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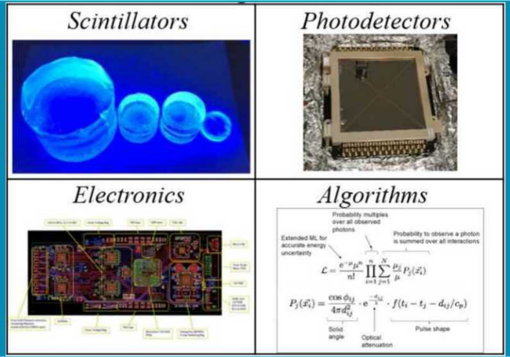
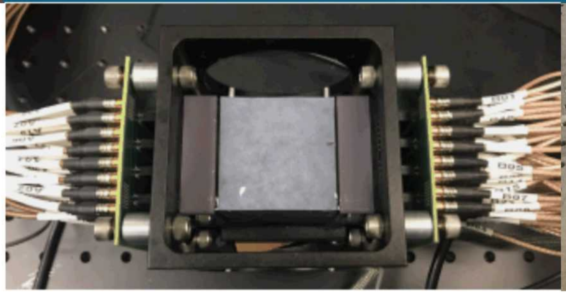
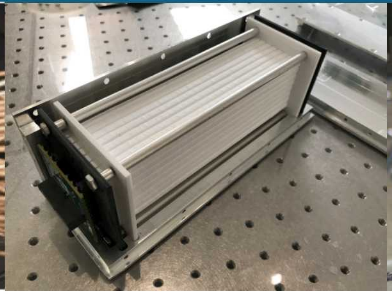
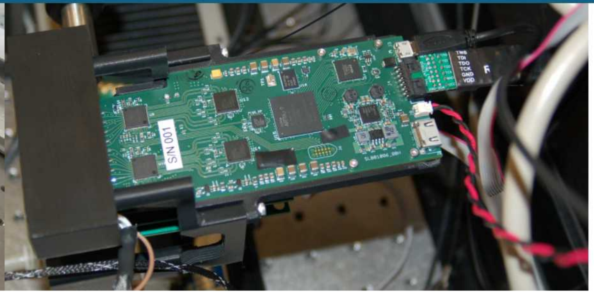


Single-Volume Neutron Scatter Camera—NSARD 2020







PRESENTED BY

Erik Brubaker, SNL/CA, ebrubak@sandia.gov

Mar 23, 2020

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Project team

Project title: "Single-Volume Scatter Camera Development"

Participants: Six institutions

- **SNL/CA** (lead): E. Brubaker, M. Sweany, J. Steele, B. Cabrera-Palmer, et al.
- **ORNL**: P. Hausladen, K. Ziock, J. Nattress, M. Folsom, et al.
- **ANL**: J. Elam, A. Mane, et al.
- **U Hawaii**: K. Nishimura, J. Learned, A. Druetzler, A. Galindo Tellez, E. Adamek, K. Keefe, B. Crow, et al.
- **UC Berkeley/LBNL**: B. Goldblum, J. Cates, T. Laplace, J. Manfredi, G. Gabella, et al.
- **NCSU**: J. Mattingly, M. Mishra, A. Moustafa

What are we trying to do?

Why neutron emission imaging?

- 1) Improves detection of weak SNM sources, enables localization.
- 2) Characterizes the spatial distribution of plutonium or other neutron emitters.

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.

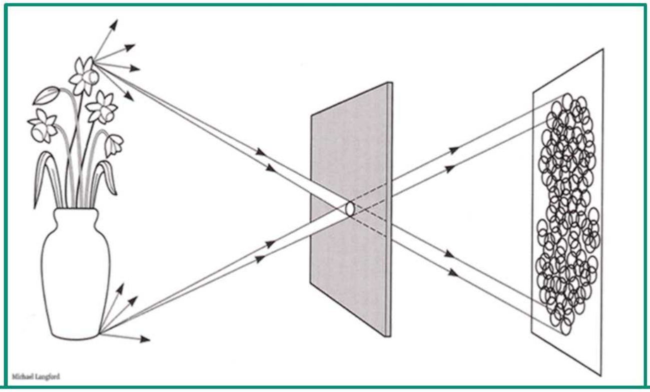
- Size goal: ~2 m^3 (NSC) → ~0.2 m^3 (MINER) → ~0.05 m^3 (SVSC)
- Efficiency goal: Order of magnitude improvement over NSC/MINER

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

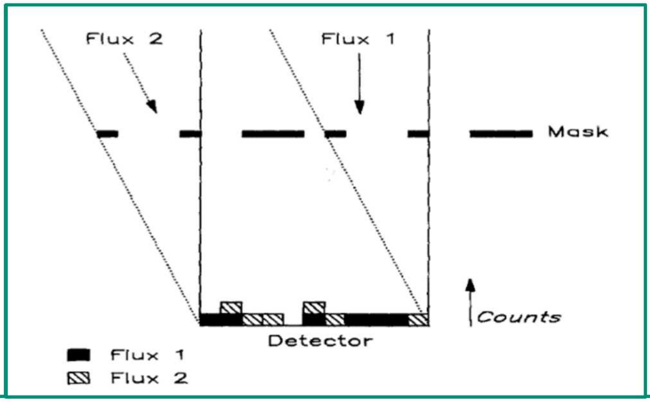
- Monolithic approach: Detect each individual photon propagating isotropically.
- Optically segmented approach: Guide light to ends of bars.

Outcomes/deliverables: Prototypes, performance studies; Improved photodetectors, electronics, scintillators; Papers, theses, human capital

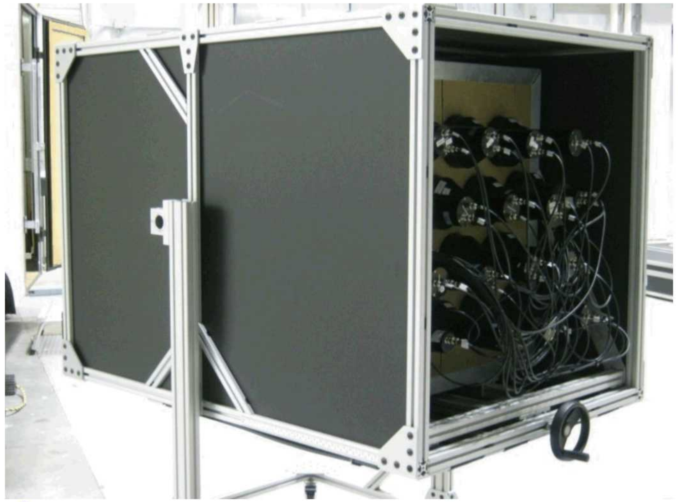
How is n emission imaging done today?

