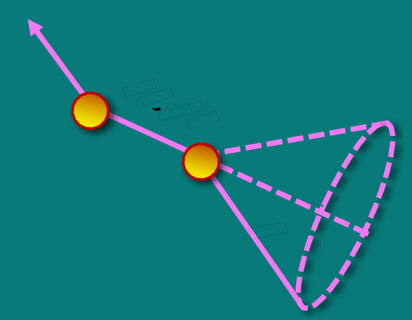
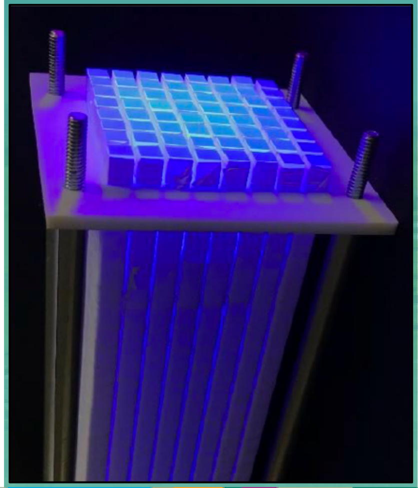
SAND2021-7937PE

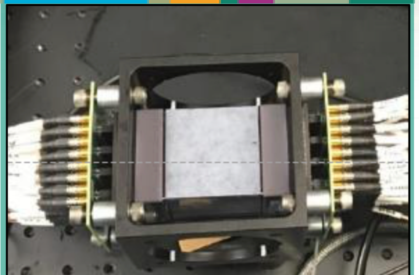
The Single-Volume Scatter Camera Project



Melinda Sweany

July 29th, 2021





The SVSC 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

@North Carolina State University

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

@Oak Ridge National Laboratory

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

@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)

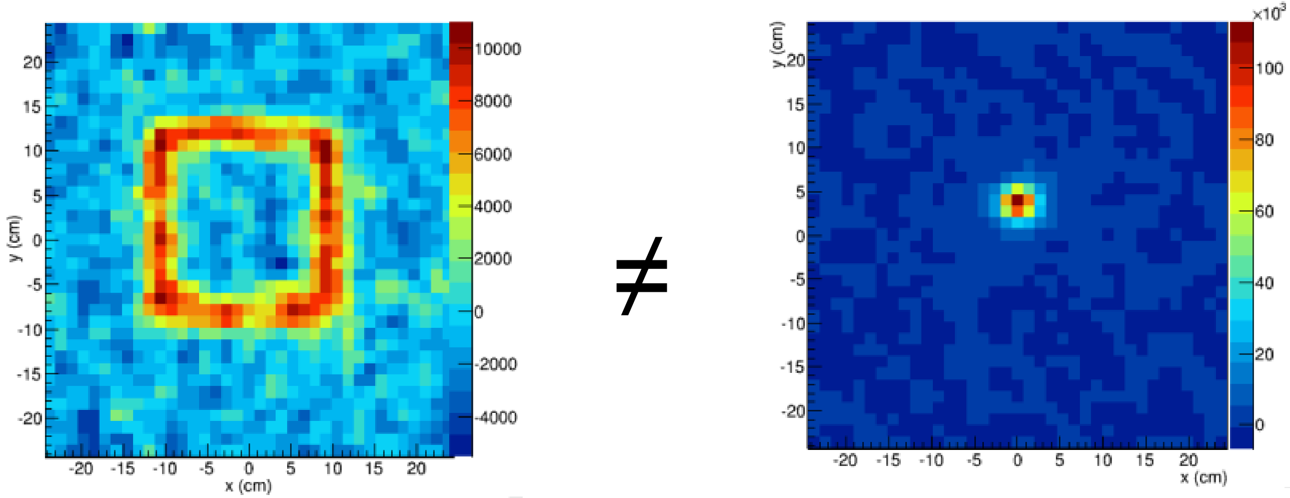
@UH Mānoa

- 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)

Why neutron imaging?

