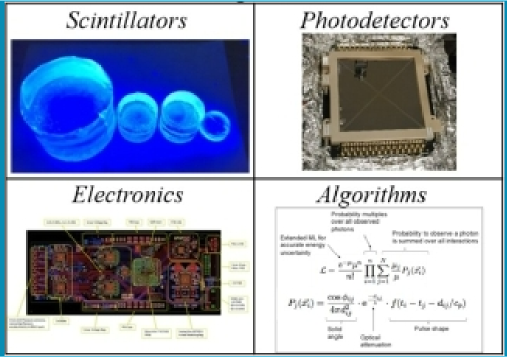
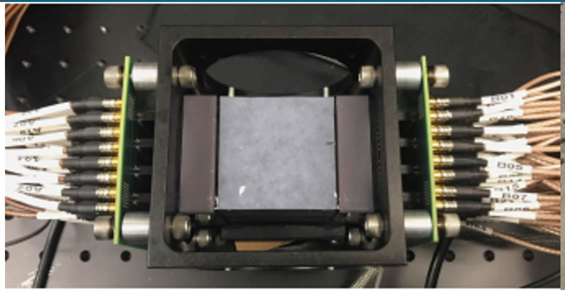
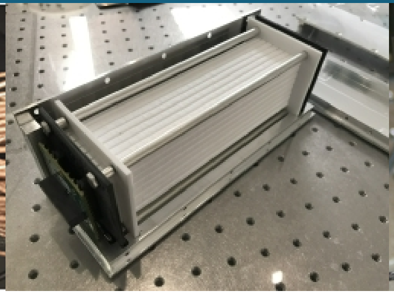
SAND2021-14286PE

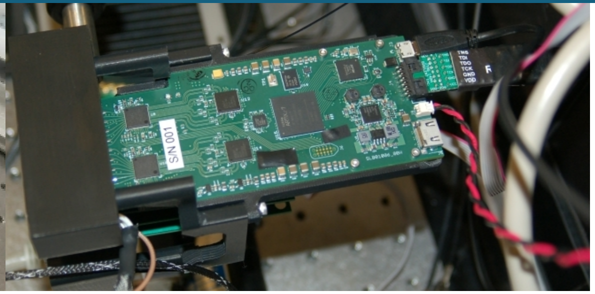
Sandia National Laboratories

Single Volume Scatter Camera: Results and Significance









PRESENTED BY

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Nov 10, 2021

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Outline

- Introduction
  - Why radiation detection?
  - Why imaging?
- Single-Volume Neutron Scatter Camera (SVSC)
  - Concept
  - Results
- SVSC Significance
  - Interaction-resolving detectors
  - Readout electronics
  - Scintillator characterization (Bethany)

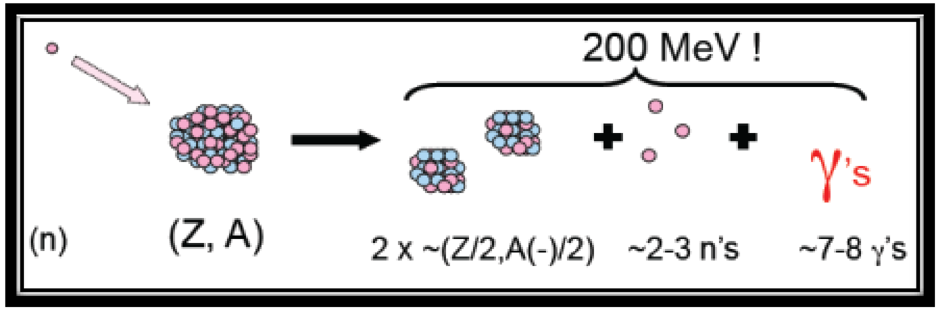
Nuclear nonproliferation applications

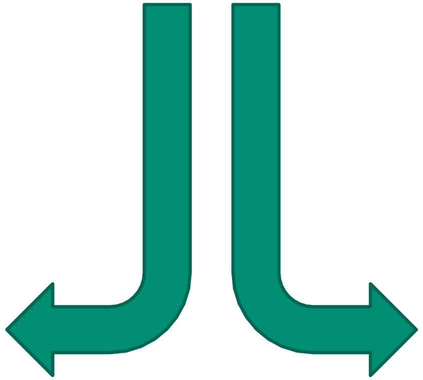
Why radiation detection?

Why radiation imaging?

The two sides of the nuclear coin

Nuclear Fission

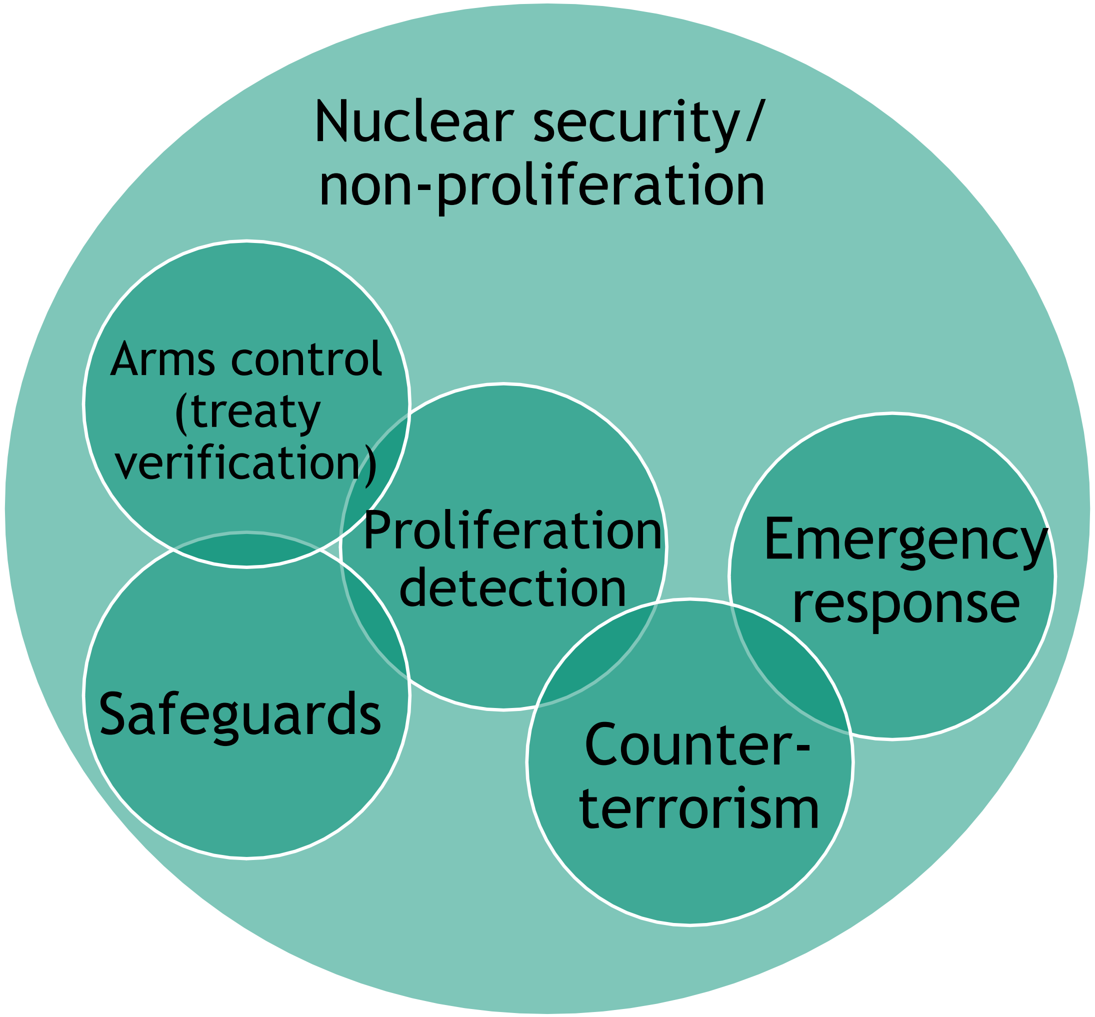




Nuclear Power

Nuclear Weapons

Nuclear non-proliferation application space

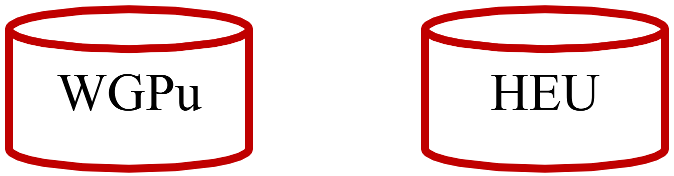


- Various dimensions to reducing nuclear dangers
  - Limit existing arsenals: nuclear arms control
  - Prevent diversion to military use: nuclear safeguards
  - Etc.
- Policy goals drive technical needs
- Special nuclear material (SNM) is the common element.
  - Detect
  - Locate
  - Characterize

Special Nuclear Material

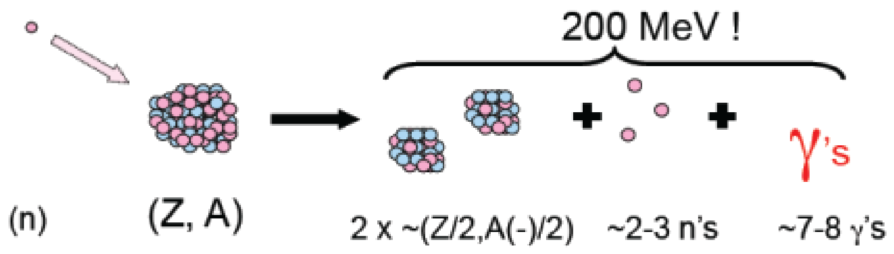
What is it?

- Plutonium, or
- Uranium enriched in U-233 or U-235.
- Sine qua non of a nuclear explosive.



What does it look like?

- Many different forms & colors.



Special nuclear material emits ionizing radiation.

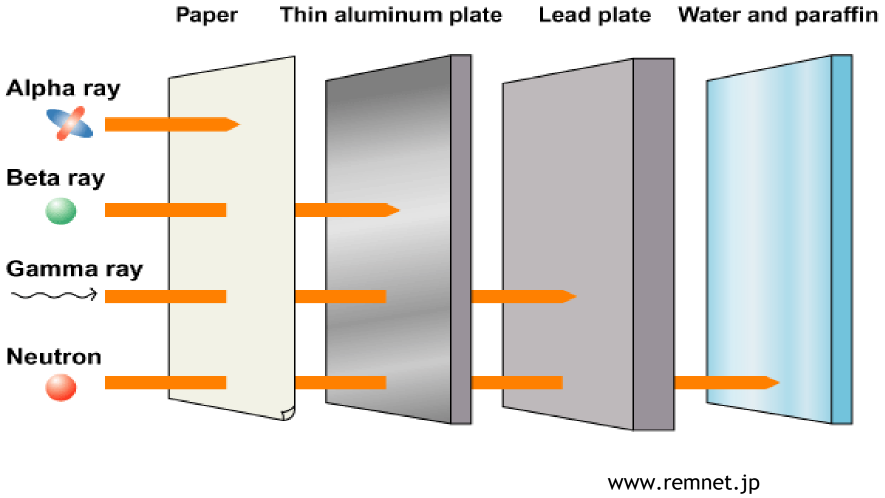
- *Sensitive* and *specific* signature
- Only neutral particles (n,γ) useful in most cases

Physical processes …

- Spontaneous fission
- Induced fission
- Other radioactive decays

… produce signatures

- Gamma (photon) spectrum
- Neutron fission spectrum
- Time correlations

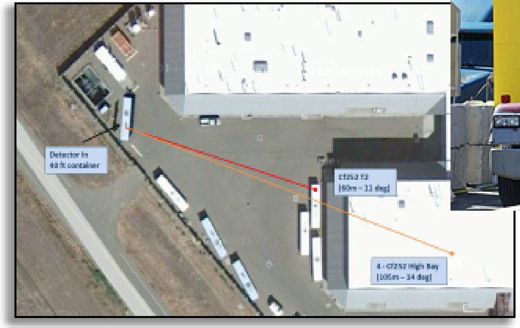


Emission of radiation from SNM is *impossible to turn off* and *difficult to shield*, making radiation detection a key tool in nuclear non-proliferation applications

