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SAND2019-3602PE

National Nuclear Security Administration
Defense Nuclear Nonproliferation

Defense Nuclear Nonproliferation Research & Development

Nuclear Security Applications
Research & Development Portfolio Review
NSARD 2019

Single-Volume Neutron Scatter Camera Development

Erik Brubaker
Sandia National Laboratories
Apr 11, 2019

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. Brown, J. Steele, B. Cabrera-Palmer, et al.
  - **ORNL**: P. Hausladen, K. Ziock, M. Febbraro, M. Folsom, J. Nattress, et al.
  - **ANL**: J. Elam, A. Mane, M. Gebhard, A. Letorneau
  - **U Hawaii**: K. Nishimura, J. Learned, A. Druetzler, A. Galindo Tellez, R. Dorrill, K. Keefe, N. Kaneshige, et al.
  - **UC Berkeley/LBNL**: B. Goldblum, T. Laplace, J. Manfredi, et al.
  - **NCSU**: J. Mattingly, K. Weinfurther, M. Mishra, A. Moustafa

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What are we trying to do?

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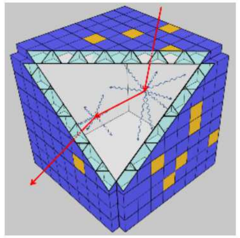
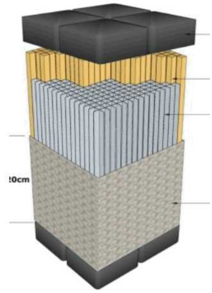
- **Why neutron emission imaging?**
  - **1) Improves detection of weak SNM sources, enables localization.**
  - **2) Characterizes the spatial distribution of plutonium or other neutron emitters.**
- **A compact imager is easy to transport and deploy, has high efficiency, and can be placed near an item 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**





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How is n emission imaging done today?

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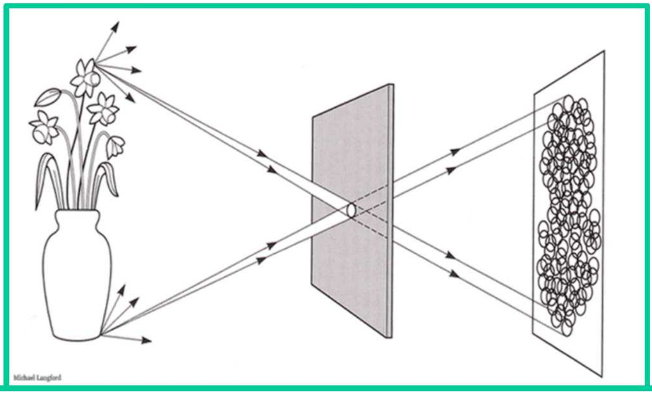
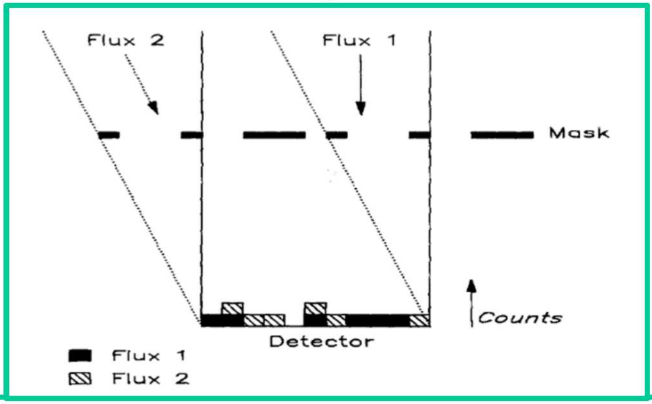
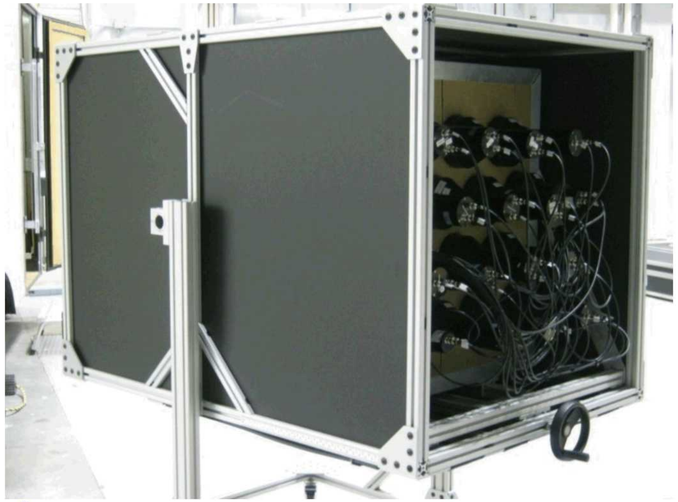
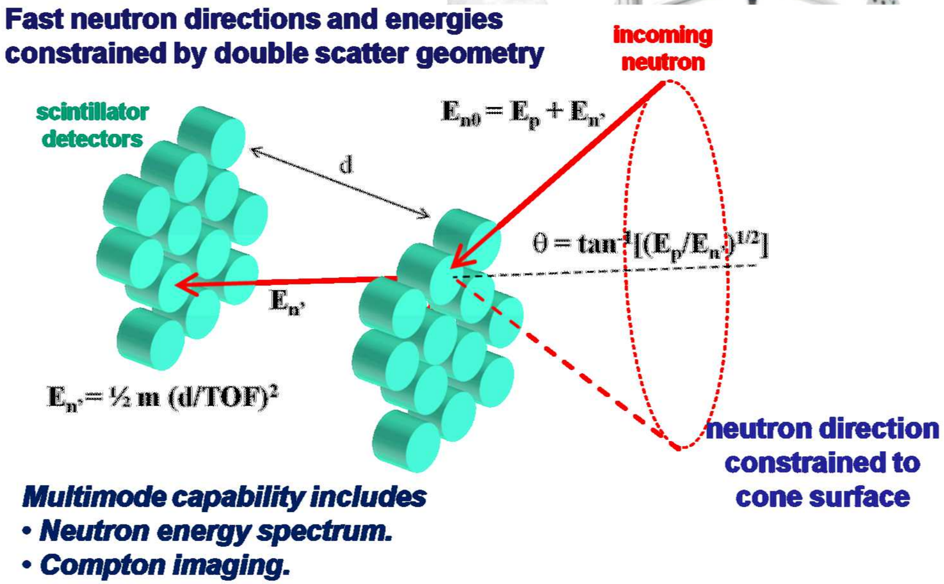


Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput

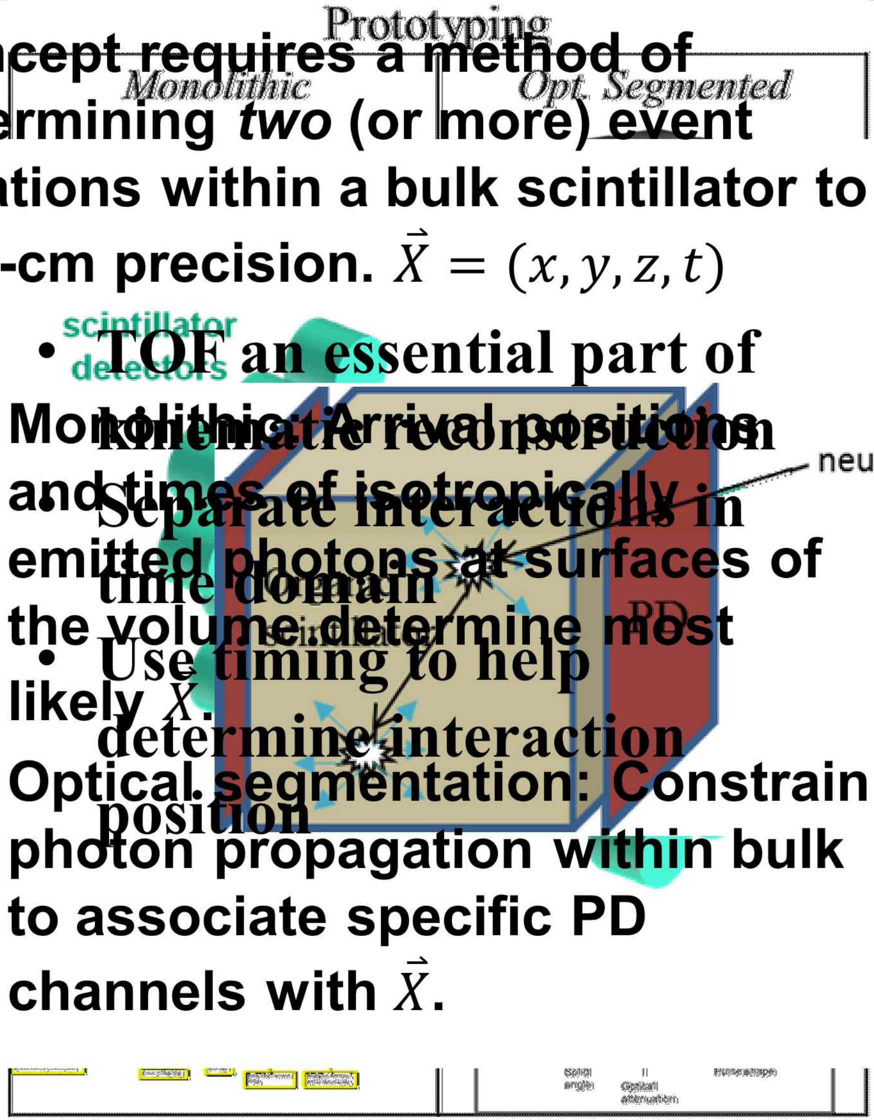




What is our new approach?

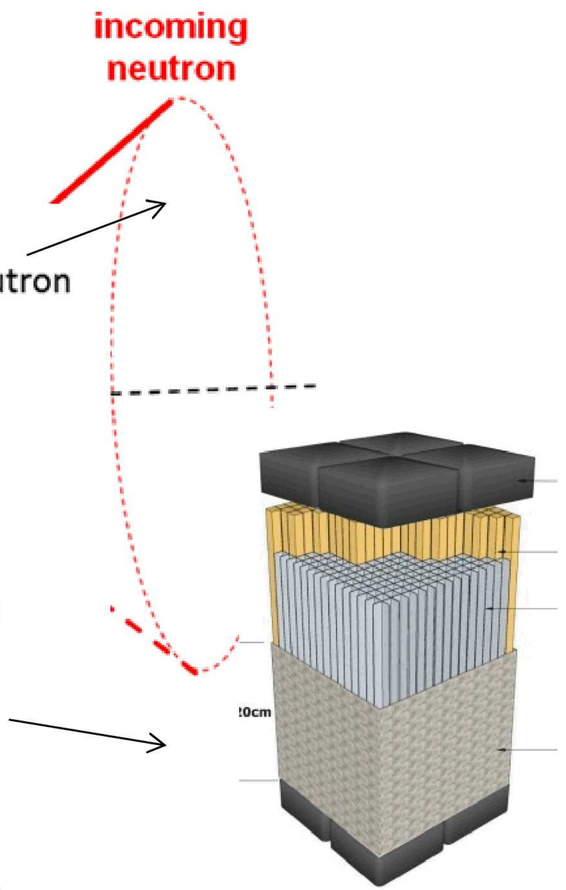
- **Cell-based → single volume**
- **Two configurations:**
  - **Monolithic scintillator**
  - **Optically segmented scintillator**
- **Both rely on excellent time resolution:**
  - **TOF an essential part of kinematic reconstruction**
  - **Separate interactions in time domain**
  - **Use timing to 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** $\vec{X}$**.**



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Who cares? What difference will it make?