Enables localization, characterization of SNM

- in unknown radiation environment, imaging improves signal to noise compared to radiation counter
- for neutrons, less background sources compared to gammas
- characterizes spatial distribution of plutonium or other neutron emitting materials



Two imaging methods for fission-energy neutrons:

- ~~coded aperture~~ and kinematic neutron imaging

How kinematic imaging works - theory

Exploits neutron scatters off of hydrogen:

- two body scatter in Hydrogen reference frame,

x-axis along in-coming neutron trajectory

- COM: $v_n = v'_n \cos\theta + v'_p \cos\varphi$

$$0 = v'_n \sin\theta + v'_p \sin\varphi$$

- rearrange: $v_n - v'_n \cos\theta = v'_p \cos\varphi$

$$v'_n \sin\theta = v'_p \sin\varphi$$

- square and add:

$$v_n^2 + v'^2_n \cos^2\theta - 2v_n v'_n \cos\theta = v'^2_p \cos^2\varphi$$

$$+ \quad v'^2_n \sin^2\theta = v'^2_p \sin^2\varphi$$

$$\rightarrow v_n^2 + v'^2_n - 2v_n v'_n \cos\theta = v'^2_p = v_n^2 - v'^2_n$$

$$-2v_n v'_n \cos\theta = -2v'^2_n$$

$$\sin^2\theta + \cos^2\theta = 1$$

COE

$$E_n = E'_n + E'_p$$

$$\vec{p}_n = \vec{p'}_n + \vec{p'}_p$$

$$m_n = m_p$$

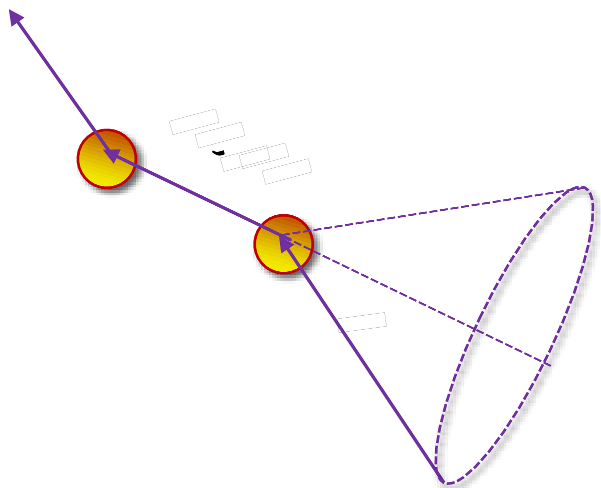
$$\cos\theta = \sqrt{\frac{E'_n}{E_n}}$$

- okay, we have a relation with the incoming angle…now what?

Need the incoming/scattered neutron energy:

- total incoming neutron energy is: $E_n = E'_n + E'_p$
- first neutron scatter loses energy proportional to scintillation light resulting from proton recoil: E'_p
- remaining energy is measured through non-relativistic time-of-flight:

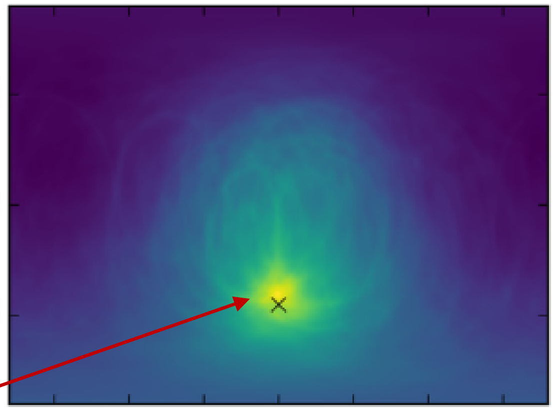
$$E'_n = \frac{1}{2} m_n \left(\frac{\Delta d}{\Delta t}\right)^2$$



- in terms of things we actually measure:

$$\cos\theta = \sqrt{\frac{\frac{1}{2} m_n \left(\frac{\Delta d}{\Delta t}\right)^2}{\frac{1}{2} m_n \left(\frac{\Delta d}{\Delta t}\right)^2 + E'_p}}$$

- we must fully reconstruct the positions/times of two neutron interactions, energy of the first to get:
- a series of cones that will overlap at the source



Why not neutron imaging?