SNM detection/imaging

We develop systems for eventual application in a range of scenarios:

Standoff detection



Cargo screening

SNM detection applications

- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

Arms control treaty verification

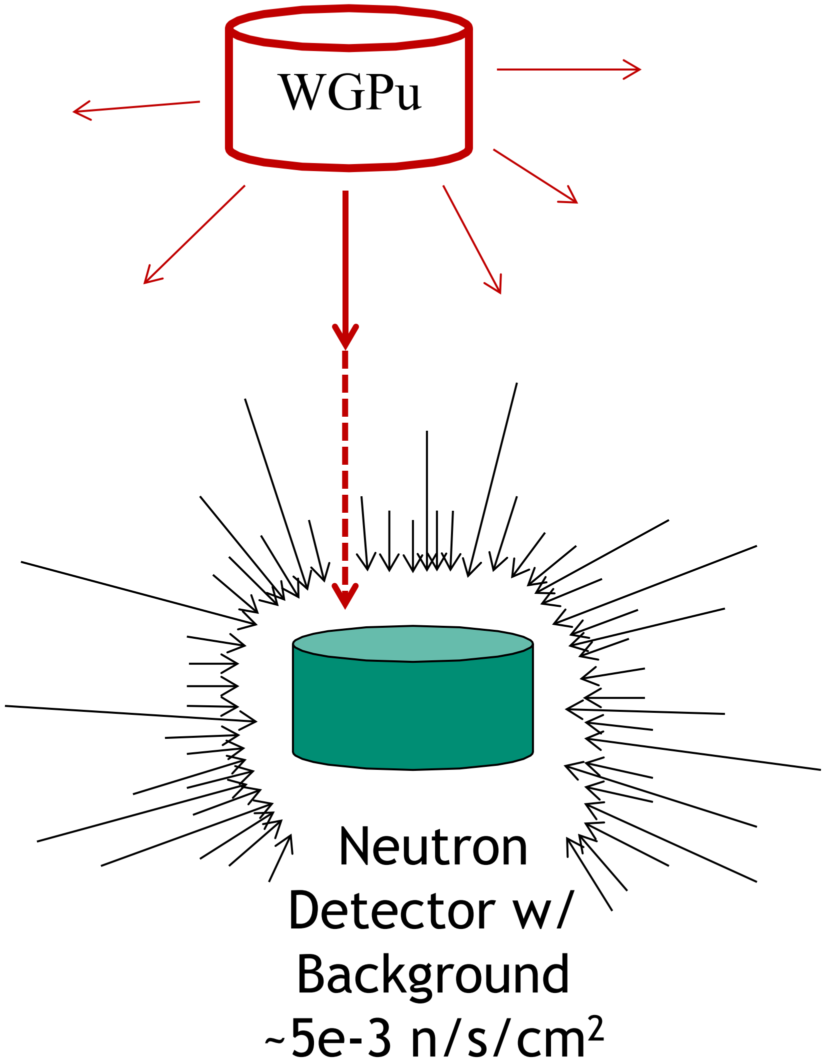
Emergency response

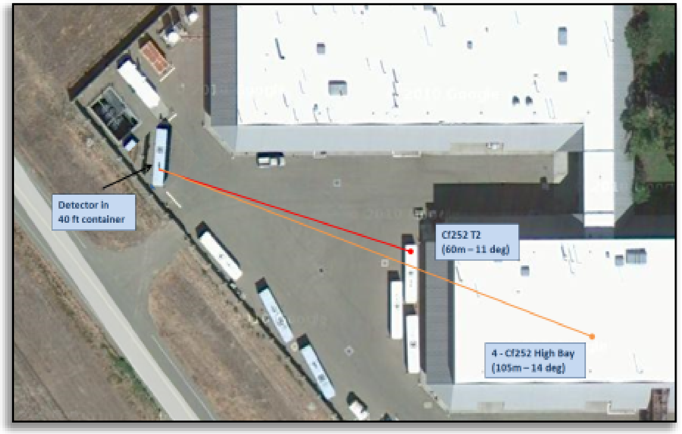
SNM imaging applications

- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

Standoff detection

~5.5e4 n/s/kg
IAEA sig = 8 kg





Case: background unknown

Example: Large stand-off application (100 m)

- 8 kg WGPu = ~4.4e5 neutrons/s $\rightarrow$ 4.4e5 *exp(-R/100 m)/4$\pi R^2 \approx$ **1.3 neutrons/s/m²**
- Background = **~50 neutrons/s/m²** (at sea level)
- 100% efficient, 1 m² detector $\rightarrow$ 5σ detection in **~13 minutes**
- 10% efficient, 1 m² detector $\rightarrow$ 5σ detection in **~2 hours**
- 10% efficient, 1 m² detector, *3% bg rate systematic* $\rightarrow$ 5σ detection in **never**

Directional information, however, allows to simultaneously measure signal and background, change never to < never.

Detection again

What about when the background is independently known?

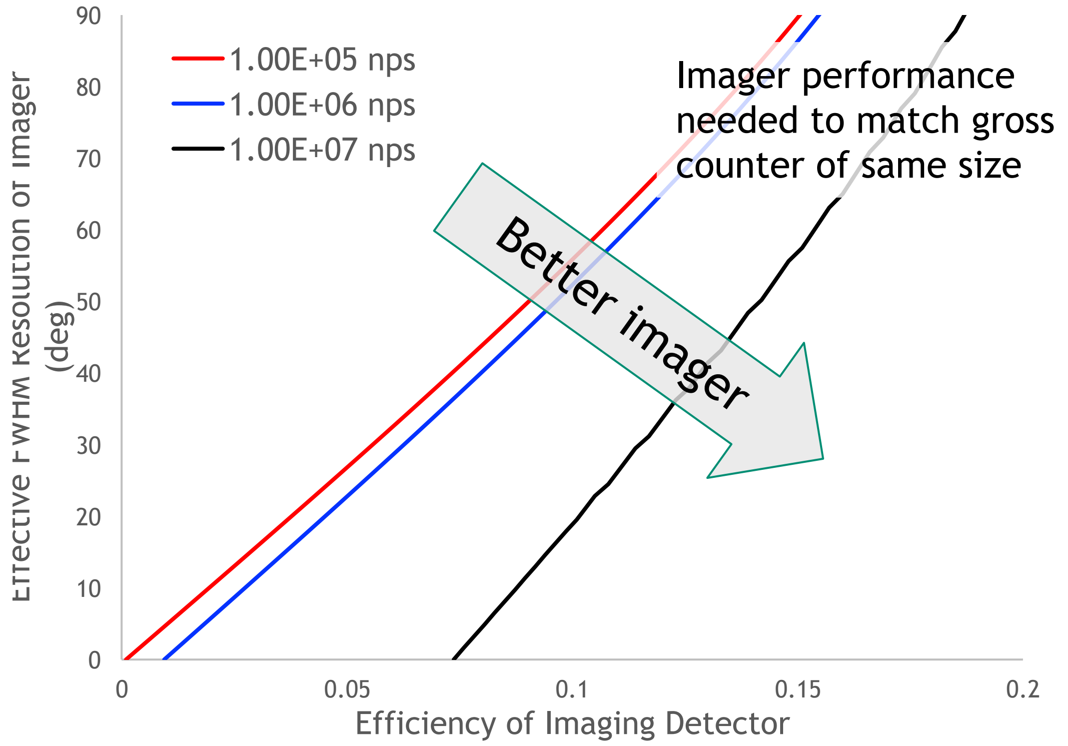
- Example: portal monitor. Effectively have repeated background measurements in between occupancies.
- Example: building monitoring. Looking for changes in the rad field due to an approaching source.

Now is there an advantage from imaging?

- **In principle**, yes, because background is reduced by directional info.
- **But** real imagers have complex directional info (angular resolution).
- **Also** generally take a hit on efficiency.

- Study by Paul Hausladen (ORNL)
- Equal area detectors, background known
- Specific plot below uses one particular set of assumptions (bg rate, exposure time, etc.)
- *Punchline: Difficult to achieve performance to beat gross counter.*

Case: background known



Single-Volume Neutron Scatter Camera (SVSC)

Concept

Results

Single-Volume Scatter Camera Development: project team

@Sandia National Laboratories (Lead Laboratory)

- Jon Balajthy (post-doc)
- Erik Brubaker (PI)
- Belkis Cabrera-Palmer
- Patrick Feng
- Paul Maggi (post-doc)
- Peter Marleau
- John Steele
- Melinda Sweany

@Argonne National Laboratory

- Jeff Elam (PI)
- Anil Mane

@Lawrence Berkeley National Laboratory/UC Berkeley

- Josh Brown
- Josh Cates
- Gino Gabella (post-bac)
- Bethany Goldblum (PI)
- Thibault Laplace
- Juan Manfredi (post-doc)

@North Carolina State University

- John Mattingly (PI)
- Mudit Mishra (post-grad)
- Ahmed Moustafa (grad)

@Oak Ridge National Laboratory

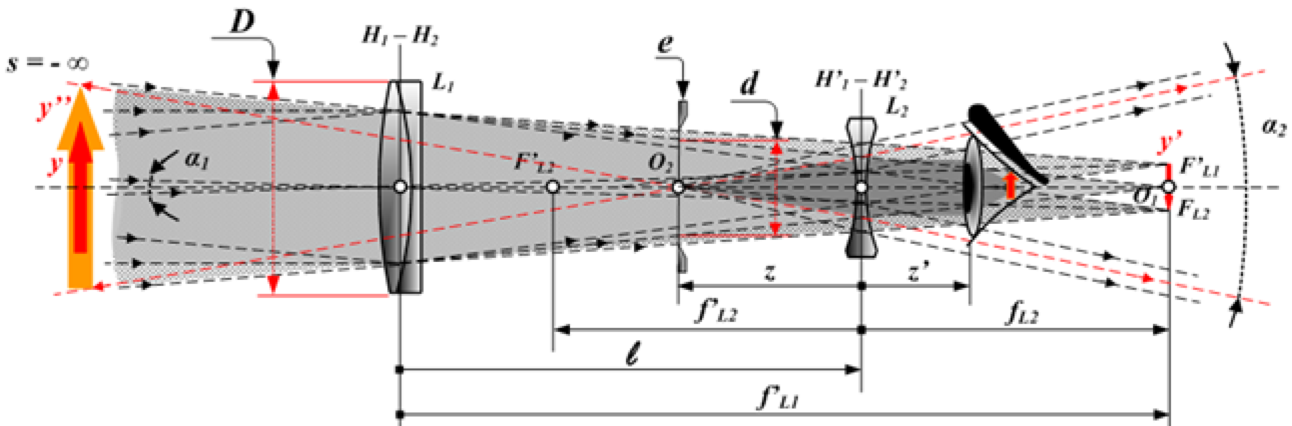
- Micah Folsom (grad)
- Paul Hausladen (PI)
- Jason Nattress (post-doc)
- Klaus Ziock