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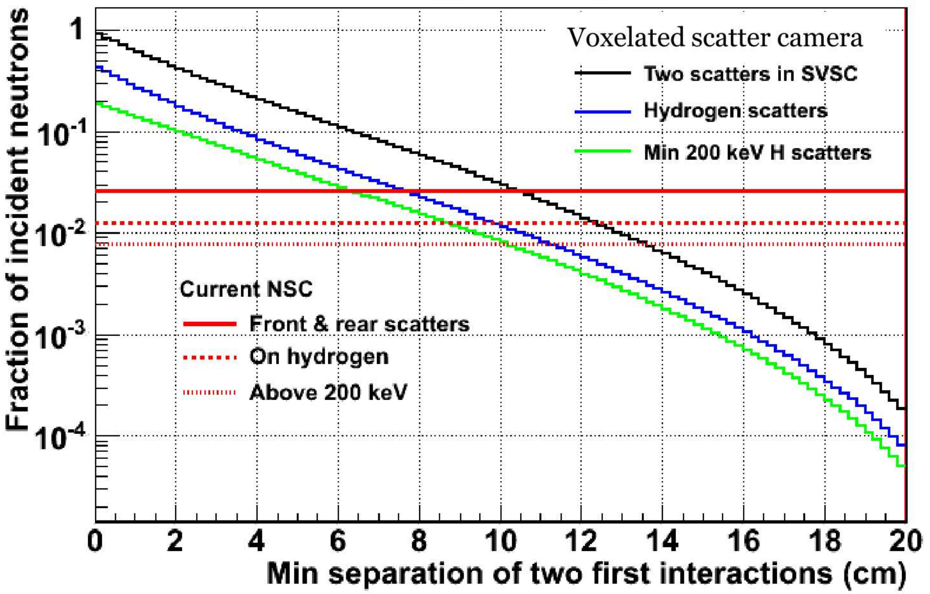
Compact high-efficiency neutron imager:

- 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

Efficiency comparison



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.

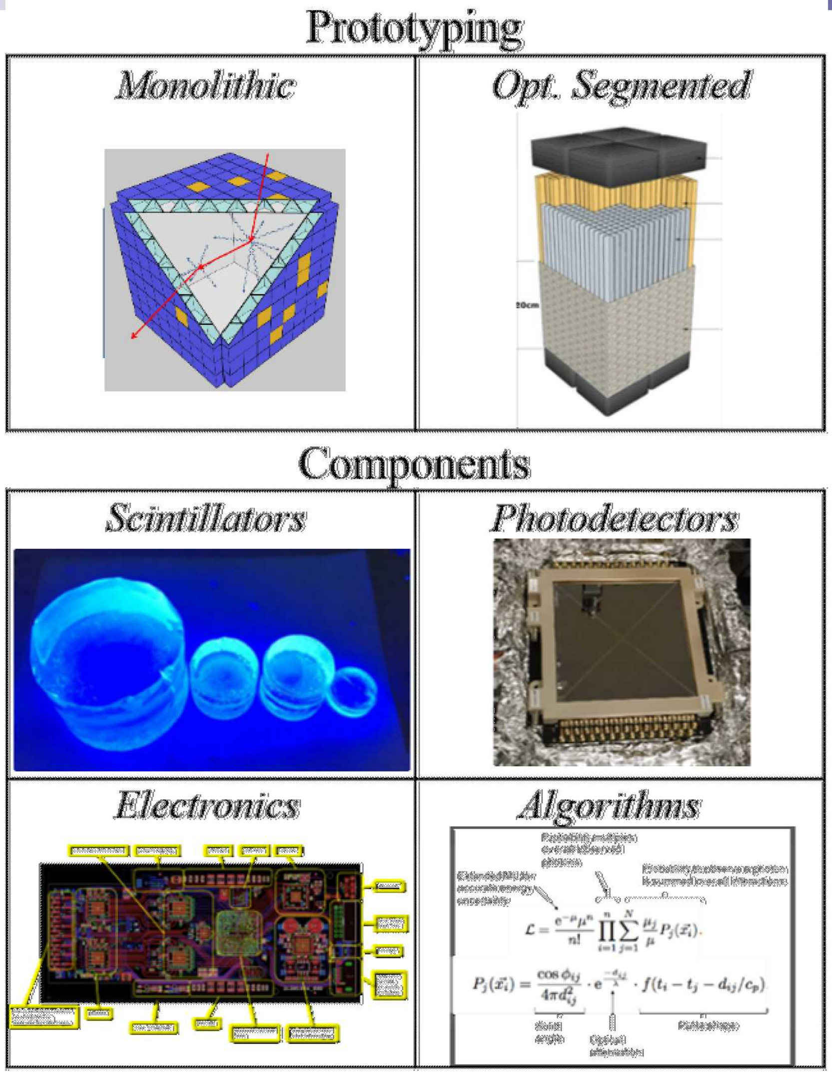
If successful:

- 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

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Monolithic prototype development

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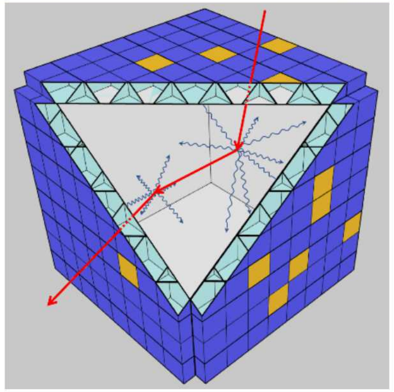
- First prototype constructed at ORNL:
  - 5 cm x 5 cm x 5 cm EJ-204
  - 2x H12700 multi-anode PMTs
  - DRS4-based Caen V1742 digitizers
- Observed unexpected crosstalk in H12700 PMTs
- Likelihood reconstruction method updated for variable pixel size, variable QE, and non-hermetic photodetector coverage
- **See next talk: Mike Febbraro, ORNL**



Extended ML for accurate energy uncertainty

Probability multiples over all observed photons

Probability to observe a photon is summed over all interactions

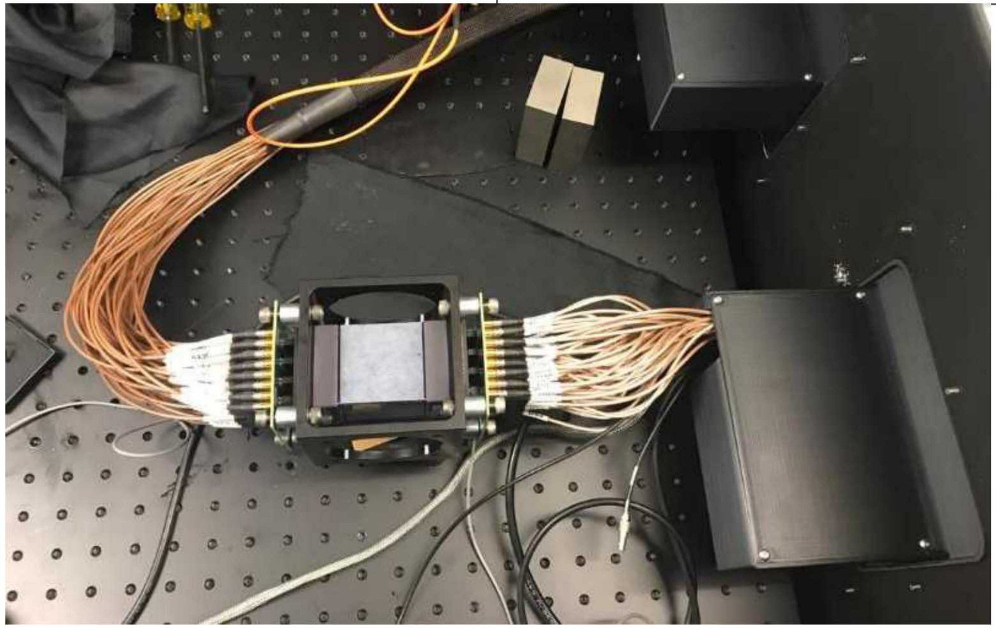
$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_j(\vec{x}_i)$$