Typically large (poor SWaP), and inefficient detection systems

- position resolution is ~size of 2/3 inch scintillator cell
- timing resolution limited by 250 MHz data acquisition/TTS of PMTs
- distributed scintillator volumes have poor geometrical acceptance
- high channel count, power requirements

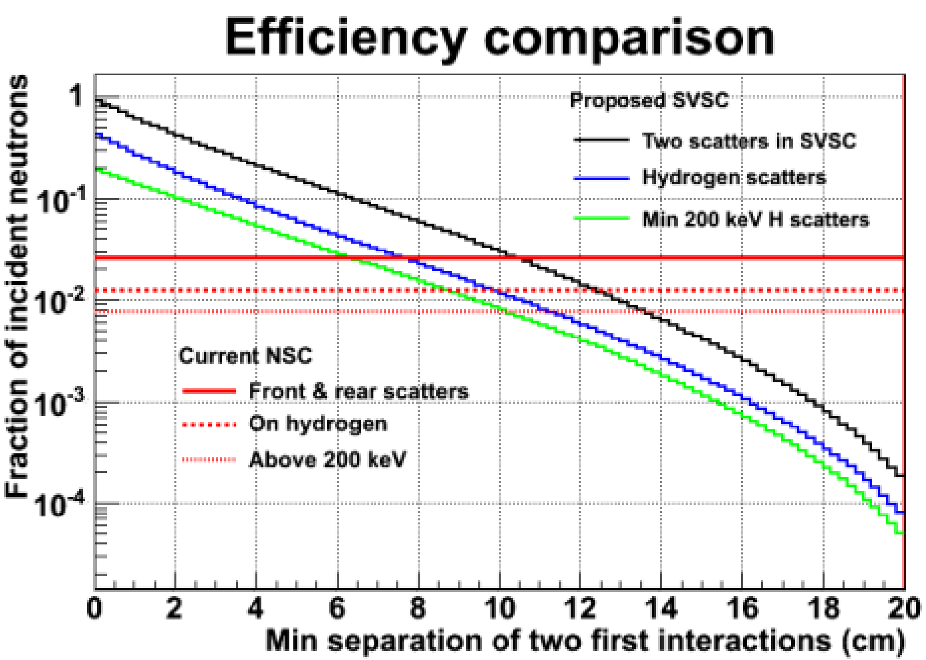
SNL's first neutron scatter camera system