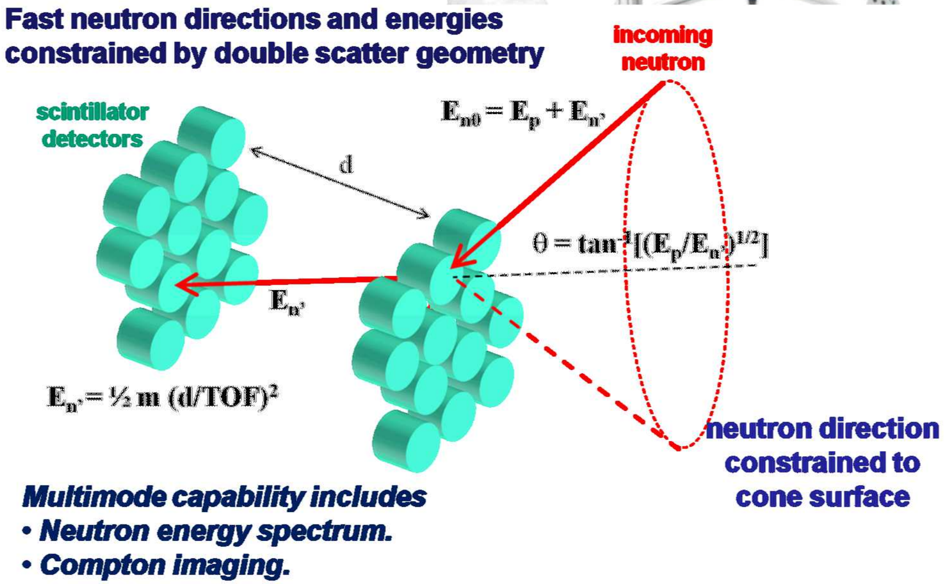


Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput





What is our new approach?

Cell-based → single volume

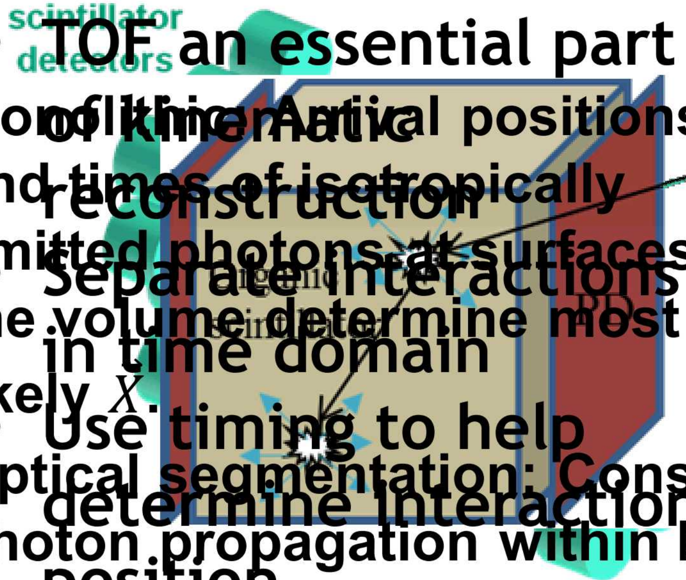
Two configurations:
- Monolithic scintillator
- Optically segmented scintillator

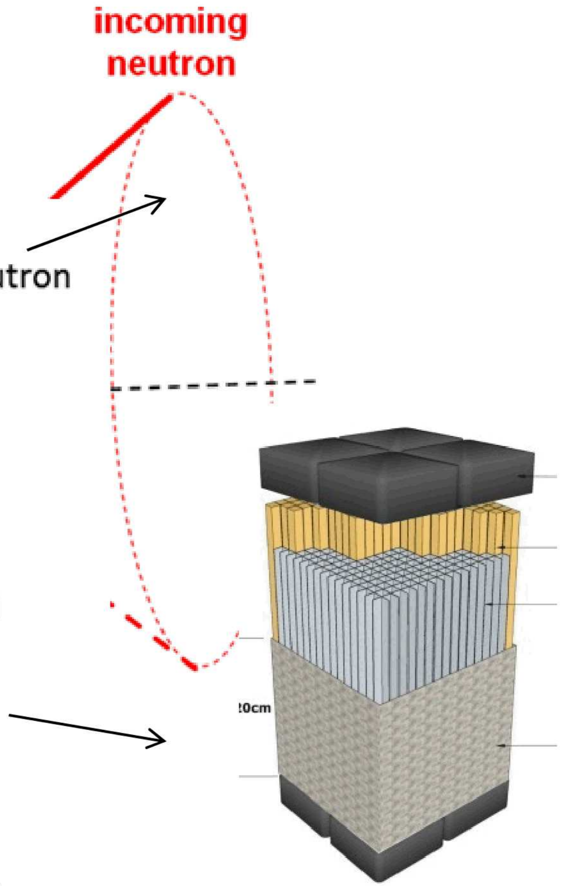
Both rely on excellent time resolution:
- TOF an essential part of kinematic reconstruction
- Separate interactions in time domain
- Use timing to help determine interaction position

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

- TOF an essential part of kinematic reconstruction
- Separate interactions in time domain
- Use timing to help determine interaction position

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** $\vec{X}$**.**





Prototyping
Monolithic
Opt. Segmented

Who cares? What difference will it make?

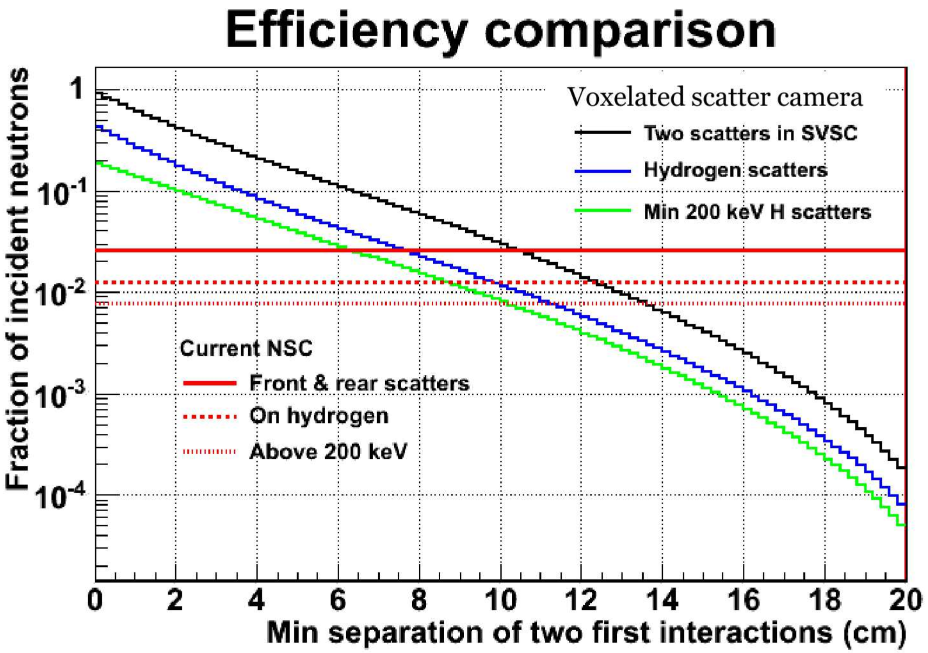
Compact high-efficiency neutron imager:

High efficiency reduces measurement time to acquire given information.

Compact form factor allows easy transport, deployment in tight spaces, close approach to threat sources.

Application spaces:

- SNM search/standoff detection
- Cargo screening
- Arms control
- Emergency response



Technology development:

Fast pixelated photodetector/readout enables other improved systems: coded aperture, transmission neutron imaging, etc.