$$P_j(\vec{x}_i) = \frac{\cos\phi_{ij}}{4\pi d_{ij}^2}\cdot e^{\frac{-d_{ij}}{\lambda}}\cdot f(t_i - t_j - d_{ij}/c_p)$$

Solid angle

Optical attenuation

Pulse shape



Optically segmented prototype development

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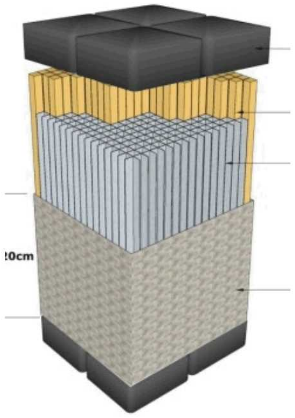
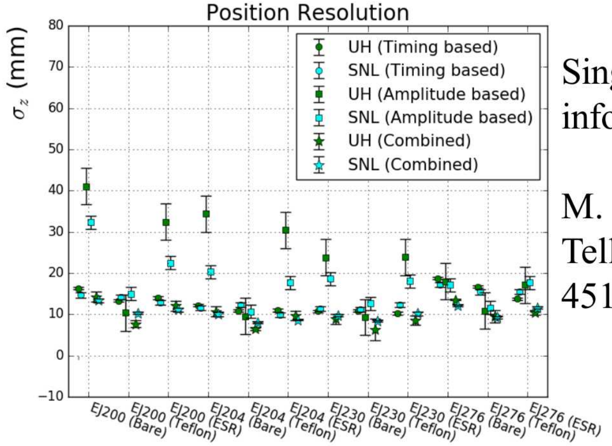
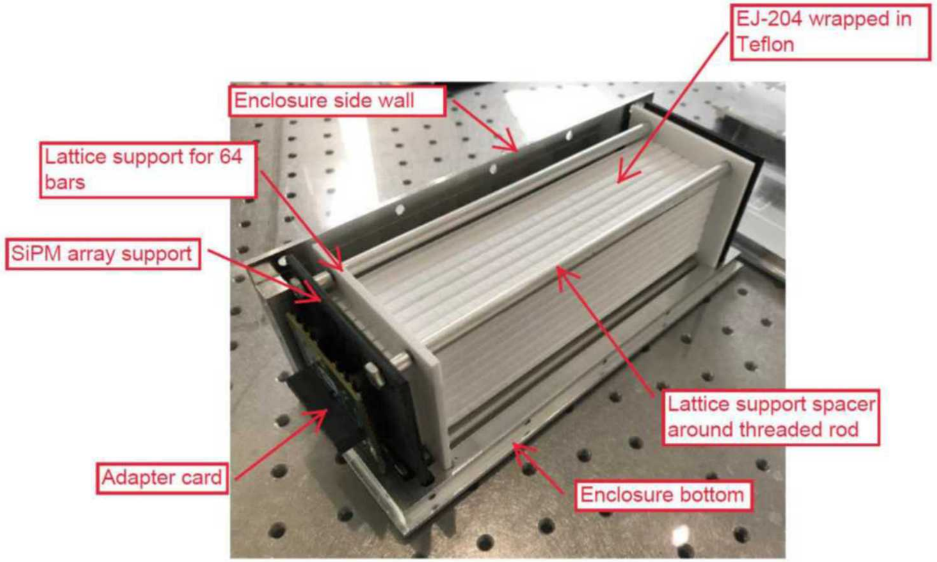
- First prototype constructed at U of Hawaii:
  - 64x 5 mm x 5 mm x 20 cm EJ-204
  - 2x SensL J-series 6 mm SiPM arrays
  - UH IRS3D-based digitization
- Currently performing calibrations, testing for crosstalk (optical & electronic)
- Simulation studies generating comparison points for data; investigating particle ID via TOF in absence of PSD
- **See last talk: Melinda Sweany, SNL**





Single-bar testing results informed prototype:

M. Sweany, A. Galindo-Tellez, et al., NIM A927, 451-462 (2019)



Materials development/evaluation

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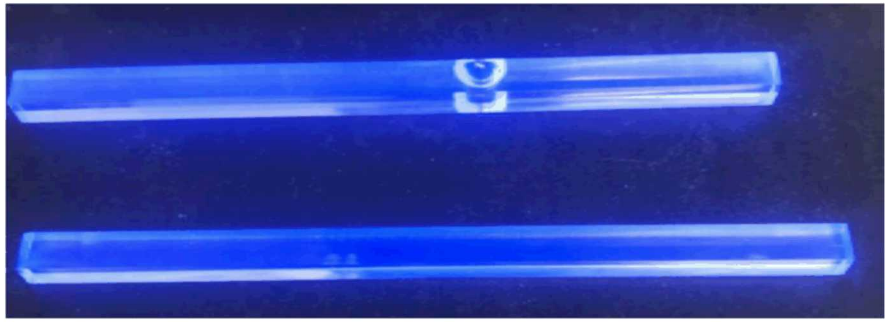
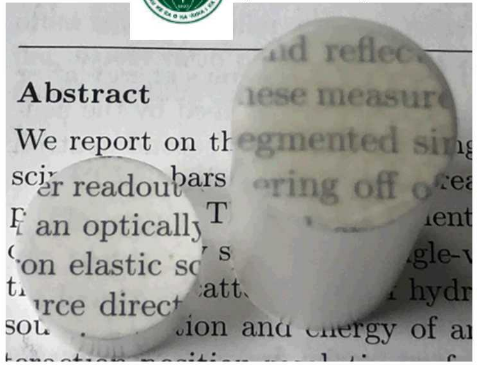
- **Organic glass (Feng, Carlson)**
  - SNL formulations being considered for OS detector
- **Gradient Refractive Index (GRIN) scintillator (Febbraro)**
  - GRIN polymers used in other applications. Can we make GRIN scintillator?
  - Provides natural guiding and improved time resolution (equalizes photon path lengths)
  - Need to polymerize in centrifuge
- **Tranloc**
  - Concept based on transverse Anderson localization. Scintillating Tranloc under development at Paradigm/Incom.