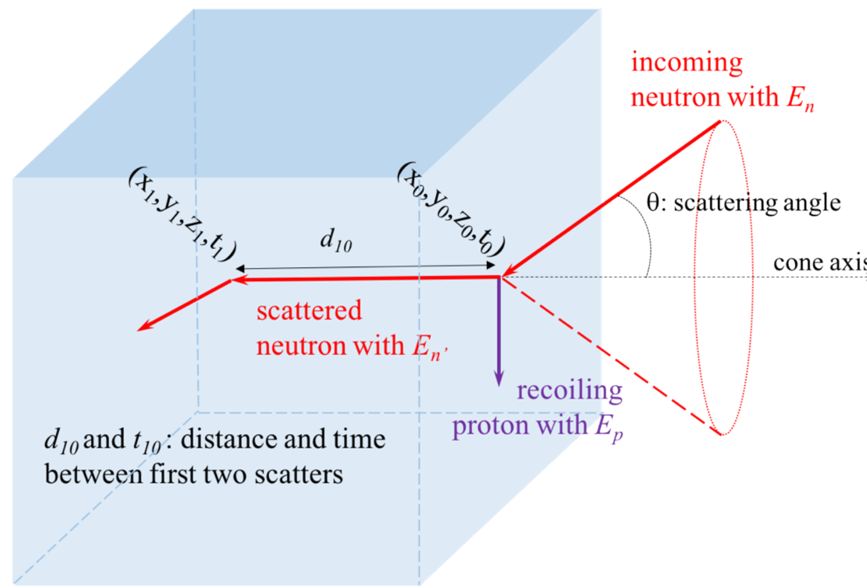
SNL's MINER system with improved SWaP

Why Single-Volume Scatter Camera?

Portability, combined with improved geometrical acceptance

- potentially a factor of 10 improvement in overall efficiency compared to NSC
- requires ability to detect two neutron scatters *O(1cm)/O(1ns)* apart
- recent advances in fast photodetectors and electronics may enable this!





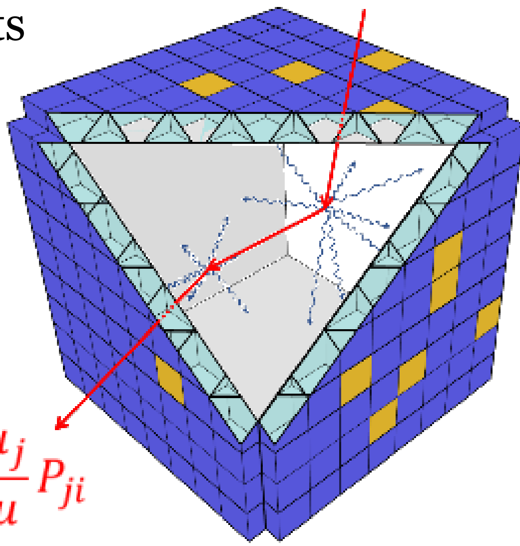
Our two-pronged approach

Two prototype paths: monolithic vs. optically segmented

- surround cube of scintillator with photodetectors: 64*6 = 384 channels
- use individual photon time/position hits in a complex likelihood function to reconstruct events

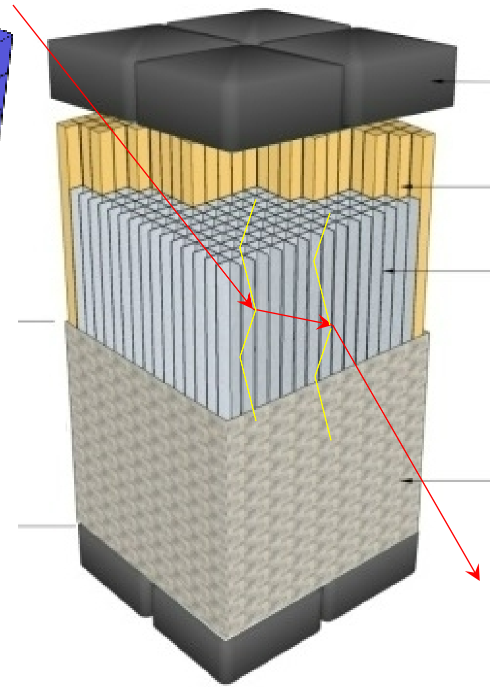
- optically segment into scintillator bars with photodetectors on the ends
- reduce channel count to 64*2 = 128
- simplify reconstruction to linear relations in one dimension