Advances in scintillators & characterization methods, photodetectors, electronics feed other fields: medical imaging, basic science, etc.

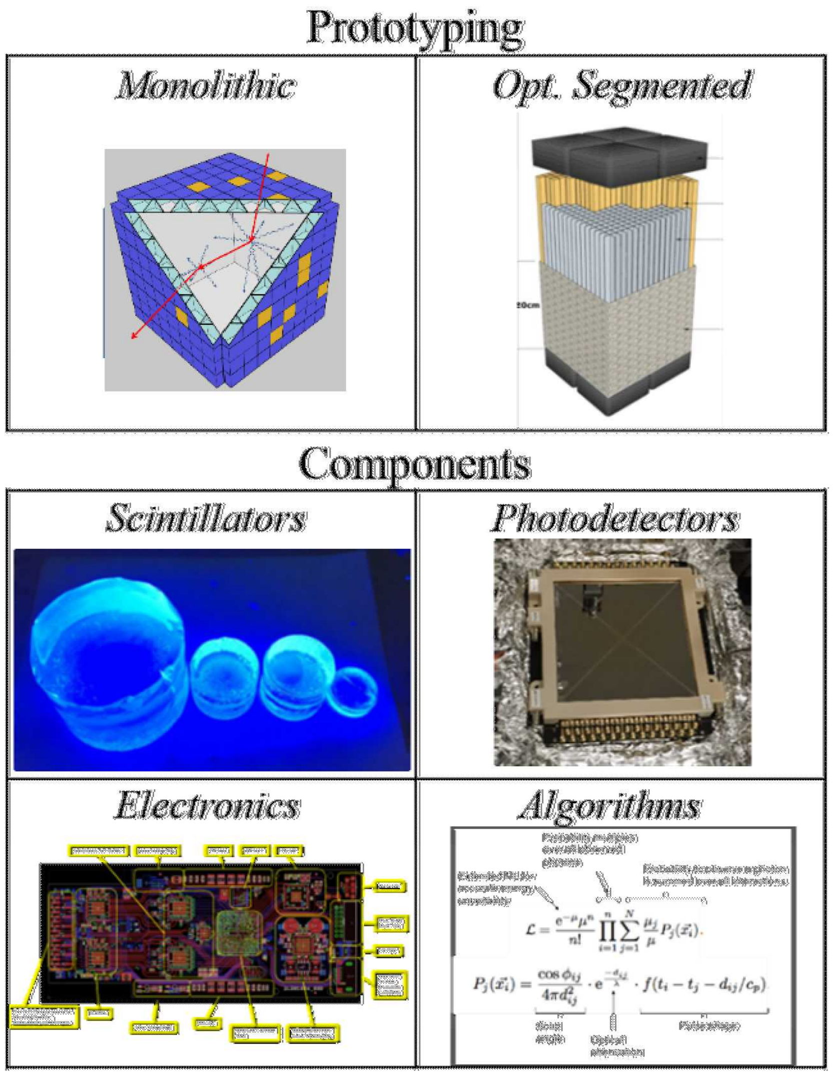
If successful:

- Spectroscopic capability
- Good per-event angular resolution
- High efficiency
- Compact form factor

SVSC project

We have demonstrated feasibility in simulation—information content is there.

Technical achievability is not guaranteed—need to integrate multiple cutting-edge technologies.



Why is fast timing important?

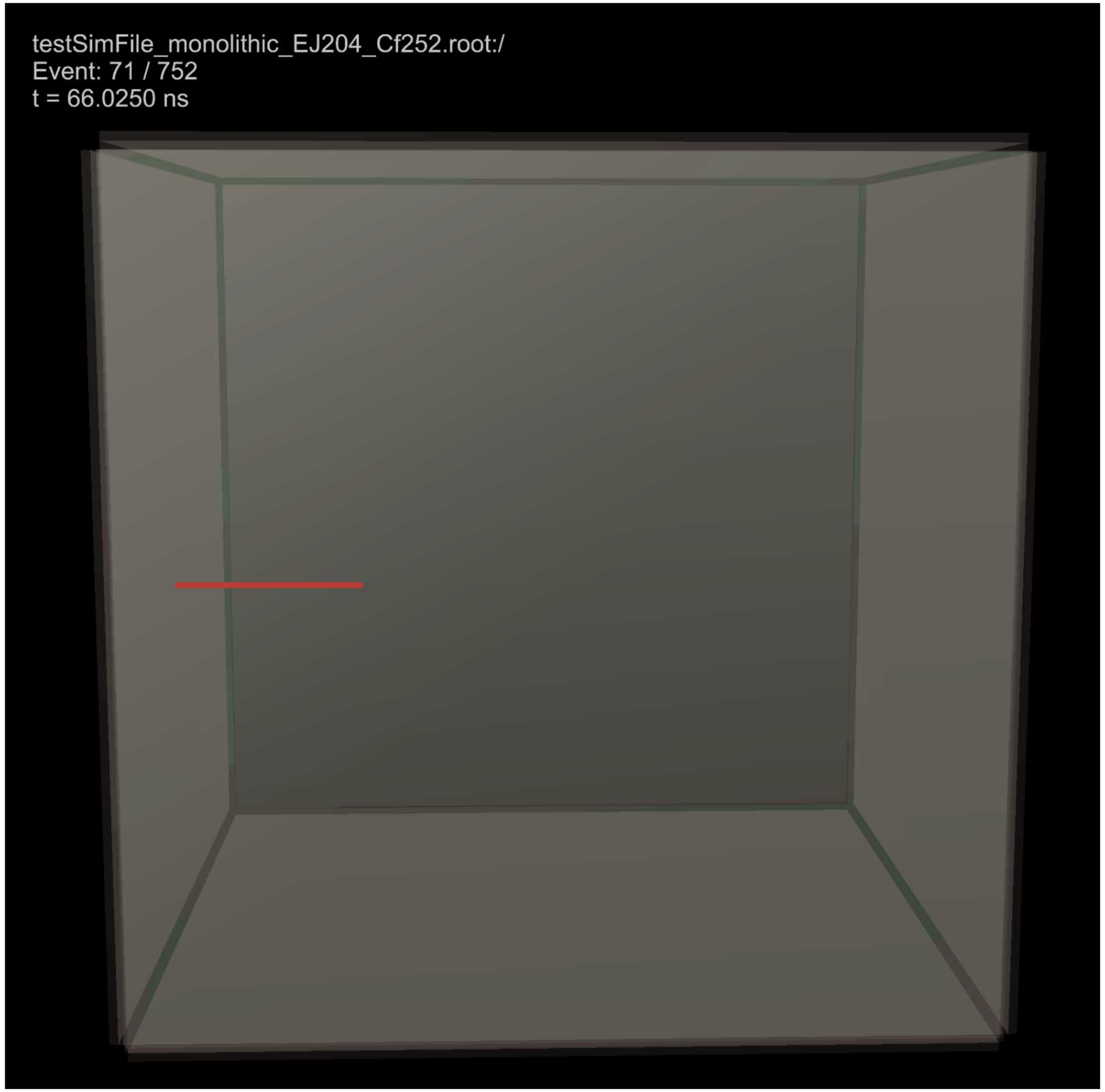
- Distinguish interactions 2 ns & 3 cm apart
- Determine TOF to ~10% → 200 ps
- Correlated with position resolution: c/n = 20 cm/ns → 3 mm ~ 15 ps