(Keefe)



Scintillator characterization

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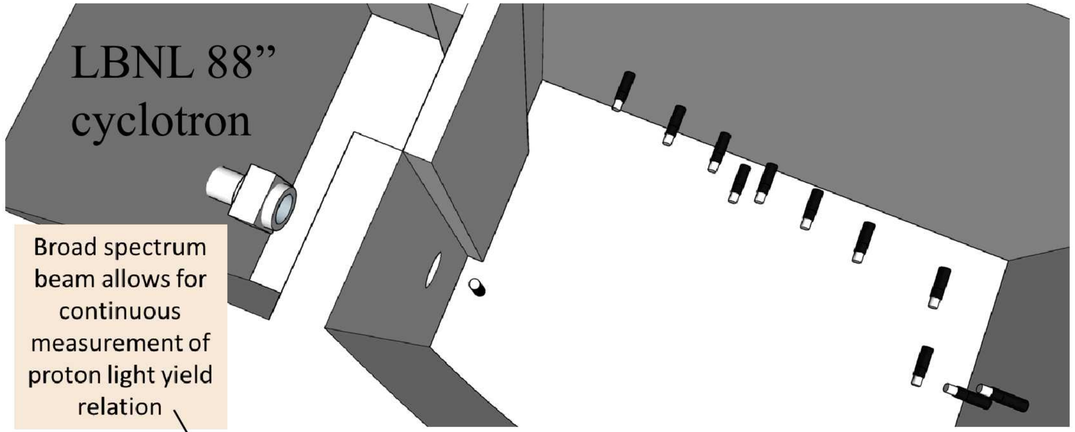
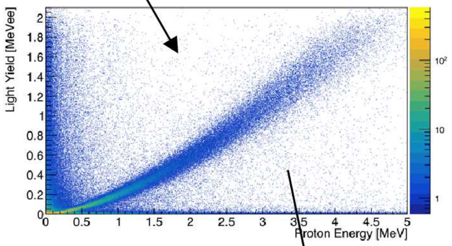
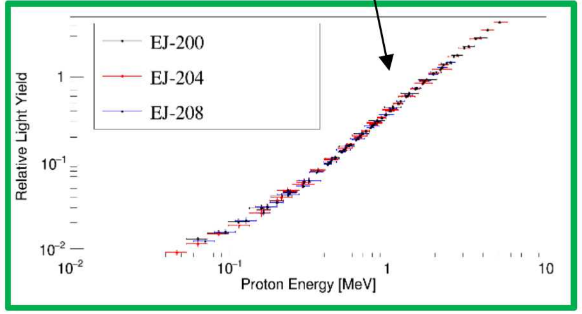
Thibault Laplace,
Juan Manfredi,
Bethany Goldblum

- Scintillator properties need to be thoroughly understood:
  - Material selection
  - Simulation inputs
  - Likelihood reconstruction
- **Proton light yield** largest systematic uncertainty for cell-based scatter cameras
- **Pulse shape** even baseline not well known, much less energy-dependent neutron shape

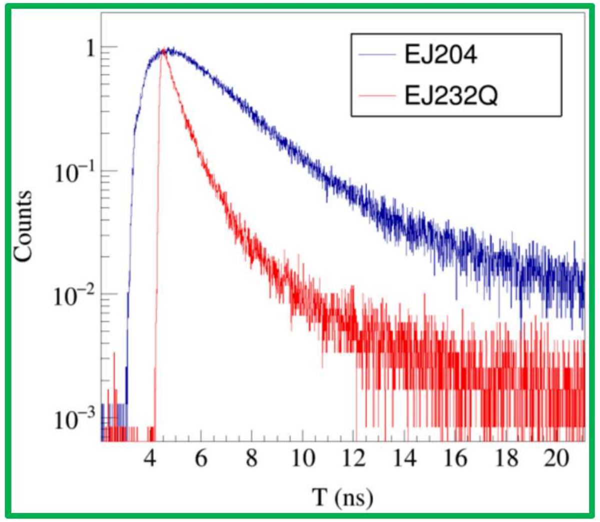






- Proton recoil energies down to 50 keV!
- General consistency with commercial equivalents

Josh Brown



- Pulse shapes measured to ~50 ps resolution
- Significant differences among formulations: binary vs ternary?
- Next step: proton-specific shapes, with energy dependence

See also: Thibault Laplace poster #1B

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Atomic Layer Deposition (ALD) for MCP-PMTs

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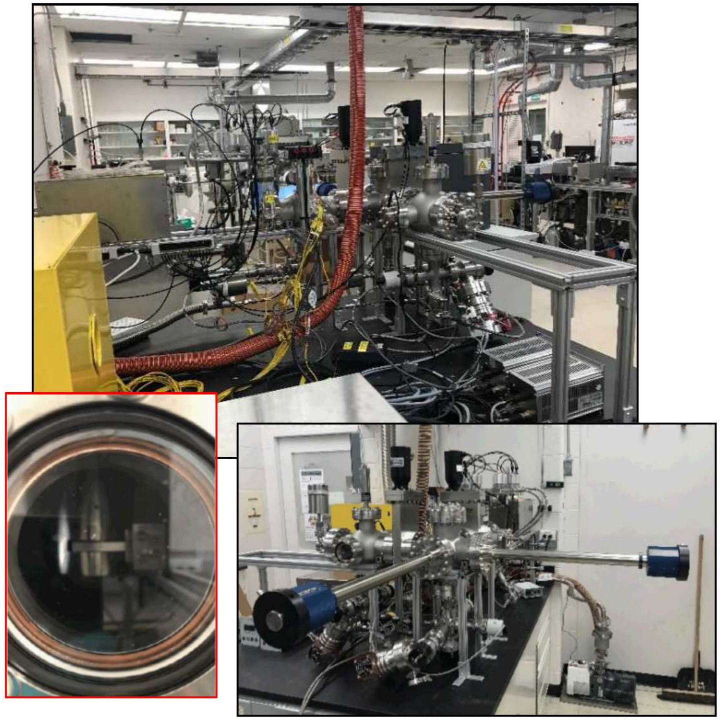
Argonne NATIONAL LABORATORY
Anil Mane, Max Gebhard, Steven Letorneau, Jeffrey Elam

