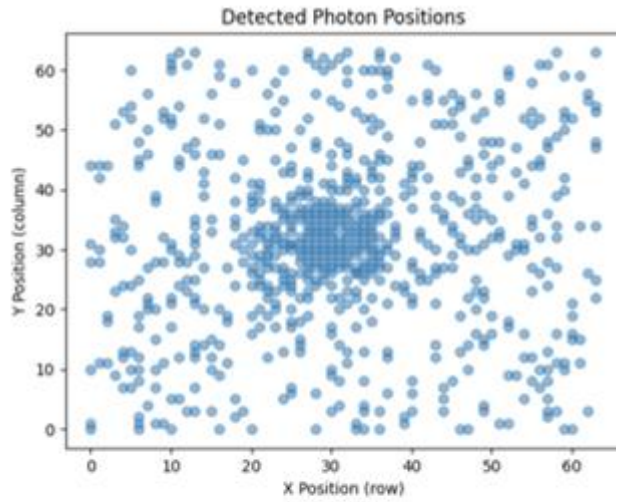
- Example Simulation
  - EJ276D block
  - 5/6 sides wrapped in ESR reflector
  - Optical Grease
  - Single PDC cell
- Fired 1000 neutrons at the cell to see how the simulation behaved



Deliberately lowered scintillation yield for this presentation

Implemented preliminary version of geometries, buildable MC worlds, data return, tile controller simulator based on previous Universite de Sherbrooke work

Active development = full implementation of previous work, validation, user testing



Photons from a single neutron event

D. Mathews, ORNL

US PDC Users Group

- Inaugural meeting 17 August, 2026
- Led by ORNL with UdeS support
  - UdeS informally supporting Canadian users
  - ORNL as point of contact for US users
- 10 involved institutions (labs, government, academic institutions, 29 researchers
- Intended monthly frequency, biweekly when efforts ramp up
- Goal = encourage collaboration and facilitate the use of 3D-PDCs