@UH Mānoa

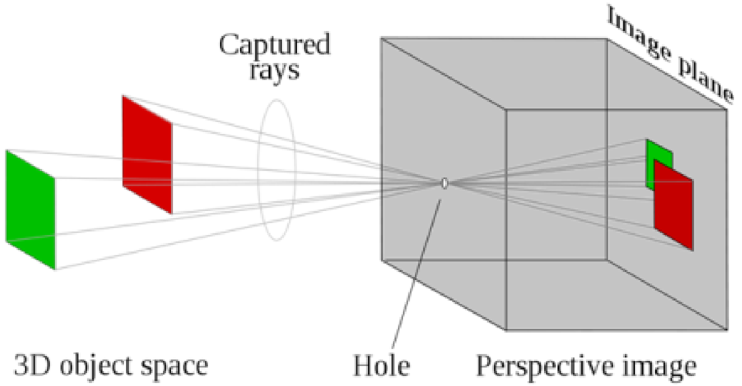
- Evan Adamek (post-doc)
- Hassam Alhajaji (undergrad)
- Brian Crow (grad)
- Andrew Druetzler
- Aline Galindo-Tellez (post-doc)
- Kevin Keefe (grad)
- John Learned
- Kurtis Nishimura (PI)
- Benjamim Pinto Souza (undergrad)
- Eric Takahashi (post-bac)

Optical cameras vs energetic radiation imaging

- **Optical lens** converts position in the real world to position on a small position-sensitive detector
- **But we can't lens neutrons** (or energetic photons, i.e. gammas)
- **Pinhole** works for neutrons and gammas, but radiation imaging stats-starved
  - 100 W bulb emits 7 x 10^{18} ph/s
  - 8 kg WGPu emits 4.4 x 10^{5} n/s



https://www.howtogeek.com/63409/htg-explains-cameras-lenses-and-how-photography-works/



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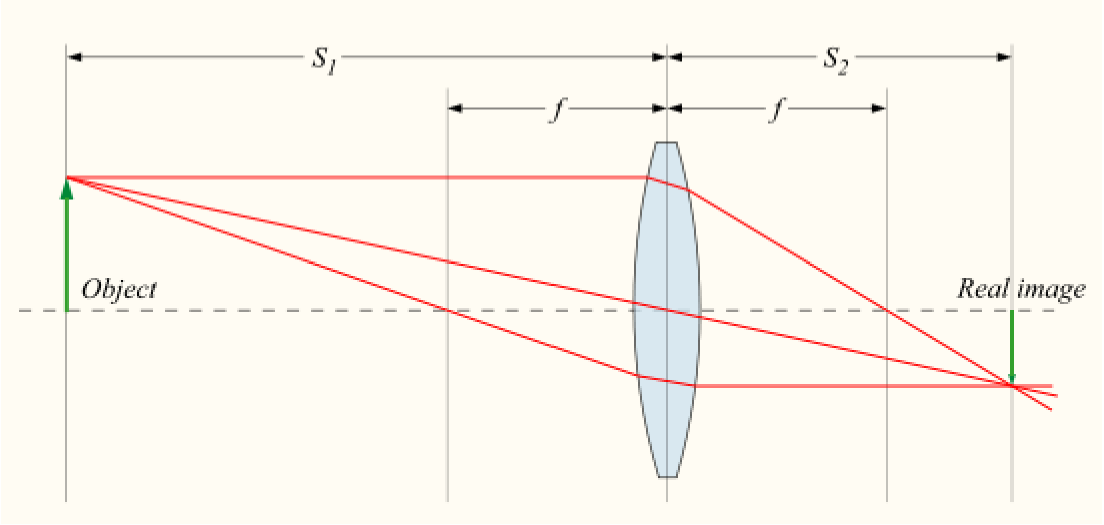
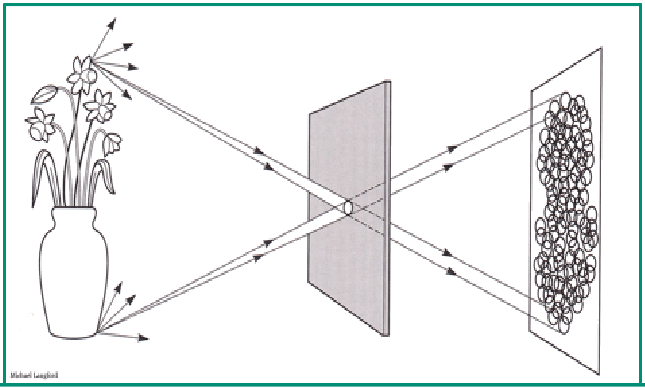
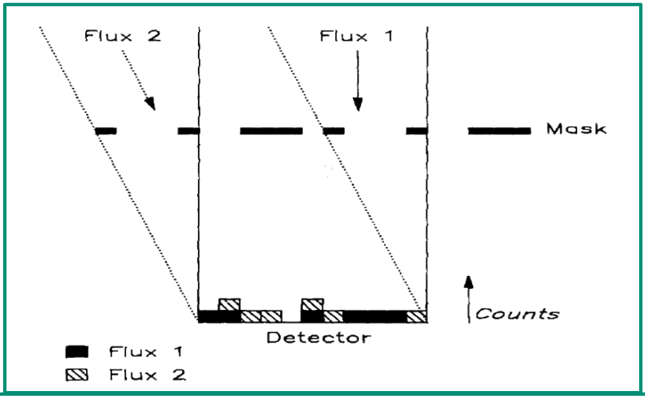


https://aijaz.net/2010/01/23/how-camera-lenses-work/index.html

How is n emission imaging done today?

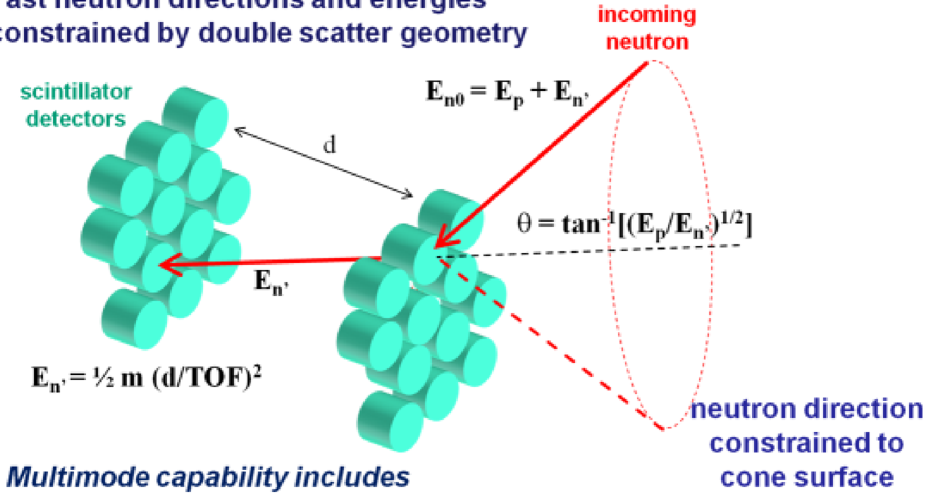


Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput

Fast neutron directions and energies constrained by double scatter geometry



Multimode capability includes
- *Neutron energy spectrum.*
- *Compton imaging.*

What are we trying to do?

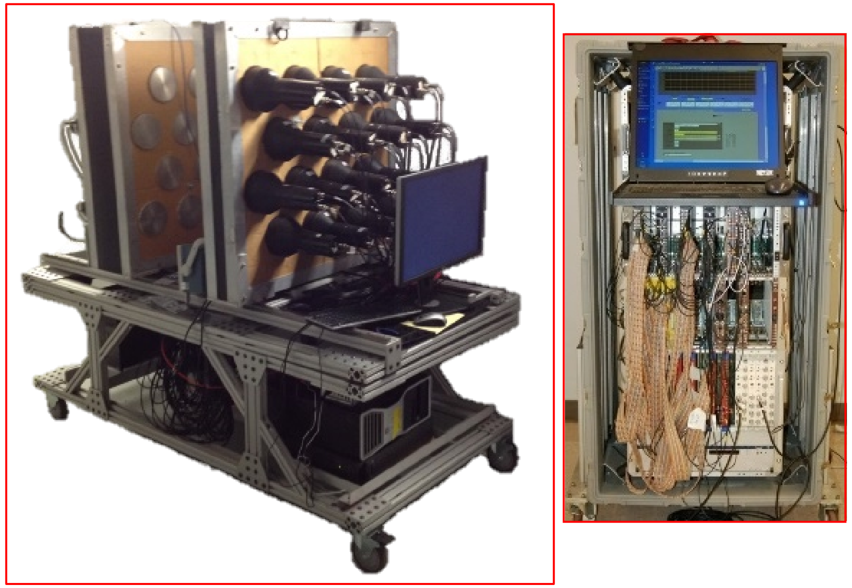
A compact imager is easy to transport and deploy, has high efficiency, and can be placed near an item to increase sensitivity & spatial resolution.

For passive neutron imaging to be useful for nuclear security, we need to improve on existing systems by making them smaller *and* more efficient.

- Size goal: ~2 m^3 (NSC) → ~0.2 m^3 (MINER) → ~0.05 m^3 (SVSC)
- Efficiency goal: Order of magnitude improvement over NSC/MINER

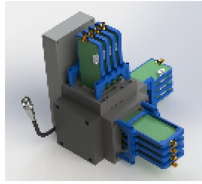
How? Detect and resolve 2+ neutron scatters in a single active region.

Neutron Scatter Camera (NSC)



Mobile Imager of Neutrons for Emergency Responders (MINER)

Single-Volume Scatter Camera (SVSC)



What is our new approach?

Cell-based → single volume

Two configurations:
- Monolithic scintillator
- Optically segmented scintillator

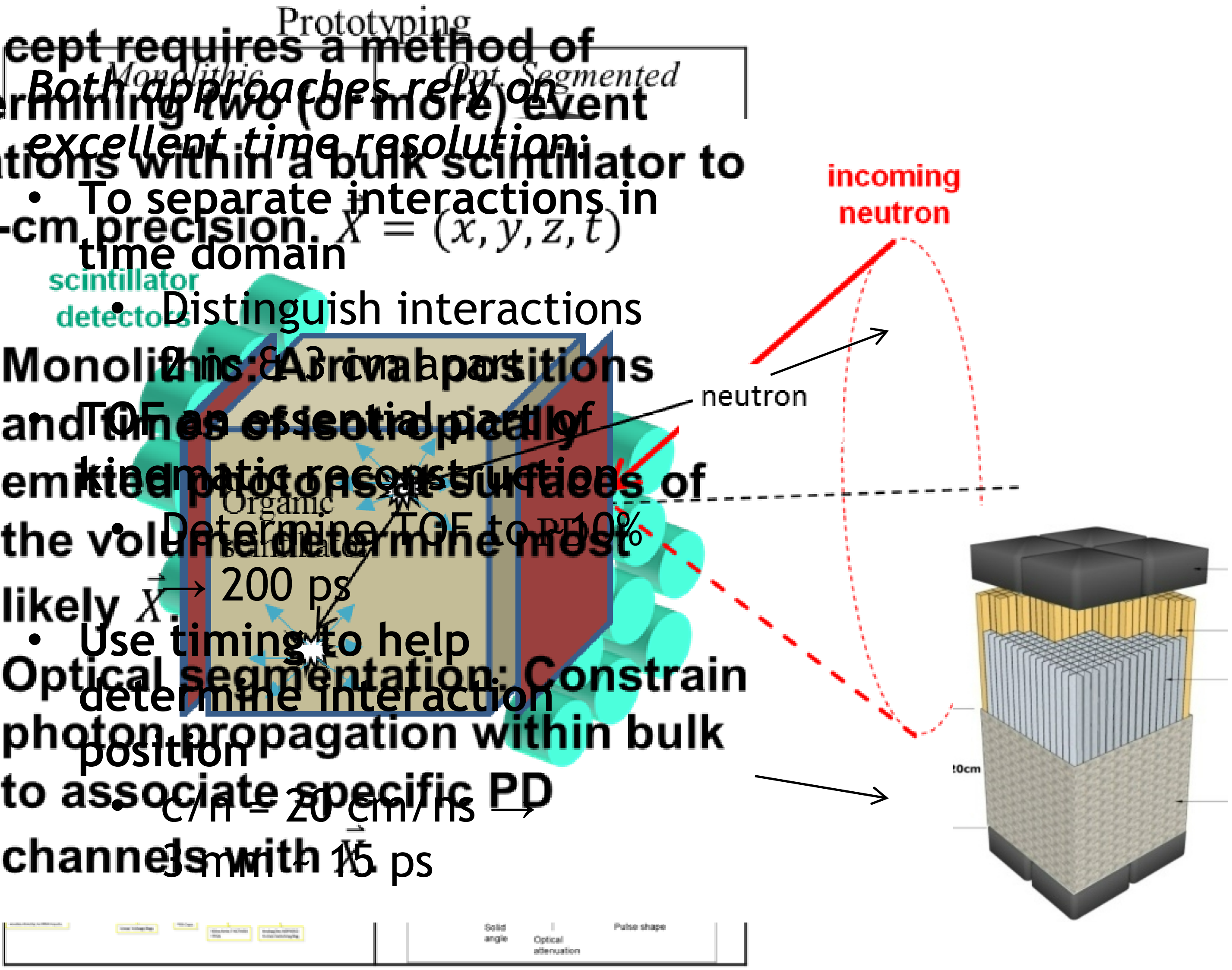
Both rely on excellent time resolution:
- To separate interactions in time domain
- TOF an essential part of kinematic reconstruction
- Use timing to help determine interaction position