Easy detector, complicated reconstruction



$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_{ji}$$

$$P_{ji} = \frac{\Omega_{jk(i)}Q_{k(i)}e^{\frac{-d_{jk(i)}}{\lambda}}}{4\pi\sum_k \frac{\Omega_{jk}}{4\pi}Q_k e^{\frac{-d_{jk}}{\lambda}}} f(t_i - t_j - \frac{d_{jk(i)}n}{c})$$



$$\ln\frac{A_1}{A_2} = \frac{L}{\lambda} - \frac{2z}{\lambda}$$

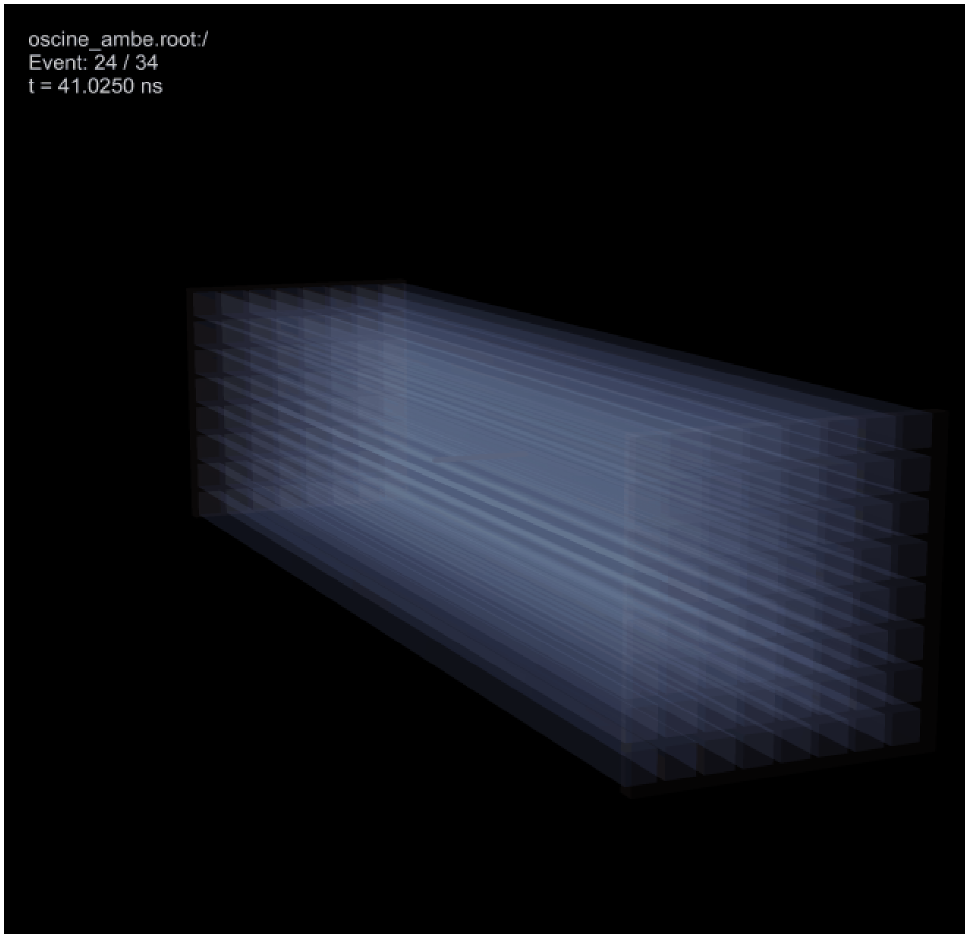
$$t_1 - t_2 = \frac{2z}{v} - \frac{L}{v}$$

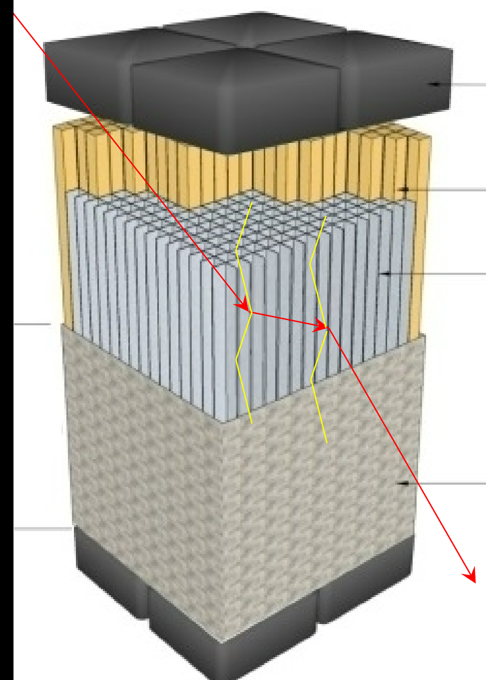
Complicated detector, easy reconstruction