System components:

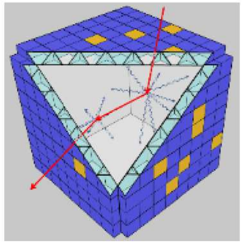
1. Organic scintillator—fast plastic, O(1 ns) decay time
2. Fast photodetectors—MCP-PMTs, SiPMs, etc. Low tts ~100 ps if possible
3. Fast electronics—sufficient to take advantage of PDs. Must be scalable
4. Algorithms—use all information available

Recent research progress

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

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

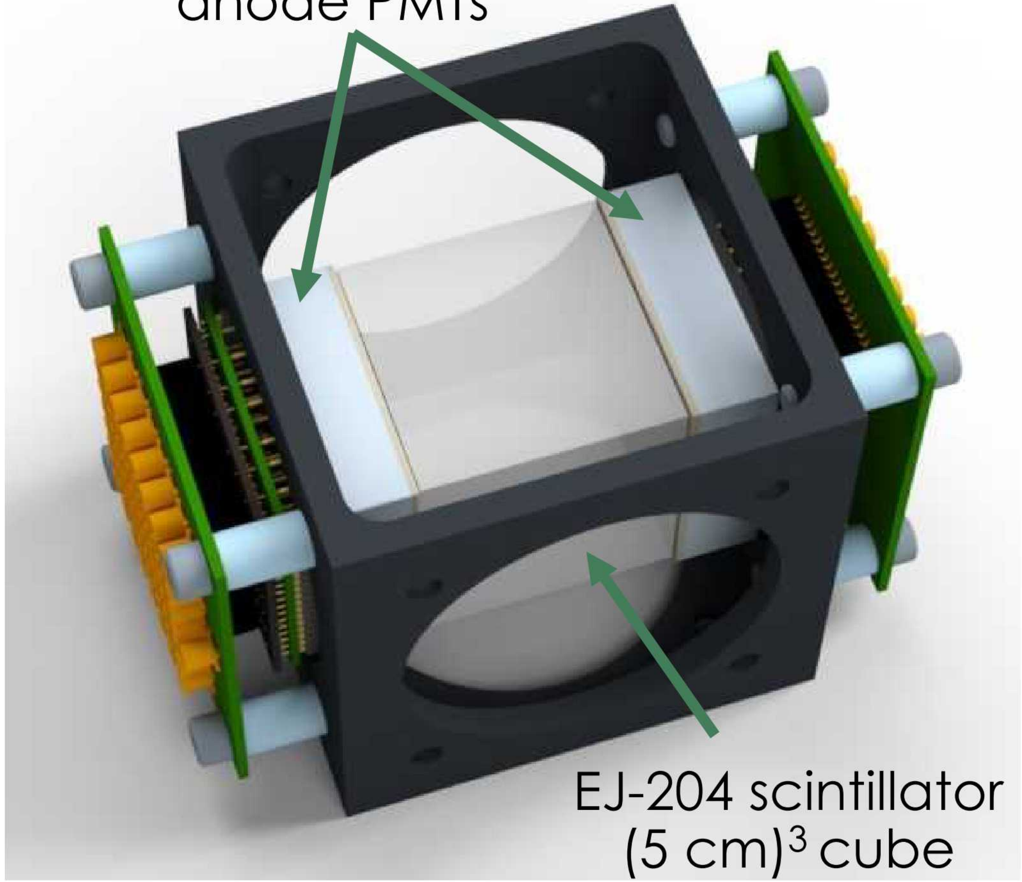
Solid angle — QE — Optical attenuation — Pulse shape

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

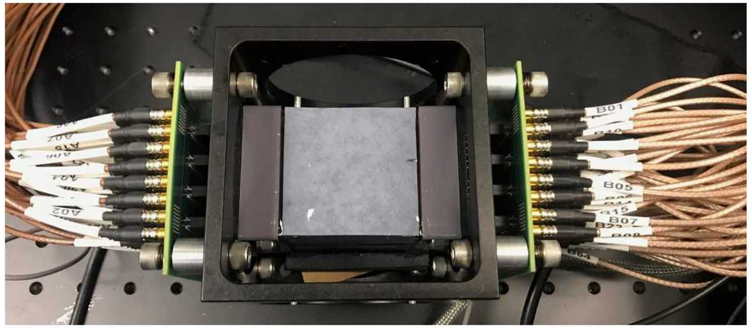
$$\Gamma_j = \sum_{k=1}^{n_{anode}}\frac{\Omega_{jk}}{4\pi}Q_k \cdot e^{-d_{jk}/\lambda}$$

Normalization

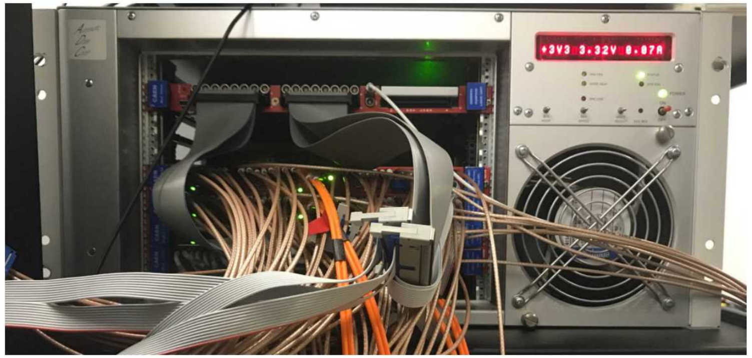
Monolithic integrated prototype @ ORNL



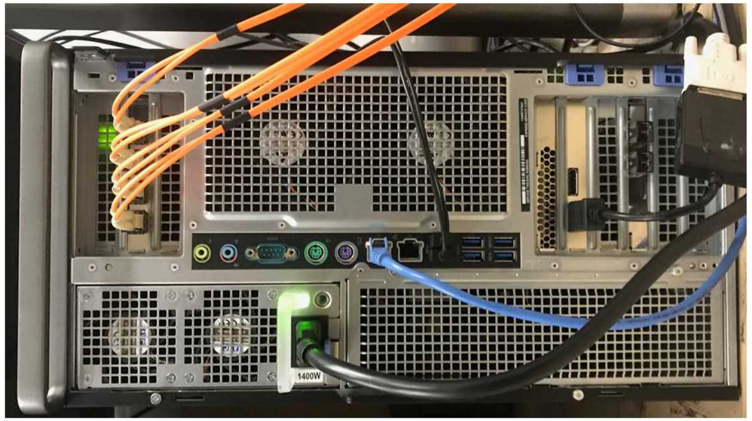
Scintillator and PMTs



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



Dell 7920 16-core workstation + CAEN A3818 optical interface



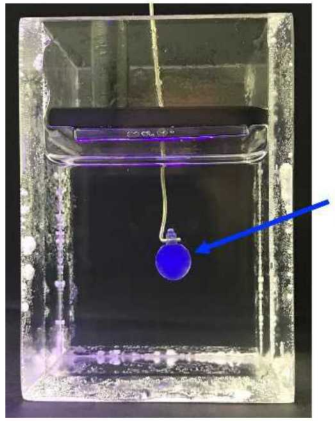
Monolithic single-interaction results

Use a 7.5 mm scintillating bead in a mineral oil bath to acquire data with known interaction position