System components:
- Organic scintillator—fast plastic, O(1 ns) decay time
- Fast photodetectors—MCP-PMTs, SiPMs, etc. Low tts ~100 ps if possible
- Fast electronics—sufficient to take advantage of PDs. Must be scalable
- Algorithms—use all information available

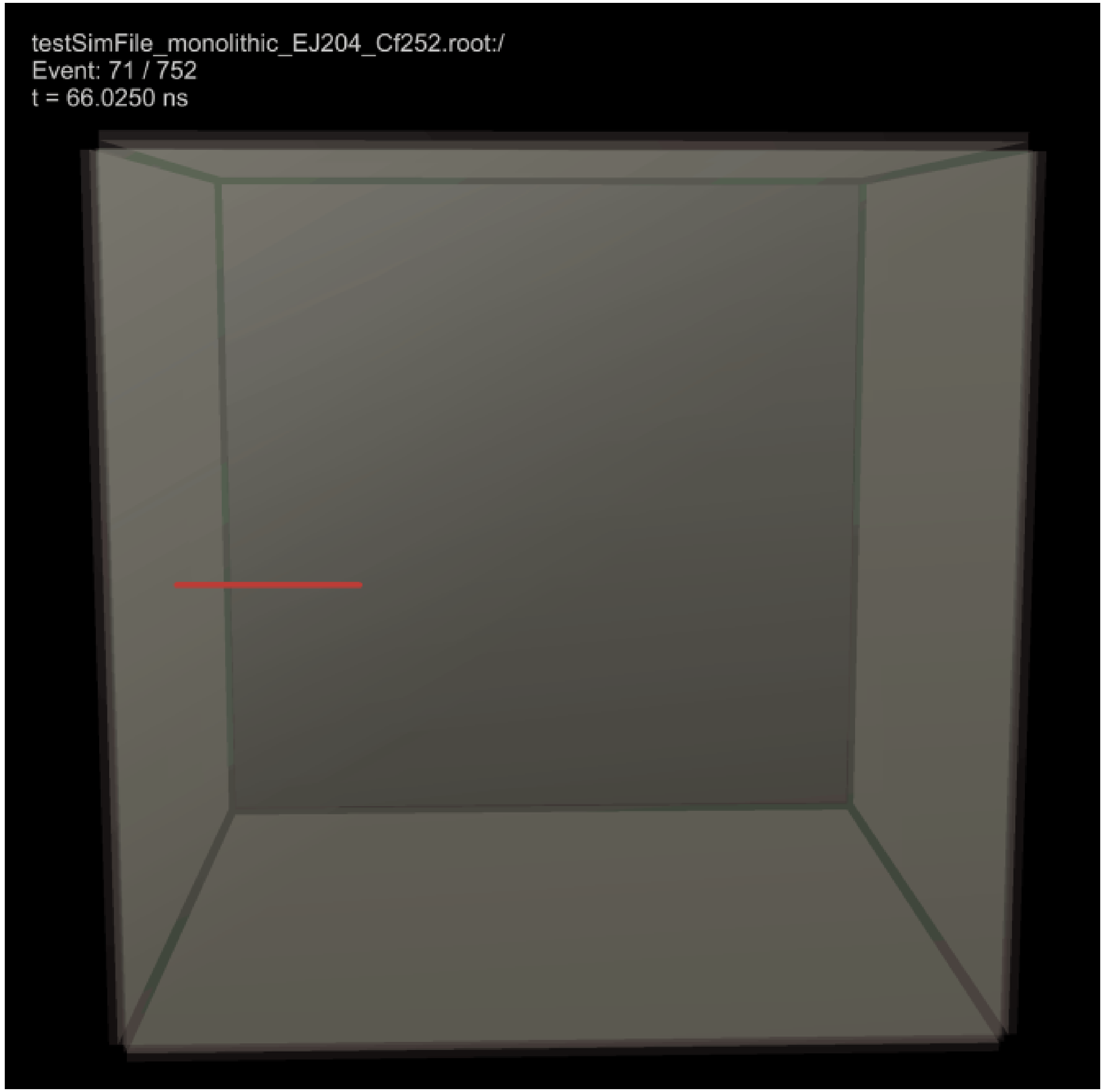
Concept requires a method of determining two (or more) event locations within a bulk scintillator to sub-cm precision. $\vec{X} = (x, y, z, t)$

1. **Monolithic: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely** $\vec{X}$.
2. **Optical segmentation: Constrain photon propagation within bulk to associate specific PD channels with** $\vec{X}$.

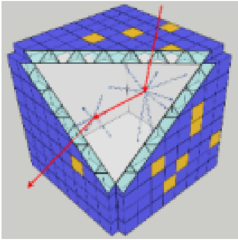
Both approaches rely on excellent time resolution:
- To separate interactions in time domain
  - Distinguish interactions 2 ns: 8 cm apart
- TOF an essential part of kinematic reconstruction
  - Determine TOF to 10% → 200 ps
- Use timing to help determine interaction position
  - c/n = 20 cm/ns → 3 mm : 15 ps



Monolithic detector concept



Monolithic: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely $\vec{X}$.



Probability multiplies over all observed photons

Probability to observe a photon is summed over all interactions

$$L = \frac{e^{-\nu}\nu^n}{n!}\prod_{i=1}^{n}\sum_{j=1}^{n_{int}}\frac{\nu_j}{\nu}P_{ji}$$

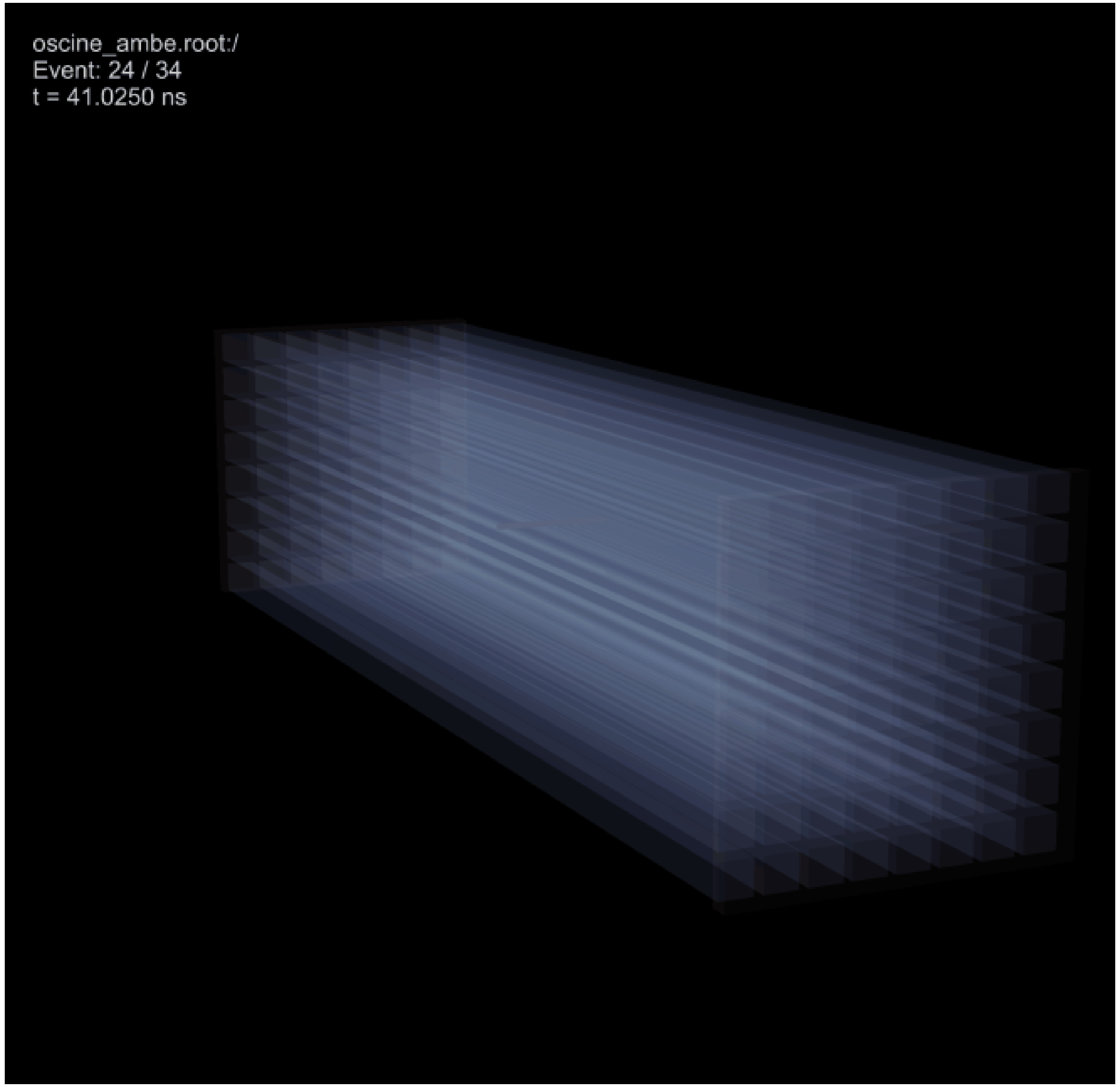
Solid angle; QE; Optical attenuation; Pulse shape

$$P_{ji} = \frac{\frac{\Omega_{jk(i)}}{4\pi}Q_k \cdot e^{-d_{jk(i)}/\lambda} \cdot f\left(t_i - t_j - \frac{d_{jk(i)}}{c_{med}}\right)}{\Gamma_j}$$

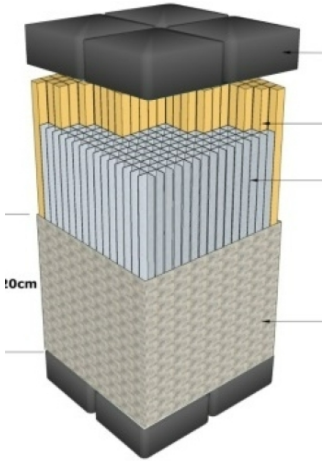
Normalization

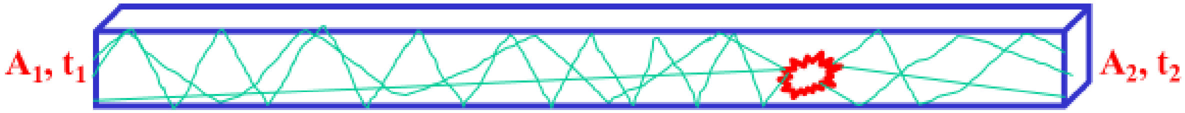
$$\Gamma_j = \sum_{k=1}^{n_{anode}}\frac{\Omega_{jk}}{4\pi}Q_k \cdot e^{-d_{jk}/\lambda}$$

Optically segmented detector concept



Optically segmented:
Constrain photon propagation within bulk to associate specific PD channels with $\vec{X}$.