Our two-pronged approach

Two prototype paths: monolithic vs. optically segmented

- optically segment into scintillator bars with photodetectors on the ends
- reduce channel count to 64*2 = 128
- simplify reconstruction to linear relations in one dimension





$$\ln\frac{A_1}{A_2} = \frac{L}{\lambda} - \frac{2z}{\lambda}$$

$$t_1 - t_2 = \frac{2z}{v} - \frac{L}{v}$$

Complicated detector, easy reconstruction

Multiple, modular components

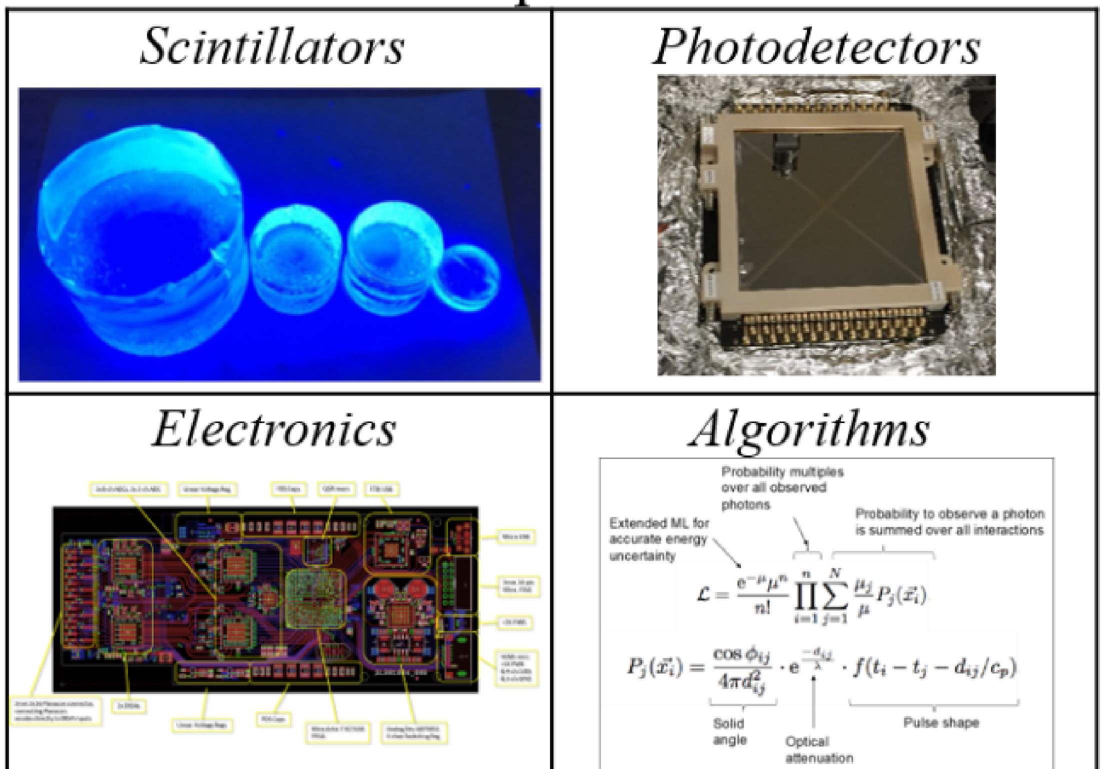
System depens on four main components

- exploring improvements in all four to be incorporated into prototypes
- characterizations are on-going