Single-interaction position reconstruction is successful

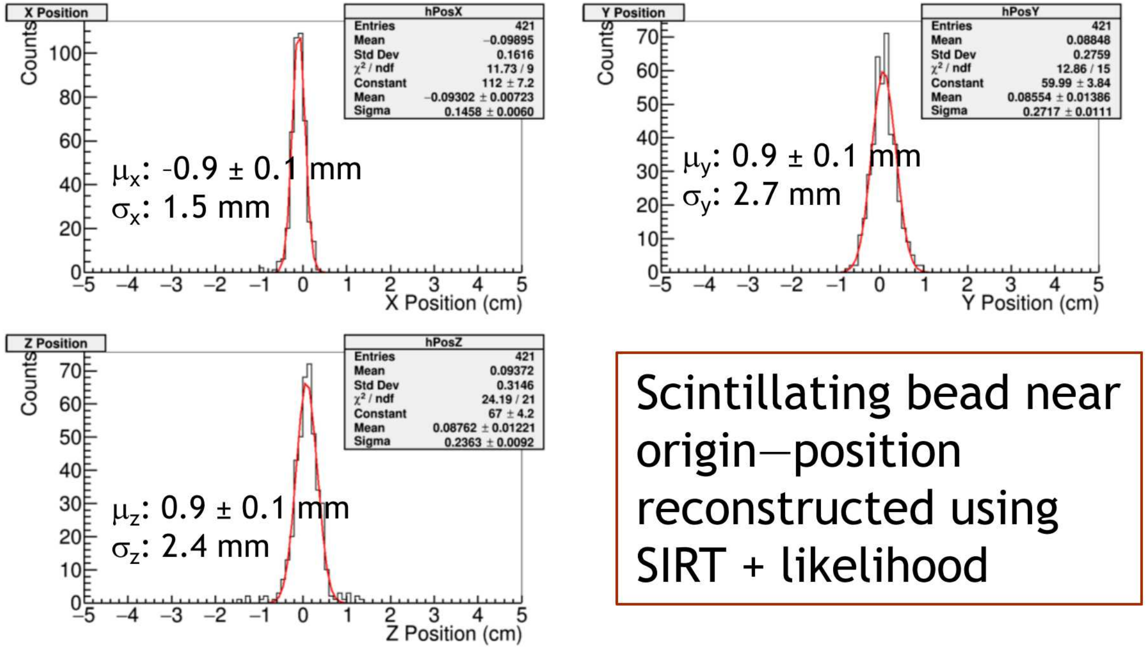
- Detailed calibrations underway to address slight position bias at center
- Investigating increases in reconstruction bias when bead is offset from center
- x,y,z resolutions ~2-4 mm σ for Cs-137 data after position corrections

Oil-filled box



EJ-204 sphere

- Crosstalk in MAPMT!
- Must correct using SIRT iterative method



Scintillating bead near origin—position reconstructed using SIRT + likelihood

Ba-133 beam tests

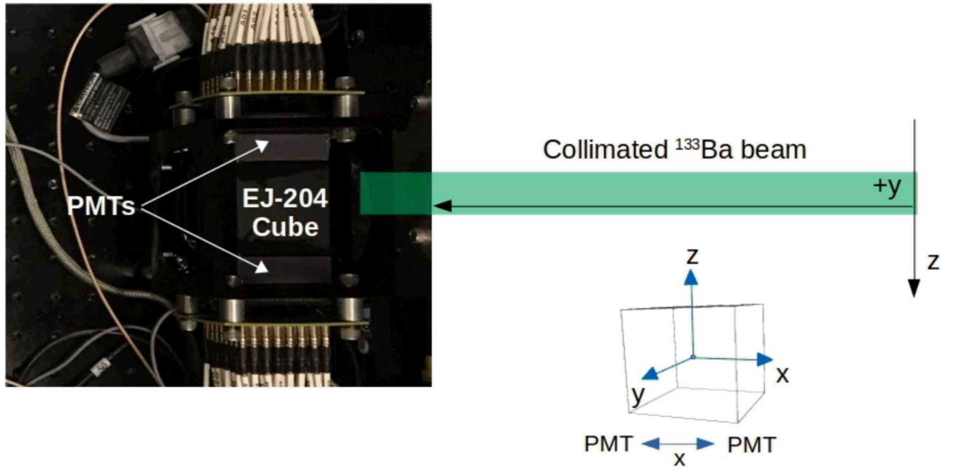
Collimated ^{133}Ba source was used to validate single-site reconstruction @ ORNL.

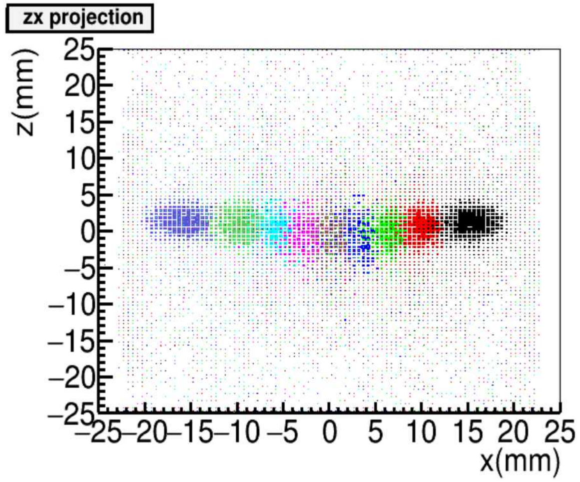
- 32 positions were measured in x-z plane, gammas toward +y
- Beam spot 2.6 mm FWHM

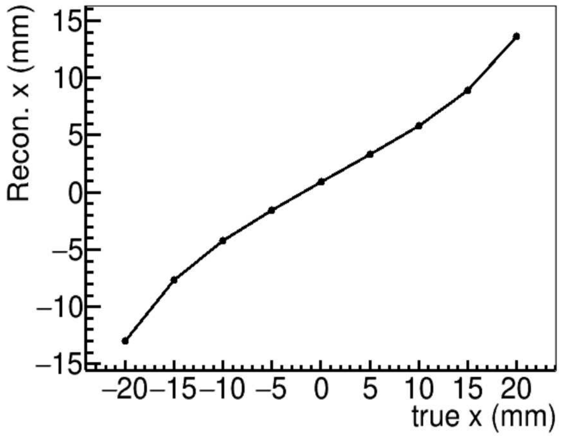
Single-site reconstruction overall tracks beam position.

But biased toward center in x (dimension connecting the two PMTs).

Z reconstruction also biased toward center, effect more dramatic at x near 0.