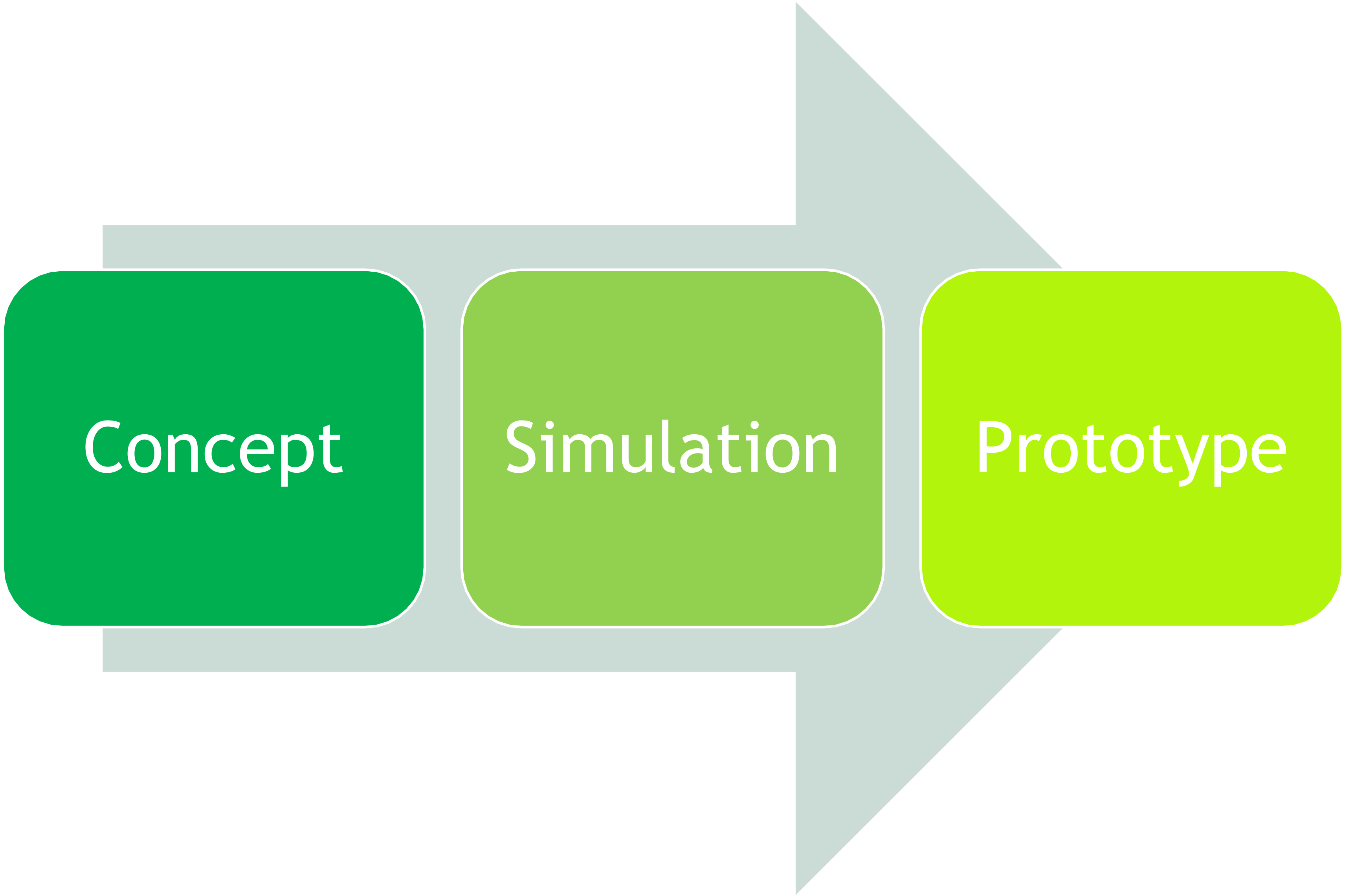




Position: $z \sim (t_1 - t_2)$ AND $z \sim \log(A_2/A_1)$
Time: $t \sim (t_1 + t_2)/2$
Energy: $E \sim \mathrm{sqrt}(A_1 A_2)$

Key questions for OS approach are resolutions of interaction position along bar and interaction timing

Can we build it?



Initial set of prototype systems

First attempts at monolithic and optically segmented systems pictured at right

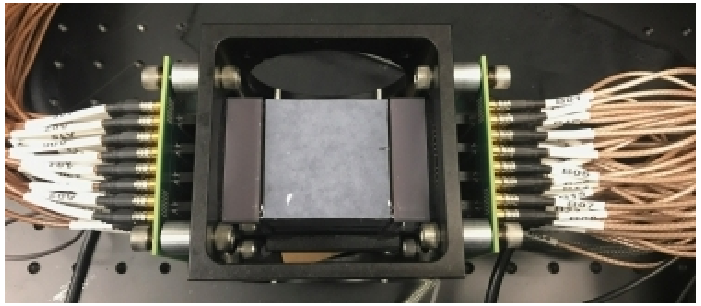
Key takeaways:

- Electronic crosstalk was an enormous issue
- Calibration difficulties, especially in OS prototype
- Internal optical reflections not consistent with simulations in monolithic prototype
- Need effort on trigger for double-scatter neutrons

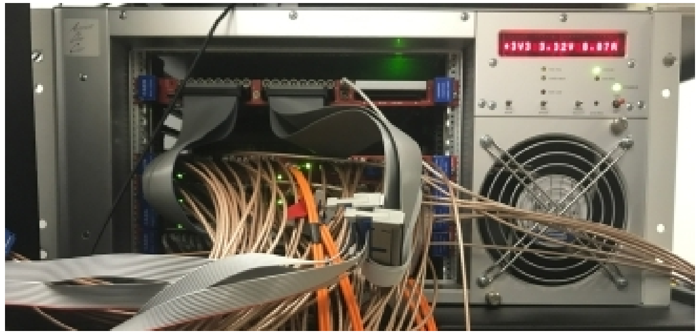
Apply lessons learned to second round of prototypes, currently under construction/integration:

- Switch to SiPM readout for monolithic
- Use same electronics where possible for both systems
- Design custom SiPM arrays to minimize crosstalk
- Modular OS architecture for easier calibrations

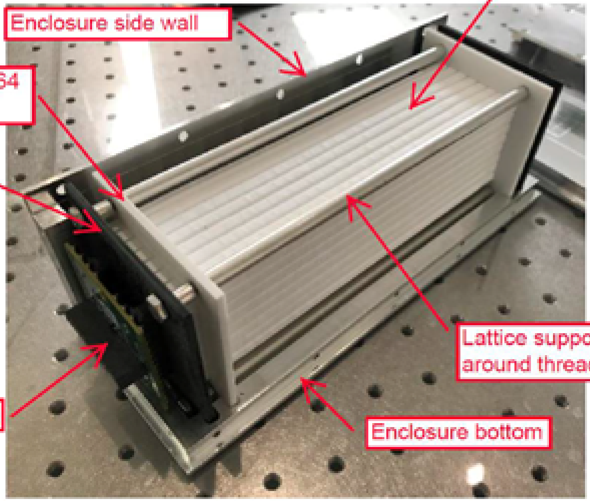
$(5\ \mathrm{cm})^3$ scintillator and PMTs



4 CAEN V1742 32-channel, 5 GSs^{-1}, 12-bit digitizers (DRS-4 chip)



64x (0.5 cm x 0.5 cm x 20 cm) bars



Second Monolithic Prototype

Jon Balajthy (SNL)

50mm x 56.2mm x 60.2mm block of Eljen-204 plastic scintillator

- Selected as a compromise of light yield and timing
- 0.7ns rise time
- High light-yield (10400 ph/MeV e-)
- Negligible attenuation (400cm)

Instrumented on two sides with four 2x8 arrays of Hamamatsu S13360-6075PE SiPMs

EJ560 Silicone rubber optical interface

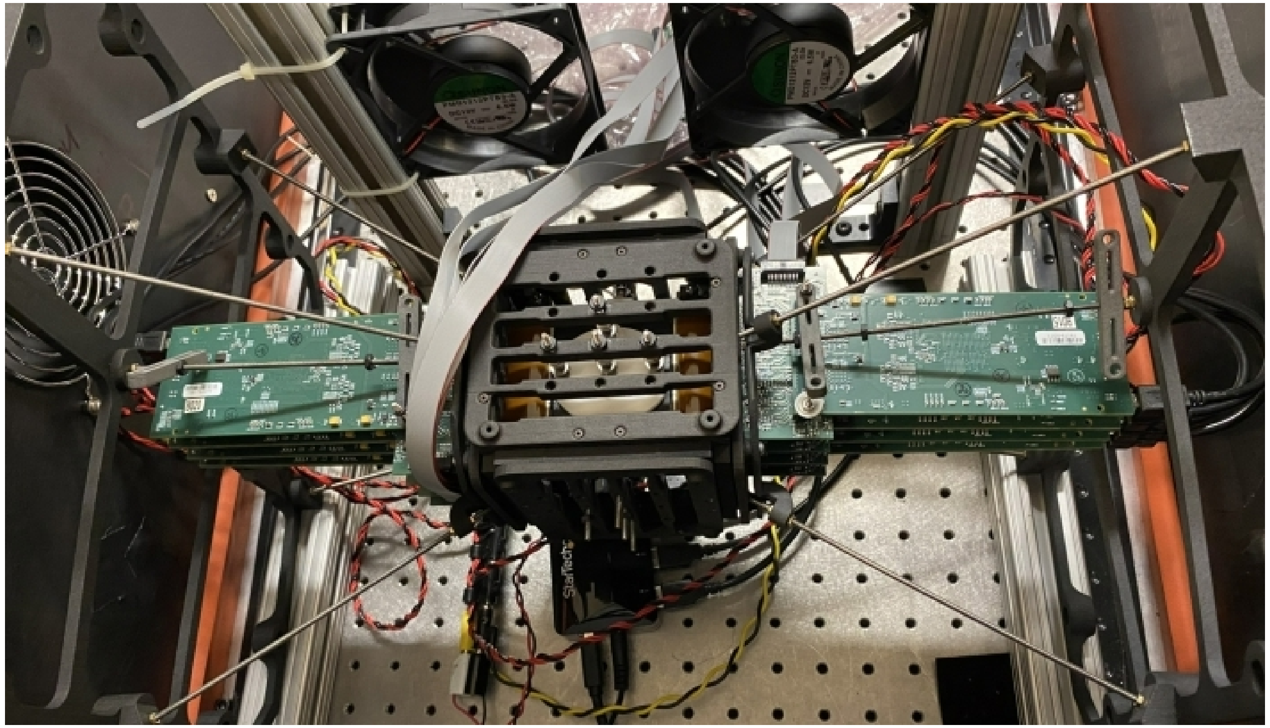
- Allows for more time-stable connection than grease
- Easier to apply and remove

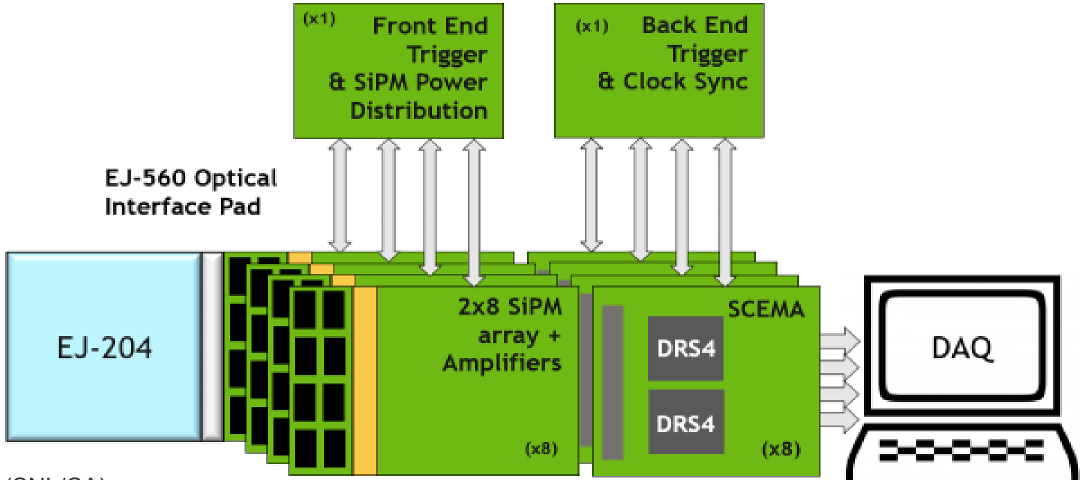
Digitized using SCEMA electronics boards

- J. Steele et al. *Journal of Instrumentation* **14** (2019) P02031.