ALD is now gold standard for functionalization of microchannel plates for MCP-PMTs: higher gain, lifetime

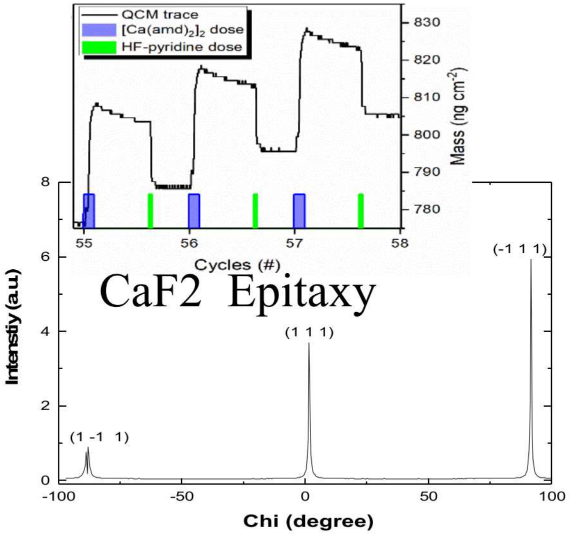
- Completed tasks of F mitigation issue and provided solution for current LAPPD ALD-MCP baseline resistive process
- Developed alternative resistive chemistries (ReAlO and ReAlSiO) and tested on MCPs
- Developed CaF2 ALD process (high quality epitaxial layer) and SEE properties evaluation is in progress
- Continuous support to Incom for ALD-MCP coating XPS characterization and TCR measurements

In-situ ALD-MCP testing system

Ready for first trial (mid-April 2019)



CaF2 ALD process



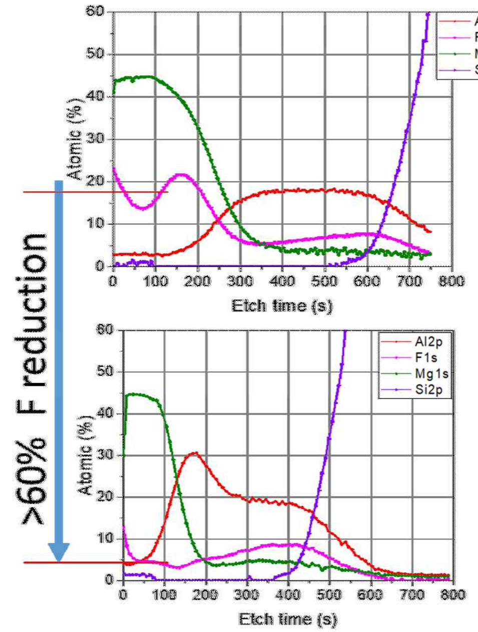
Publications:

- Invention report : ANL-IN-19-039
- Submitted two MRS 2019 and two ALD 2019 abstracts
- 2 Journal papers manuscript in final stage

See also: Anil Mane poster #1B

F mitigation issue and solution

Present LAPPD Resistive coating baseline = (Chem-1+ MgO + 400C)



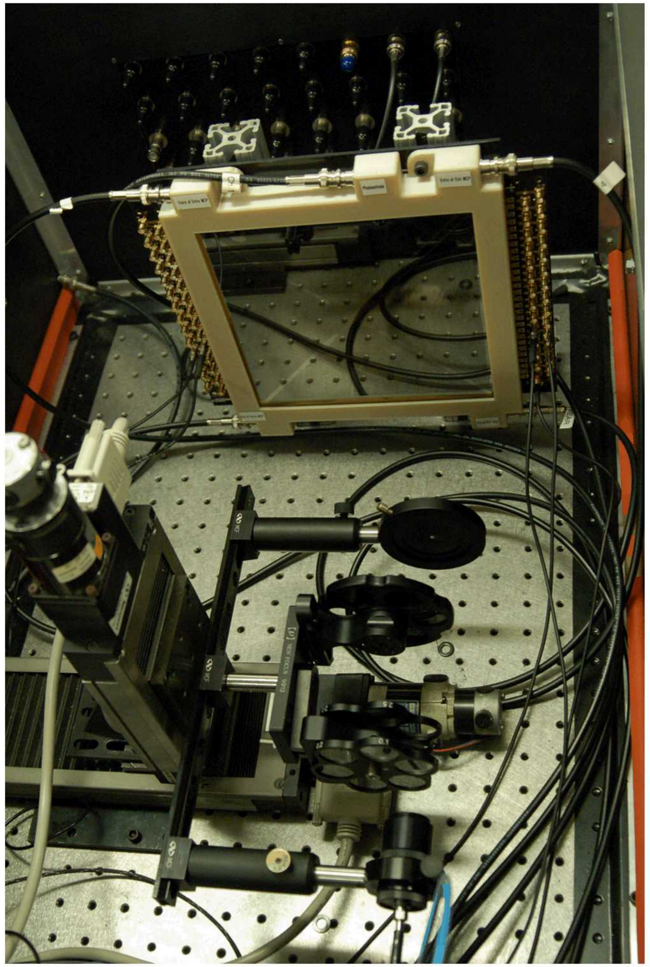
New LAPPD Resistive coating baseline =(Chem-1+ 400C + 2nmALO + MgO + 400C)