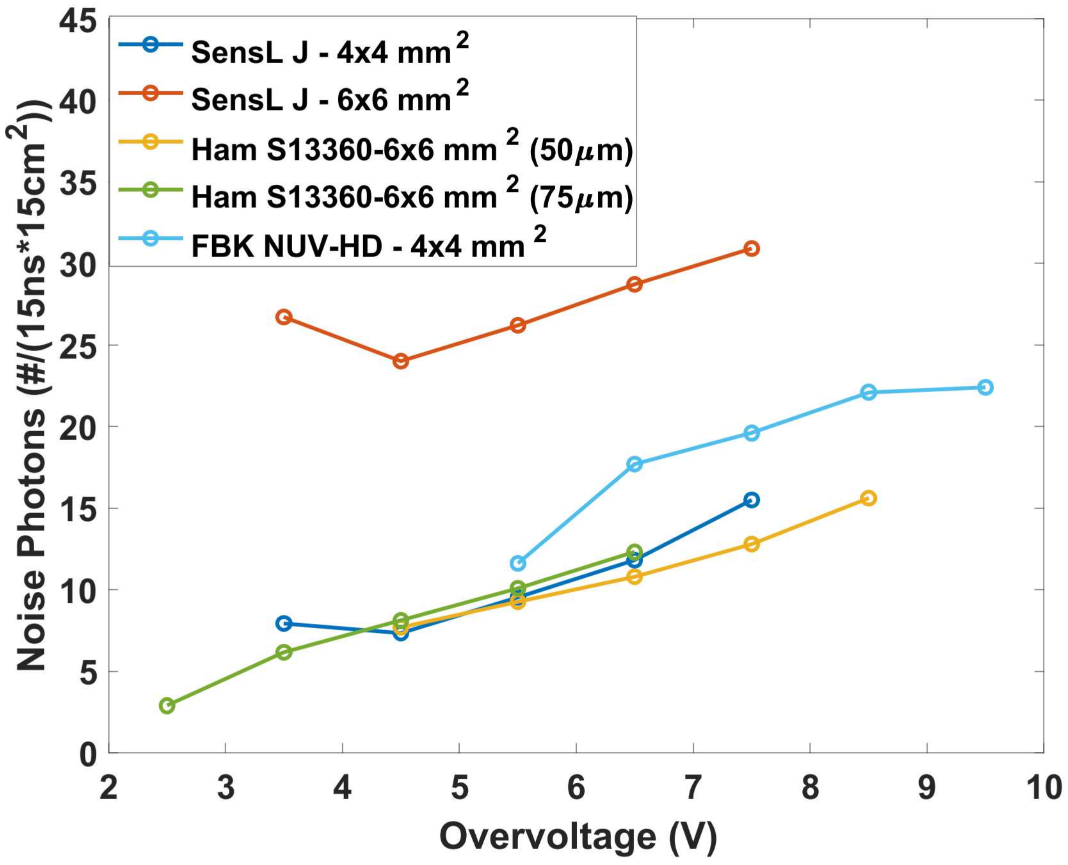


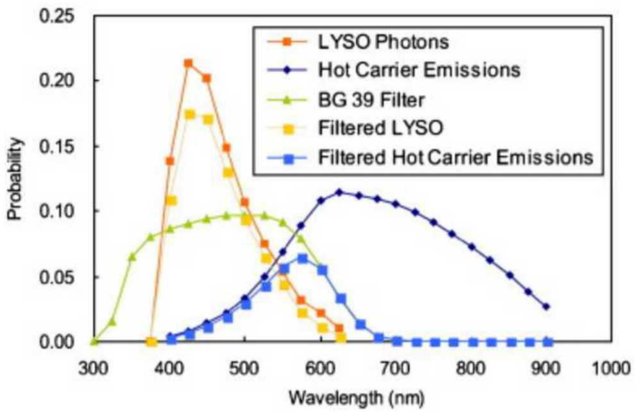


SiPM selection for next monolithic prototype

Josh Cates (LBNL) investigating SiPM and readout options for next monolithic prototype

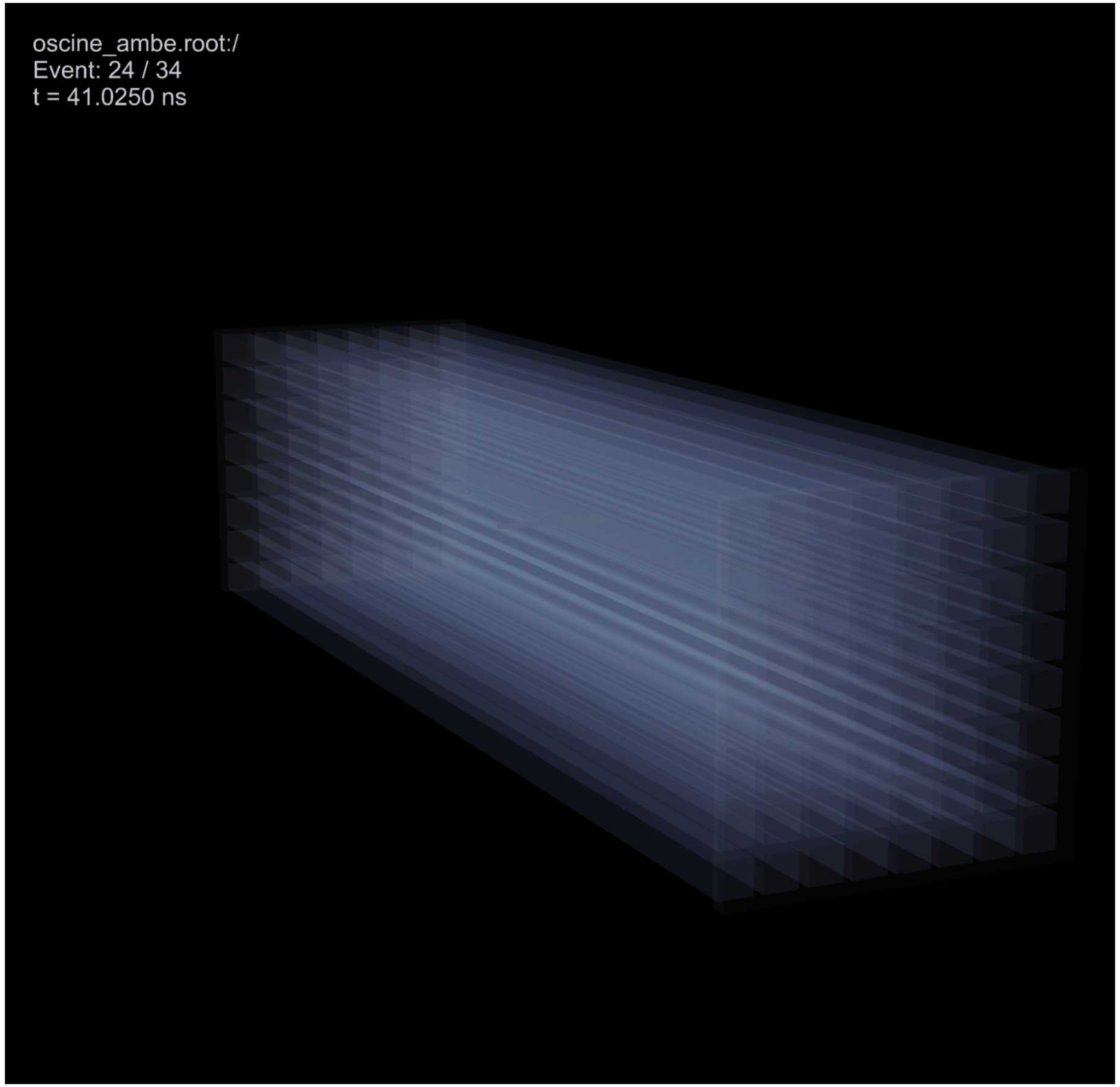
- Selected Hamamatsu S13360-6075 (6 mm, 75 um microcells)—high detection efficiency, decent noise
- Observed uncorrelated (dark counts) and correlated (internal optical crosstalk) noise looks manageable for 5 cm 6-sided detector
  - More problematic as surface area increases…
- Concern about _external_ optical crosstalk—brems photons escape SiPM into scintillator, get detected elsewhere.
  - Measuring now