Mechanical structure provided by LBL

- Each 2x8 array of SiPMs is secured to the





Collimated Cs-137 Source

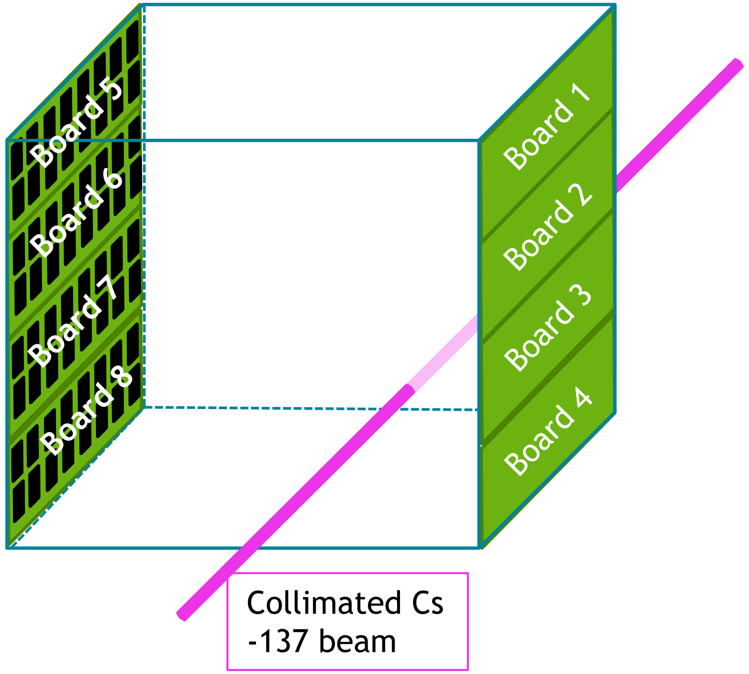
Jon Balajthy (SNL)

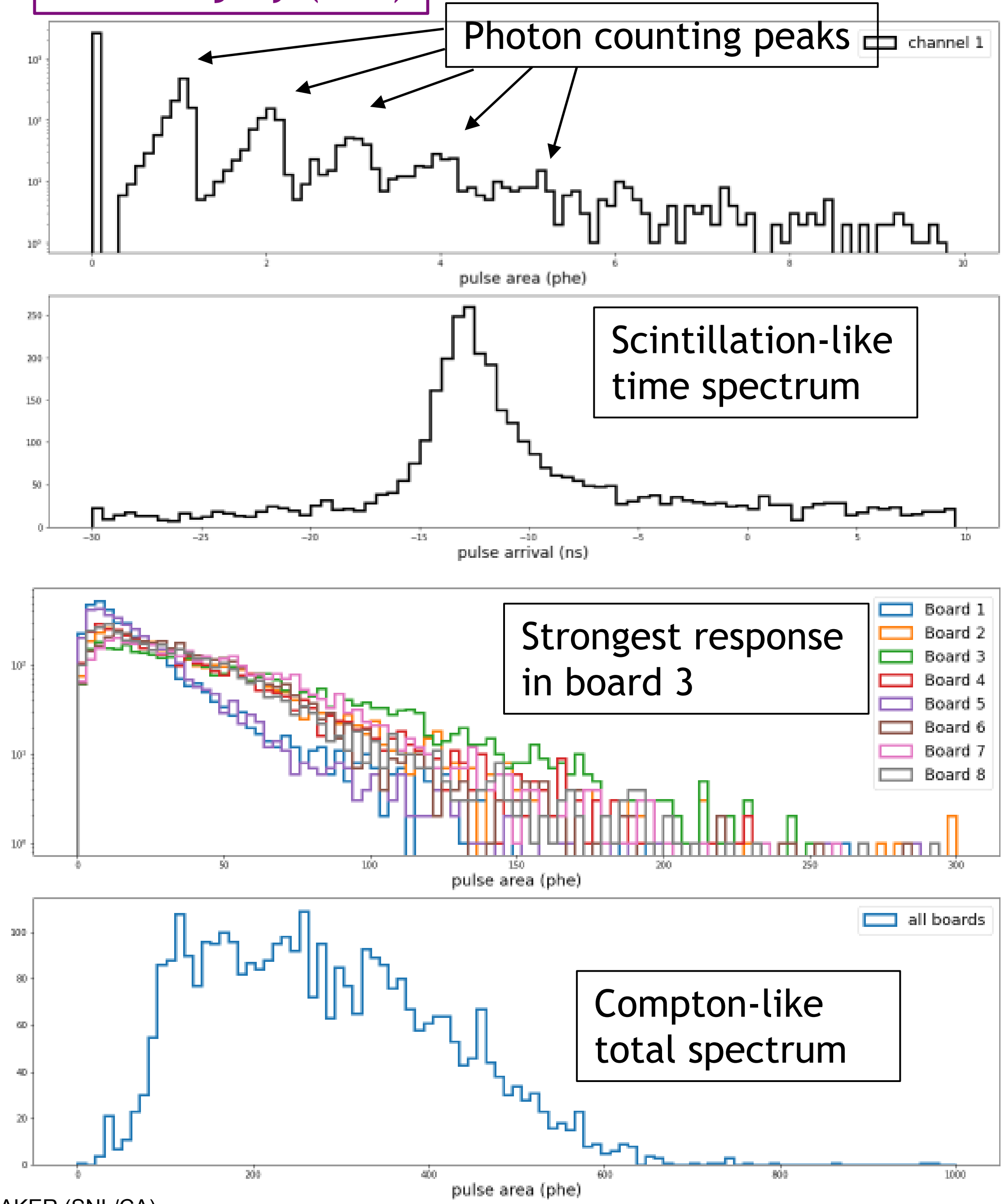
Collimated Cs-137 source:

- Aligned along long axis of 2x8 SiPM arrays
- Located nearest to board 3, and furthest from board 5

Pulse area is integrated over 26ns trigger window

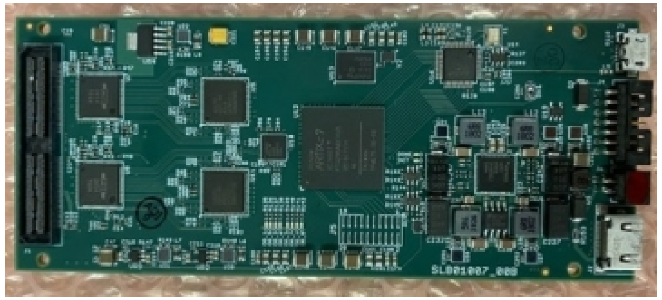
We suspect there is some trigger mismatch between the boards – resolved.



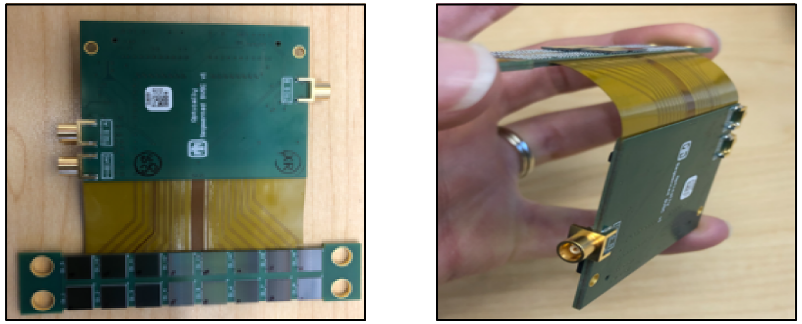


Kevin Keefe (UH/SNL)

The Second Prototype (OS2) – Detector Design



SCEMA-B



Flex-card Interposer

Design Goals:

- Reduce electrical crosstalk
- Allow particle source calibration access to all bars
- Improve modularity

OS2 Current Optically Segmented Module (OSMO) Design:

- 2x8 Modular Design of 16 Teflon wrapped 5mm x 5mm x 20cm ej204 scintillating bars
- SCEMA-B (Sandia Laboratories Compact Electronics for Modular Acquisition, rev B) design based on [5].

hannel digitization by using 2 PSI-DRS4's

s 16 (2x8) SensL j-series 6.13mm n boards.

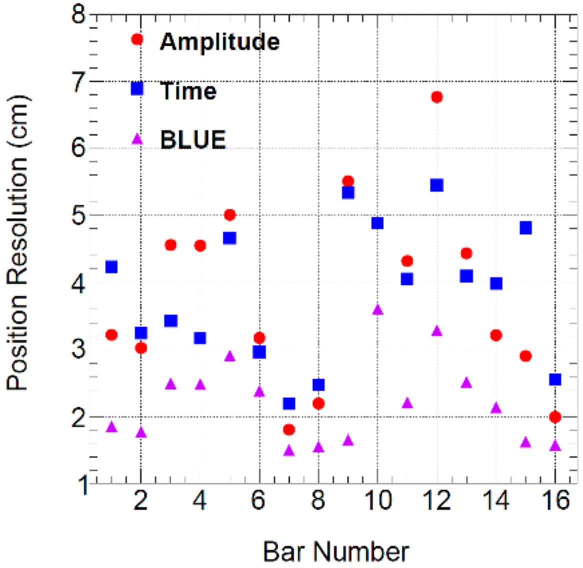
circuit which reads common cathode line of al

Kevin Keefe (UH/SNL)

Calibration Results: Optical Coupling

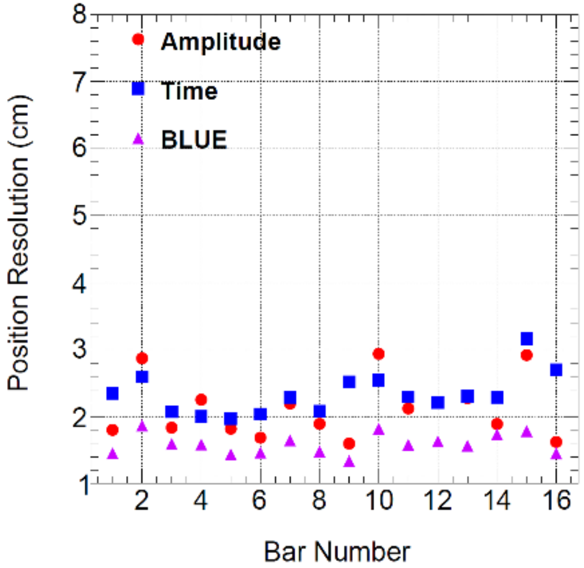
- Z-position reconstruction is obtained through pulse rise-time and pulse amplitude.
- Time and Amplitude resolutions are combined through Best Linear Unbiased Estimator (BLUE)
- “Outer bars” show poorer overall position resolution in optical pad configuration