Brubaker/SVSC

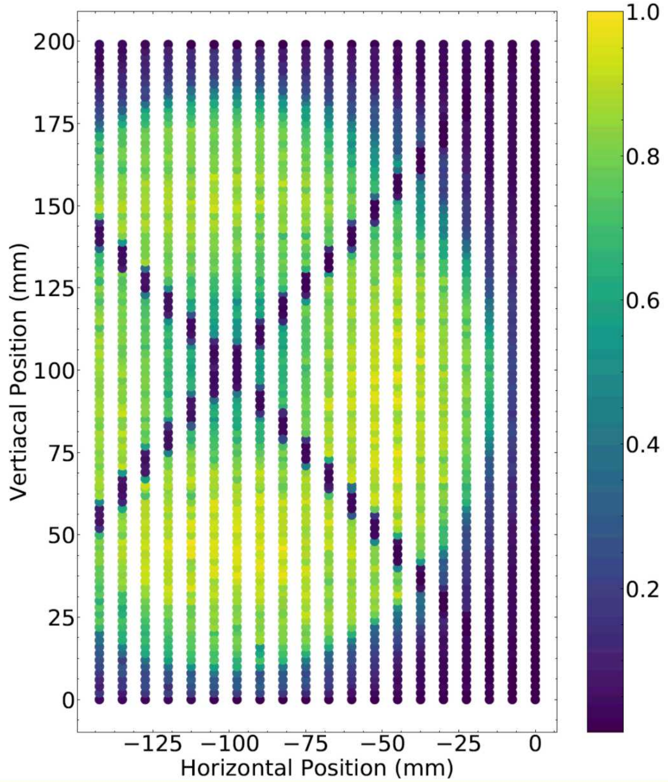
LAPPD characterization

Josh Brown (SNL), Ben Land (UCB/LBNL)

- Large Area Picosecond Photodetector (LAPPD) is a 20 cm x 20 cm MCP-PMT with sub-100 ps single-photon time resolution, few mm spatial resolution
- Second commercial unit acquired by this project for characterization
- Characterized single-photon efficiency variations, gain, gain width, timing resolution, position resolution
- Current version has strip anodes, future versions may have capacitively coupled pixelated anodes



Sample result: relative single-photon detection efficiency vs position



See also: Ben Land poster #16B

Electronics development

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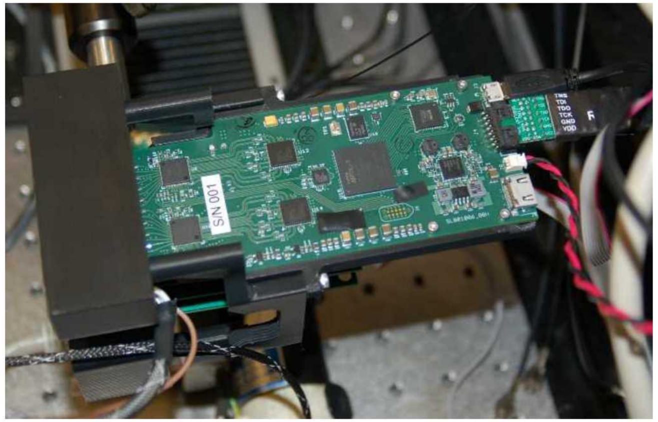
- Need high performance, high channel count, compact electronics
- Sandia Compact Electronics for Modular Acquisition (SCEMA)
  - 16+2 channels
  - 5 GS/s (DRS4)
  - 14 cm x 6 cm
  - Revision in progress
- UH SCROD
  - Full stack, 128 channels
  - 2.7 GS/s (IRS3D)
  - Self-triggering

SCEMA



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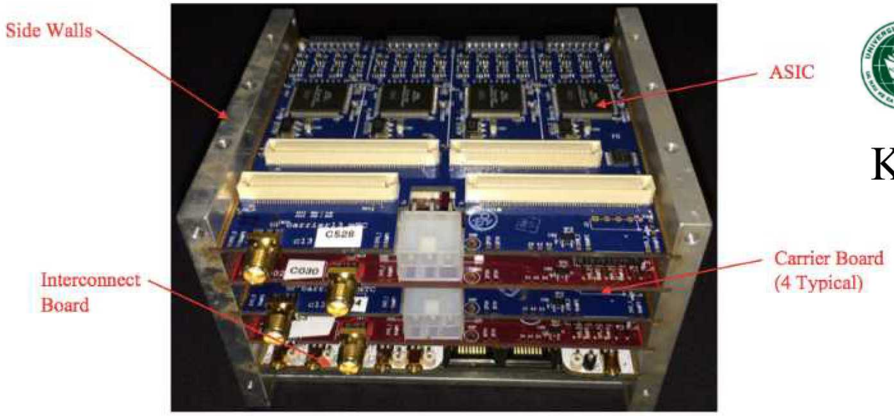
J. Steele, J. Brown, et al.
2019 *JINST* **14** P0203
doi:10.1088/1748-0221/14/02/P02031

UH electronics



University of Hawai'i Mānoa

Kurtis Nishimura, et al.

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Frequency-domain multiplexing (FDM)