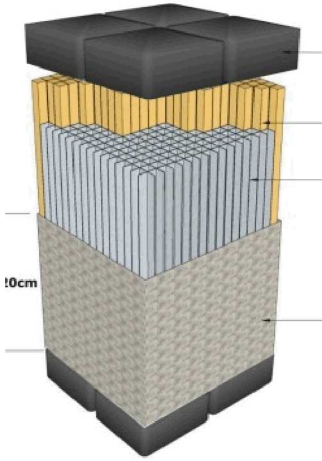


Andrea L. Lacaita et al, "On the Bremsstrahlung Origin of Hot-Carrier Induced Photons in Silicon Devices" ieee trans on elec devices (TED) vol. 40, no. 3 March 1993

Optically segmented detector concept



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

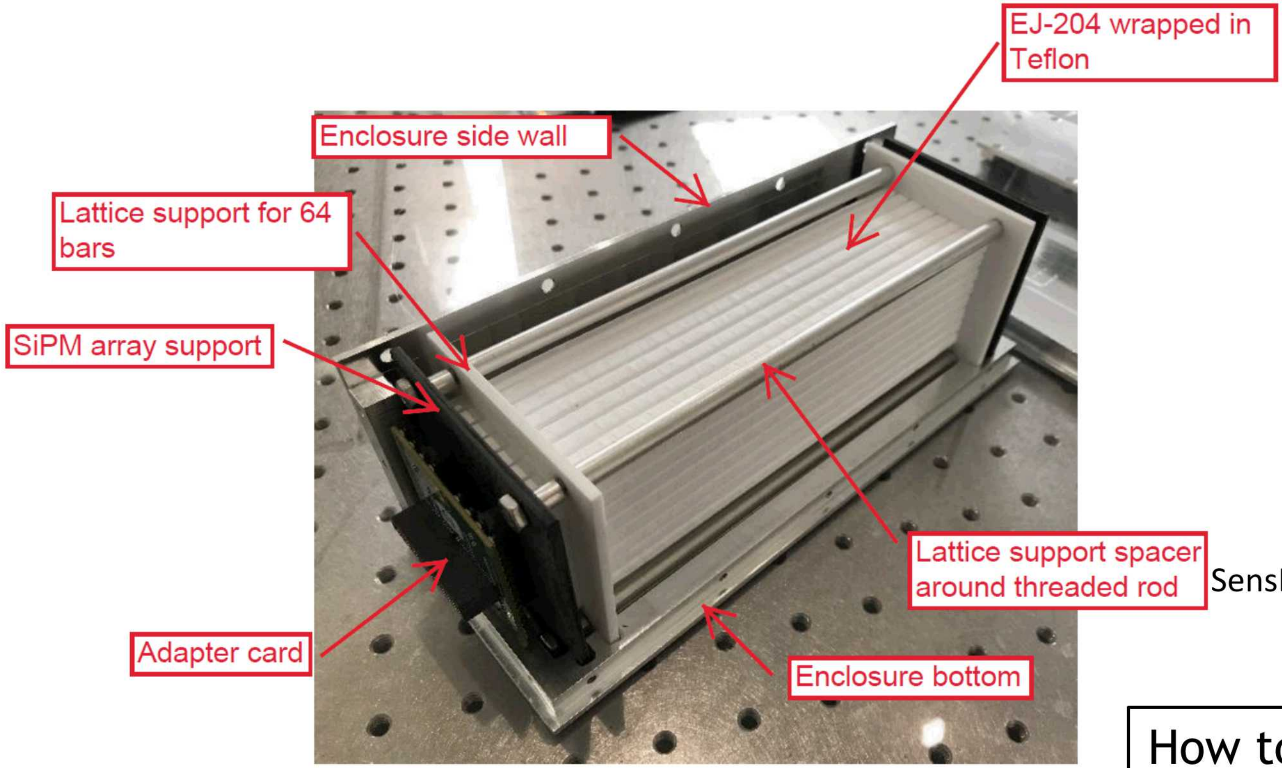


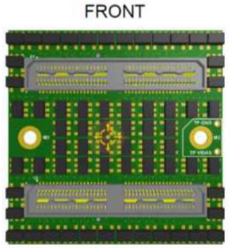
Position: $z \sim (t_1 - t_2)$ AND $z \sim \log(A_2/A_1)$
Time: $t \sim (t_1 + t_2)/2$
Energy: $E \sim \mathrm{sqrt}(A_1 A_2)$

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

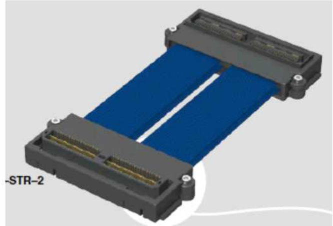
OS integrated prototype @ UH

UNIVERSITY of HAWAI'I MĀNOA

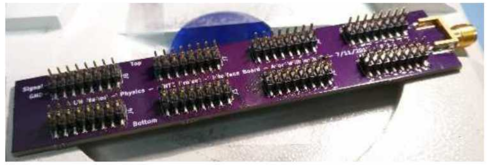




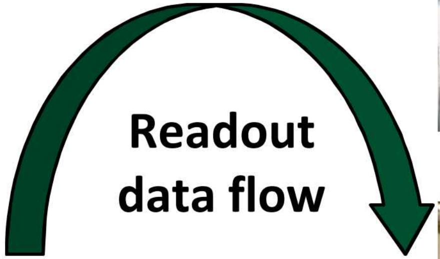
Fast Output (FOUT) Breakout [Ultralytics LLC]



Samtec EQCD Cable



Custom adapter



SensL J-series array (6 mm)

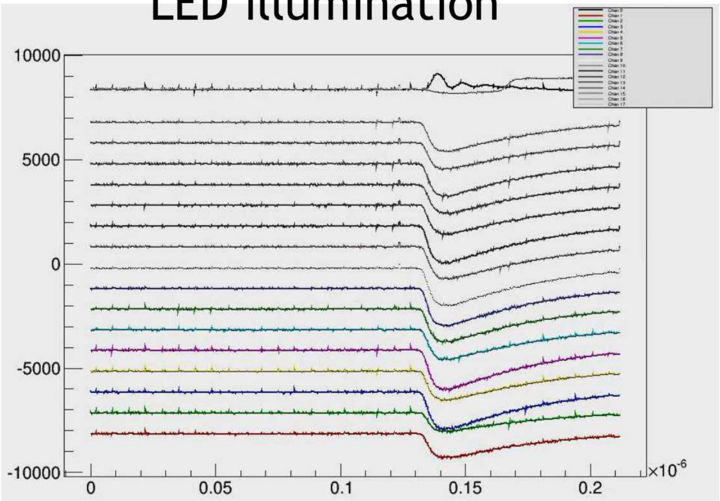
Full 64/128 channel electronics module (Custom IRS3D ASICs)

How to calibrate position reconstruction on each individual bar in the array?