EJ-560 Optical Pads

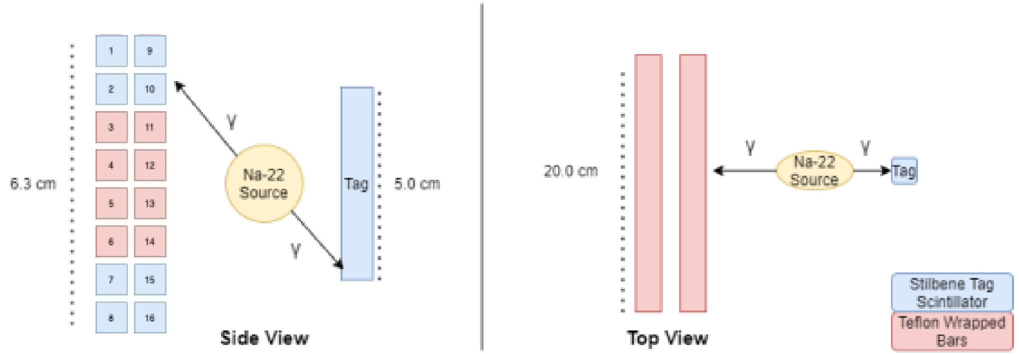


= 2.22 ±0.66

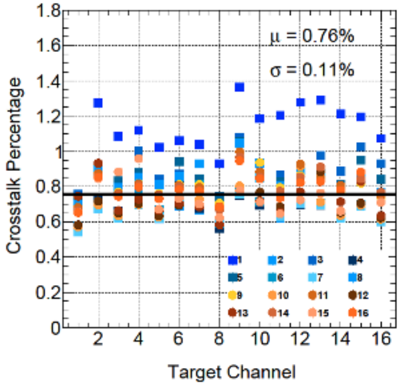
EJ-550 Optical Grease



= 1.59 ±0.15



Manageable electronic crosstalk observed



Optical Coded Aperture

Micah Folsom (UTK/ORNL)

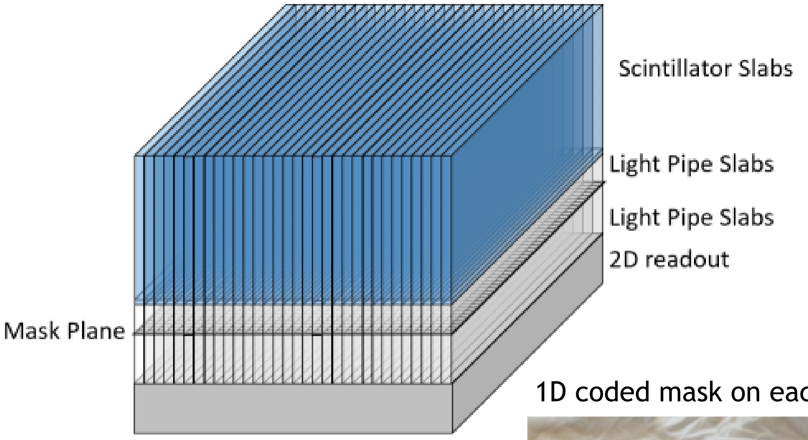
Uses coded mask on scintillation photons to determine interaction position.

Intermediate segmentation (scintillator slabs)

Photodetectors & electronics from 1st monolithic prototype

Excellent work by UTK grad student to build, characterize system

First experimental images from a compact neutron scatter camera!

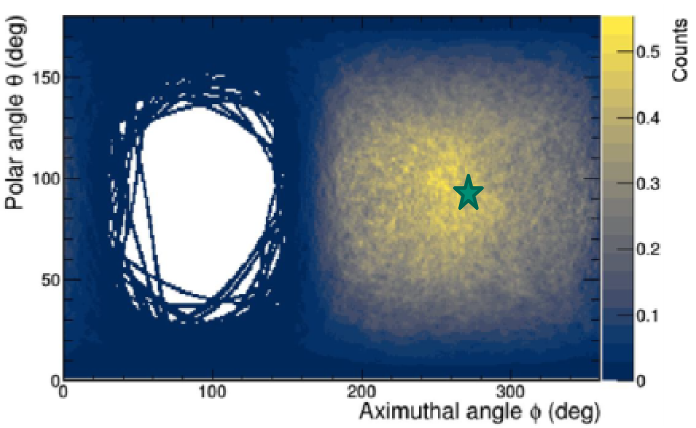


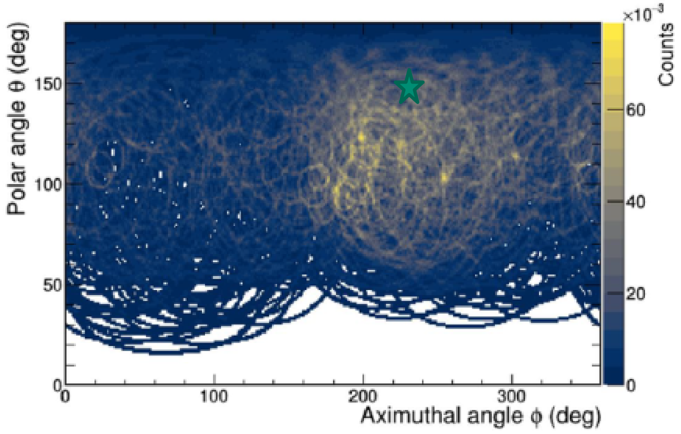
1D coded mask on each slab

Potential improvements:

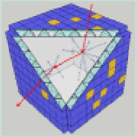
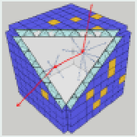
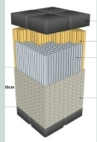
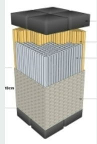
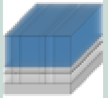
- Performance limited by same crosstalk, tim issues of 1st monolithic prototype
- Better control optical crosstalk

Experimental images!





Results summary

System	Specs	Results	Issues	Next steps
Monolithic 1st prototype 	EJ-204 + MAPMTs + Caen V1742	• Low-level calibs • Single-site position reco • Double-site consistency check	• MAPMT crosstalk • High optical reflection prob	
Monolithic 2nd prototype 	EJ-204 + Hamamatsu SiPMs + SCEMA	• Low-level calibs	• Low trigger rate • Calib difficulties	• Simulation-based calibrations • Neutron imaging
Optically segmented 1st prototype 	EJ-204 + SiPMs (SensL array) + SCRODs	• Single-site calibs	• Crosstalk in SiPMs • Electronics limitations	• Neutron imaging
Optically segmented 2nd prototype 	EJ-204 + SiPMs (custom array) + SCEMA	• Single-site calibs • Low-stats neutron image	• Low trigger rate • Resolution worse than single bar	• Neutron imaging
Optical coded aperture prototype 	EJ-204 + MAPMTs + Caen V1742	• Low-level calibs • Reconstructed neutron images	• MAPMT crosstalk	• SiPM-based readout

SVSC Significance

Interaction-resolving detectors

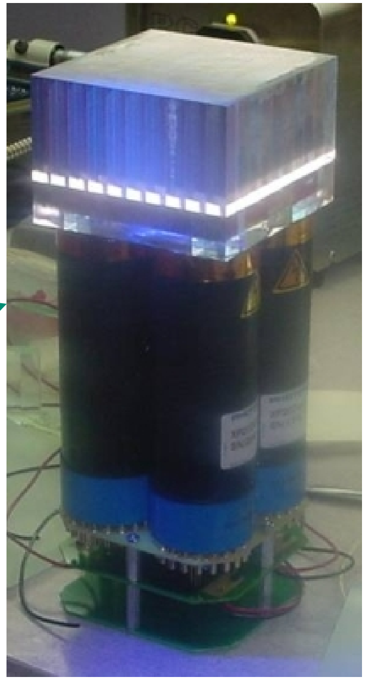
Readout electronics

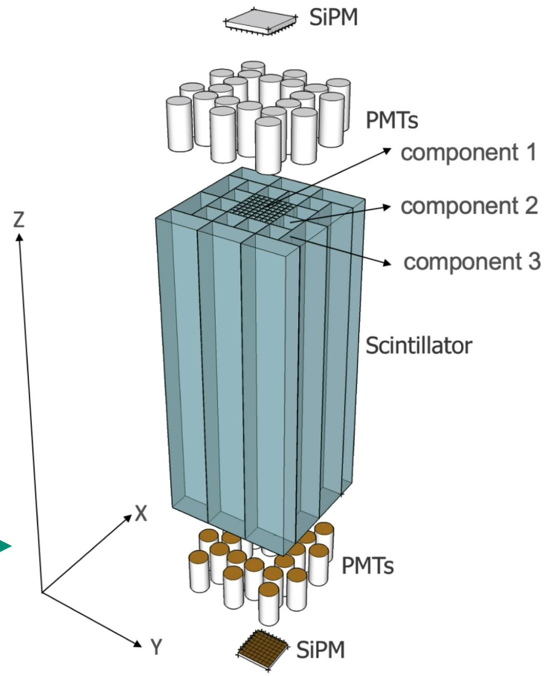
Scintillator characterization (Bethany)

Interaction-resolving detectors

The ability to resolve neutron interactions in space and time within a scintillator volume enables or advances other detection concepts for nuclear security

- Neutron coded aperture imaging with improved resolution and reduced aberrations
- Neutron transmission imaging with improved contrast and high-rate sources
- Multiplicity counting with directional information
- Neutron counting in high-rate environments
- Neutrino detection for reactor monitoring and discovery
- Medical & industrial applications





SANDD: https://doi.org/10.1016/j.nima.2021.165409

Potential paradigm shift in scintillation detection:
Aggregating information at the interaction level →
Resolving information at the individual optical photon level

Interaction-resolving detectors for medical imaging

Josh Cates (LBNL)

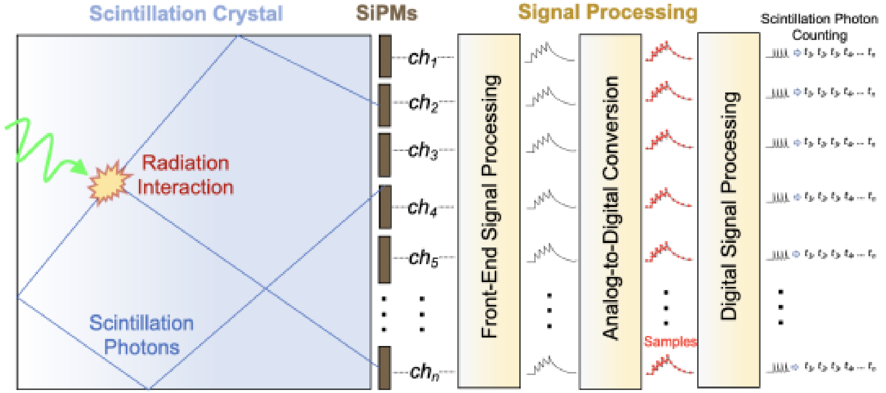
TOF-PET desires interaction position resolution ~ 3 mm, time resolution ~ 10 ps

- Reconstruction-free imaging

One approach: count every photon

- Cerenkov signal for time resolution
- Scintillation signal for position/energy resolution

Well-received presentation by Josh Cates at IEEE MIC



Readout electronics

Largest technical challenge in project: scaling readout electronics to 100s-1000s of channels while maintaining O(100 ps) resolution and compact size

- Both expected and unexpected

Result: an "ecosystem" of high-speed compact electronics (SiPM-focused) that may be of value to other projects

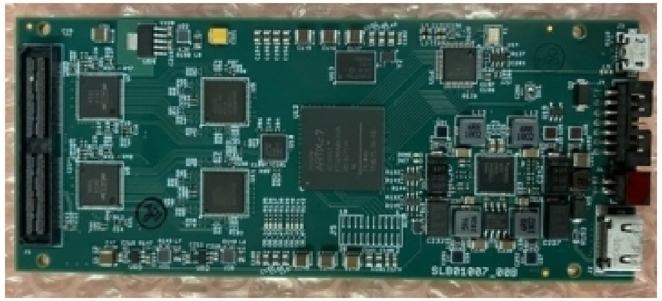
- Well-designed hardware
- Front-end flexibility