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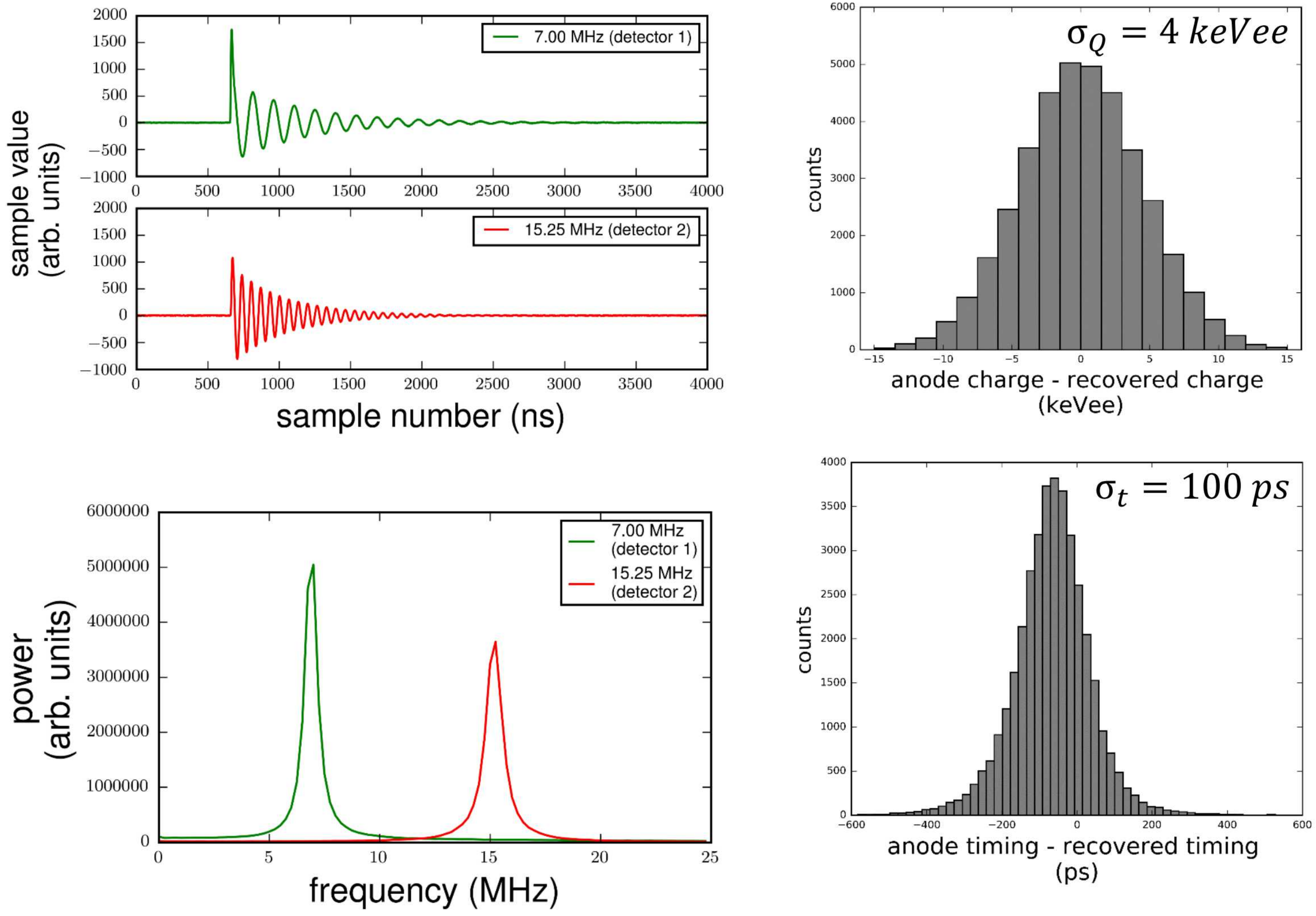
NC STATE UNIVERSITY Mudit Mishra, John Mattingly

- Detector signals are encoded in the frequency domain and combined into a single channel
- Each encoded signal is recovered by deconvolution
- This reduces the number of readout channels for a high channel-density radiation detection system
- Currently investigating performance when multiple multiplexed channels are hit
- Plan to test this year with bar geometry for possible use in future OS prototype

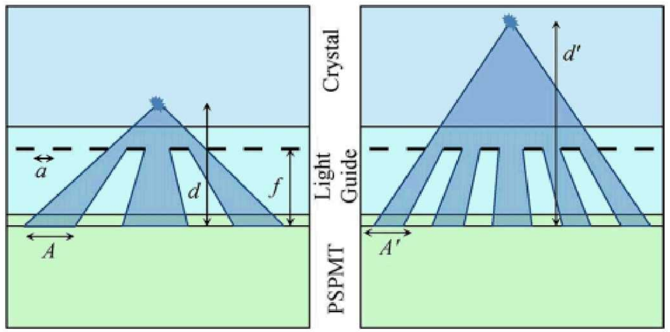


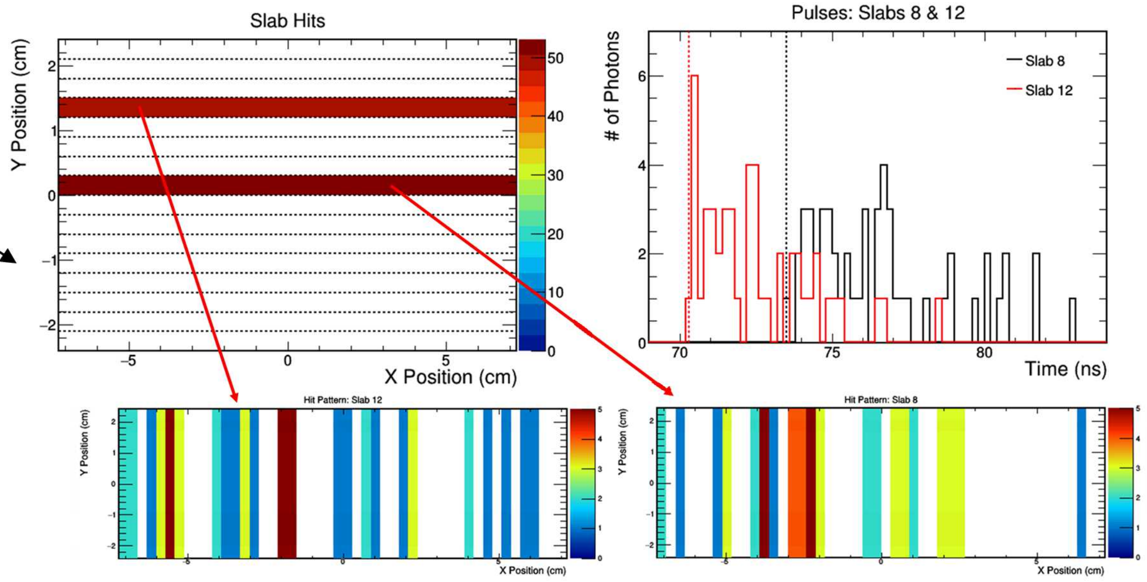
Frequency-domain multiplexed detector signals

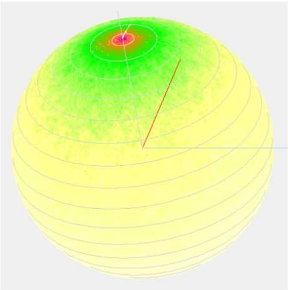
New concept study: optical coded aperture

OAK RIDGE National Laboratory
Micah Folsom, Klaus Ziock

- Consider a variation on the monolithic approach: add an optical coded aperture (OCA) btw scintillator and photodetector
  - Adds high-frequency spatial information that may improve interaction resolution
- Various configurations envisioned, including a 2d slab geometry with 1d OCA
- Simulation results indicate feasibility; current focus on optimizing design and comparing to pure monolithic approach







Simple backprojection image of 41.7k events

Future 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?**
- **Multi-anode vacuum photodetectors need to be abandoned for many-photon regime?**
- **Consider high-channel-count analog electronics?**