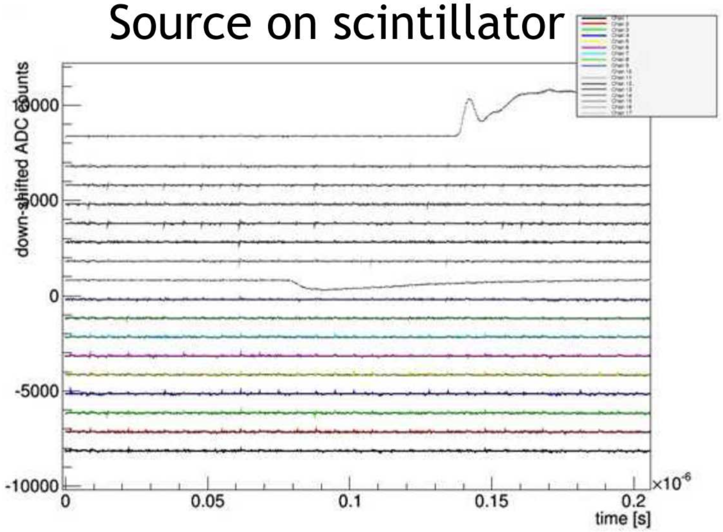
New SiPM readout module

- 2x8 SiPM array
- Flex section allows close packing w/o connectors
- SCEMA board hosts DRS4
- Full control over design to minimize crosstalk
- Modular array allows calibration of each bar

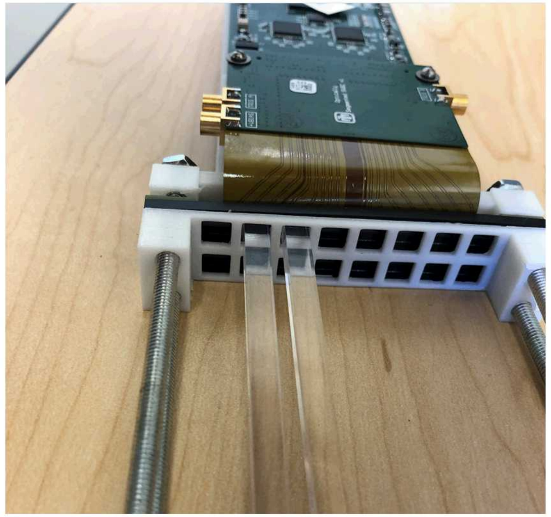
LED illumination



Source on scintillator



Assembling bar array, using UH 3DP supports



Additional technical progress

Several SiPMs and amplifiers evaluated for next monolithic prototype; downselected Hamamatsu S13360 – 75 μm cell size, 6x6 mm^2 area

Proton light yield measurements on EJ-23X scintillators published; *absolute* light yield measurements now underway at UCB/LBNL

Frequency domain multiplexing approach adapted to SiPM + DRS4 combination as for OS prototype

Patent application submitted by ANL on ALD CaF_2 process: METHOD FOR PRODUCING METAL FLUORIDE FILMS

Optical coded aperture approach has resulted in a fully assembled prototype ("slab" geometry)

Future directions

Ongoing work

Work is proceeding on multiple fronts:

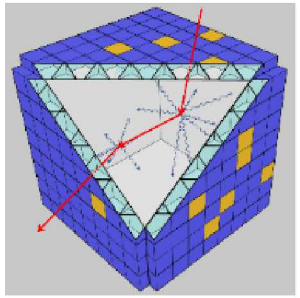
- Short-term develop, prototype, evaluate, iterate:
  - Monolithic concept
  - Optically segmented concept
- Longer-term efforts, incorporate outcomes in 1-3 yrs
  - Component test & evaluation: Tranloc material, PetSYS analog electronics, scintillator properties
  - Technology development: Scintillators, LAPPD, SCEMA, algorithms

Work toward hardware demonstrations, peer-reviewed publications, and conference presentations.

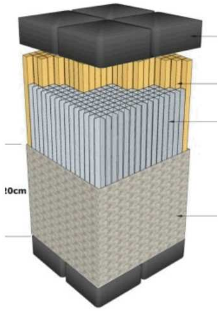
Downselect approach after next round of prototypes if possible

Prototyping

Monolithic

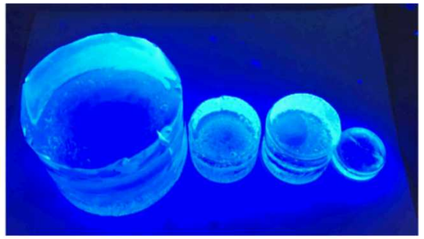


Opt. Segmented

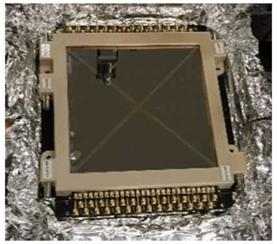


Components

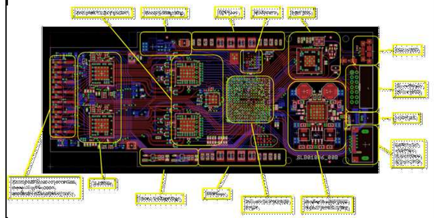
Scintillators



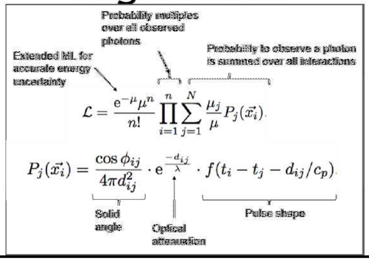
Photodetectors



Electronics



Algorithms



Project end state

Goals/expectations for the end of FY21:

* Demonstrated double-scatter neutron imaging in a compact volume.

* Advanced the state-of-the-art for high-channel-count scintillator readout.
  - Most applications could benefit in principle from improved energy resolution, timing, PSD, position resolution of detailed scintillation event reconstruction.
  - Requires pixelated photodetectors and readout scalable to many channels.

* Improved understanding of organic plastic scintillators
  - New formulations; characterize light yield, pulse shape.
  - Relevant for fast neutron detection/imaging applications.

* Improved methods for fabricating highly segmented detectors

These results can lead to **follow-on work** to pursue:

1. Further advances in double-scatter imaging
2. Improvements in neutron radiography & scatter imaging, neutron coded aperture imaging, neutrino detection/imaging, and potentially medical imaging or industrial applications

We anticipate an **ongoing technical need** for electronics development to support these applications

- Common electronics framework, eventually ASICs, 3d integration of sensors w/ front-end electronics, etc.

Impacts of COVID-19 work slowdowns

- Laboratory/hardware work at most if not all institutions is now at a halt.
- Hardware-related milestones will be delayed: prototype development, scintillator development and characterization, etc.
- Work from home may enable catch-up on backlog of in-process peer-reviewed papers.