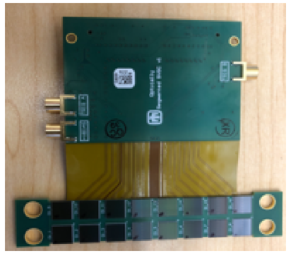
Current limitations:

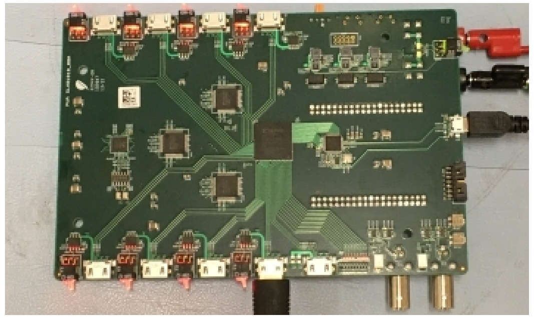
- Low max trigger rate (10-3000 Hz)
- Research-quality firmware & software

New commercial offering (Caen FERS-5200) with echoes of SCEMA design:

(not to scale)







SCEMA

- 16 chan waveform capture @ 5 GS/s (DRS4 ASIC)
- Parallel digitization
- High-speed data stream

SiPM module(s)

- Customize according to application
- Front-end circuit & trigger summing

Hub board

- Back-end sync: Power, clock, trigger distribution
- Extension for high-throughput data concentration

Trigger board

- Fast trigger decision based on summed signals from SiPM modules

Readout electronics

Needs more investment to enable capable interaction-resolving scintillator detectors

Multiple potential routes
- ASIC design for high-capability detector systems
- Modern FPGAs could support high resolution readout
- Consider low-power applications

Holy grail: digital SiPMs with integrated front-end readout
- Individually addressed microcells
- Timestamp to sub-100 ps precision
- 3d chip combining sensor and readout
- Ignore hot microcells to control dark count rate
- On-board processing to flag crosstalk

ASIC considerations

	Monolithic	Optically segmented
Assumptions	• High channel count and therefore low occupancy. • What is the assumed trigger scheme?	• Organic scintillator pulse into single channel. • What is the assumed trigger scheme?
Expected signal	Single-photon output from {MA-,MCP-}PMT or SiPM: • 0.1 – 0.5 mV (SiPM) or 5 – 15 mV (PMT) amplitude for single photon • Photon density in time: 1-10 photons over 50 ns, concentrated in first 5 ns • Event density in time (informs dead time issues): up to 10 kHz • Dark count rate: up to 1 MHz • Signal shape: typ. SiPM or PMT output	Pulse output from {MA-,MCP-}PMT or SiPM: • Peak amplitude: few mV – 2 V • Signal shape: typ. organic scintillator pulse shape • For PSD, consider EJ-276, EJ-309, stilbene, anthracene • Event rate: up to 10 kHz

Information needed	• List of counts: (amplitude, time) for each
	  • Amplitude could be in terms of # of photons; would need calibration
	  • How to handle multiple photons near in time (but not simultaneous)?
	• Timing requirements: <100 ps.
		• Amplitude (integral is best, but only for PMT?): spec?
		• Timing requirements: <50 ps for 500 mV peak amplitude and 1 ns rise time.
		• PSD: how to spec performance?

Other requirements	• Max power per channel • Max footprint per channel? • Synchronized timing across many chips, up to 1 m	• Max power per channel • Max footprint per channel? • Synchronized timing across many chips, up to 1 m

Scintillator characterization

Handoff to Bethany

Summary

Nuclear non-proliferation applications: Radiation *imaging* addresses a range of technical needs in non-proliferation

We are developing the Single-Volume Scatter Camera, a new design for *compact* and *high-efficiency* neutron imaging

- Prototypes built & studied with 125 cm^3 – 320 cm^3 active volume, 128 channel readout
- **Challenges** included scaling electronics, electrical crosstalk, difficulty of calibration, optical transport modeling
- **Successes** include readout “ecosystem”, initial neutron images from compact scatter cameras

Significance of SVSC results and outcomes goes beyond double-scatter imaging

- Interaction-resolving detectors advance non-proliferation applications, medical imaging
- Technical solutions (electronics) useful for other projects
- Organic scintillator characterization and model selection important across fields

SVSC selected publications to date:
Single-Volume Neutron Scatter Camera for High-Efficiency Neutron Imaging and Spectroscopy (http://arxiv.org/abs/1802.05261)
Model-based Design Evaluation of a Compact, High-Efficiency Neutron Scatter Camera (NIM A: https://doi.org/10.1016/j.nima.2017.11.025)
SCEMA: A high channel density electronics module for fast waveform capture (J. Instrum.: https://doi.org/10.1088/1748-0221/14/02/P02031)
Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout (NIM A: https://doi.org/10.1016/j.nima.2019.02.063)
Low energy light yield of fast plastic scintillators (NIM A [SORMA proceedings]: https://doi.org/10.1016/j.nima.2018.10.122)
Proton Light Yield of Fast Plastic Scintillators for Neutron Imaging (IEEE TNS: https://doi.org/10.1109/TNS.2019.2959979)
Design and Calibration of an Optically Segmented Single Volume Scatter Camera for Neutron Imaging (J. Instrum.: https://doi.org/10.1088/1748-0221/16/04/P04013)
Simultaneous measurement of organic scintillator response to carbon and proton recoils (Phys Rev C: https://doi.org/10.1103/PhysRevC.104.014609)

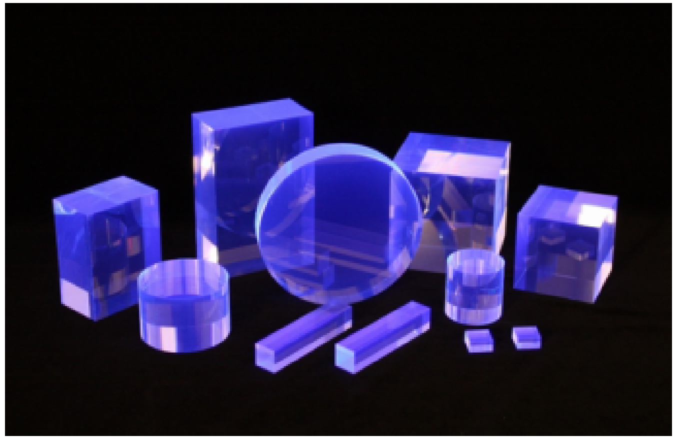
Additional Slides

Design considerations – Scintillator

Organic scintillator is natural choice for active material

We want bright, fast, robust:

- More light (photostatistics) is better for event reconstruction
  - Typical scintillator produces ~2,000 photons for a 1 MeV neutron interaction
  - Scintillation rise time < 1 ns, decay time 1-2 ns
  - We may detect ~30% of photons, depends on light collection in detector, output spectrum vs. quantum efficiency of photodetector
- Many properties not well known
  - High-fidelity characterization measurements @UCB/LBNL



Organic scintillator options from Eljen, Inc.

Scintillator	t_R (ns)	λ (cm^{-1})	N_e (MeV^{-1})	N_D (MeV^{-1})
EJ-200	0.9	380	10,000	4,905
EJ-204	0.7	160	10,400	5,084
EJ-208	1.0	400	9,200	4,378
EJ-230	0.5	120	9,700	4,557
EJ-232	0.35	-	8,400	3,679
EJ-260	-	350	9,200	3,470
EJ-262	-	250	8,700	3,548
EJ-276	-	-	8,600	4,203
EJ-276G	-	-	8,000	2,991

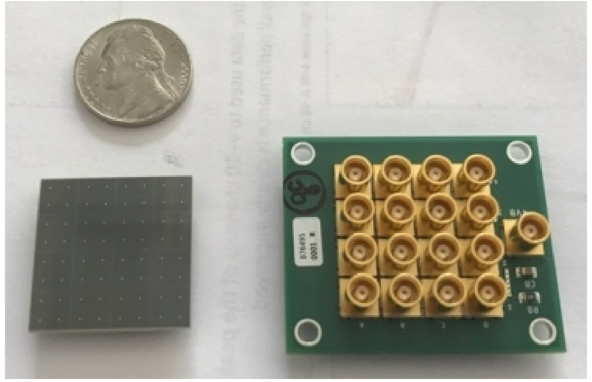
Melinda Sweany (SNL)

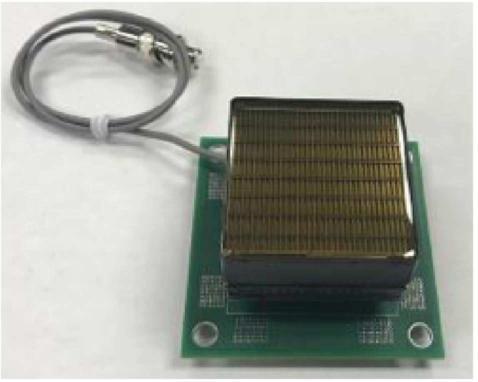
Design considerations – Photodetector (best case)

Photodetector	Photek PMT210	Photonis Planacon	Hamamatsu SiPM 50 μm	H8500 MAPMT	Comments
4 GHz scope	26 ps				Not scalable
DRS4 eval board		107 ps $(\sigma/\mu)_1$=0.53			Not scalable
Caen V1742 (DRS4)			171 ps $(\sigma/\mu)_1$=0.10	235 ps	Cables, SWaP
SLAcq board (DRS4)	41 ps	82 ps $(\sigma/\mu)_1$=0.83			Low S:N
Comments	Not scalable	Crosstalk Non-uniform	High dark rate Need 100x amp Afterpulsing	Non-uniform	

Design considerations – Photodetector

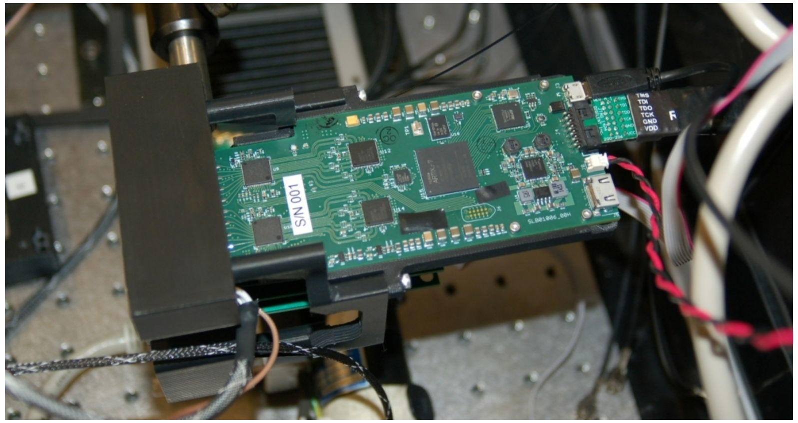
Oak Ridge National Laboratory
Paul Hausladen et al.





Category	SiPMs	MA-PMTs	MCP-PMTs
Amplification	Want ×100 for superior single PE resolution, timing	No additional amplification necessary	
Power	18 W for 64 channels	0.6 W for 64 channels	
Dark current	89k / mm^2 at a gain of 1.7e6	negligible	
PE amplitude variation	~10%	~50%	
Timing for 1 pe	~300 ps FWHM	~500 ps FWHM	~150 ps FWHM
Pulse pair resolution	Difficult to distinguish from afterpulsing	Nanosecond	
Cross talk	Expected small	OK for segmented	Known issue

Design considerations – Electronics



We need electronic readout that can take advantage of the information from fast scintillators & photodetectors

- Analog: custom circuit for timing, amplitude, pulse shape.
- Digital: digitize & save wav… analysis.

Crucially, need to instrume… channels!

Switched capacitor array: D… GSa/s waveform sampling, … available *scalable* solution.

Design our own board

- 16 channels, 14 cm x 6 cm
- This turns out to be an enormous undertaking!
- Quickly realize you need more than one board…