Components

Fast, bright organics, pref. with PSD

Fast, high PDE, scalable



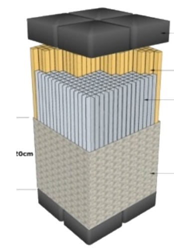
Fast, scalable

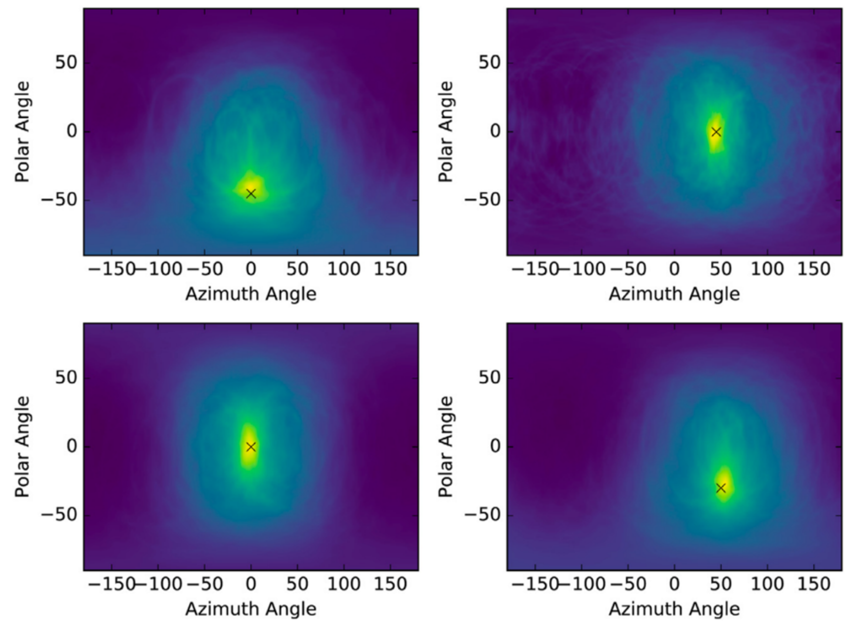
O(1cm/1ns)

Example optically-segmented reconstruction

Geant4 optical simulation results

- Geant4 optical transport for several different combinations of photodetector, scintillator, and reflector materials
  - air gap gives best results
  - absolute values likely best case (mostly due to polish): ~5 mm
- particle transport in MCNPX/Polimi with smearing of timing, position
  - ^{252}Cf, 1 meter away
  - 20x20x20 cm with 1x1 cm pixels
- conclusion: with 1x1 cm pixels imaging is doable in a simulated world

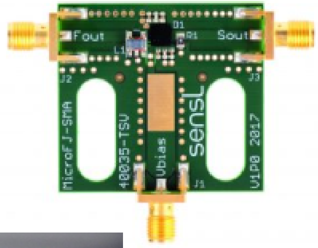




K. Weinfurther, J. Mattingly, K. Brubaker, and J. Steele. "Model-based design evaluation of a compact, high-efficiency neutron scatter camera" *Nucl. Instr. And Meth. A* 883 (2018) 115-135

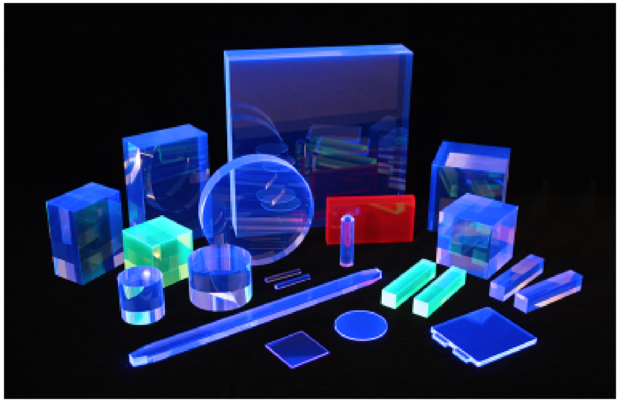
Experimental Single-bar testing

What components to use in prototype?



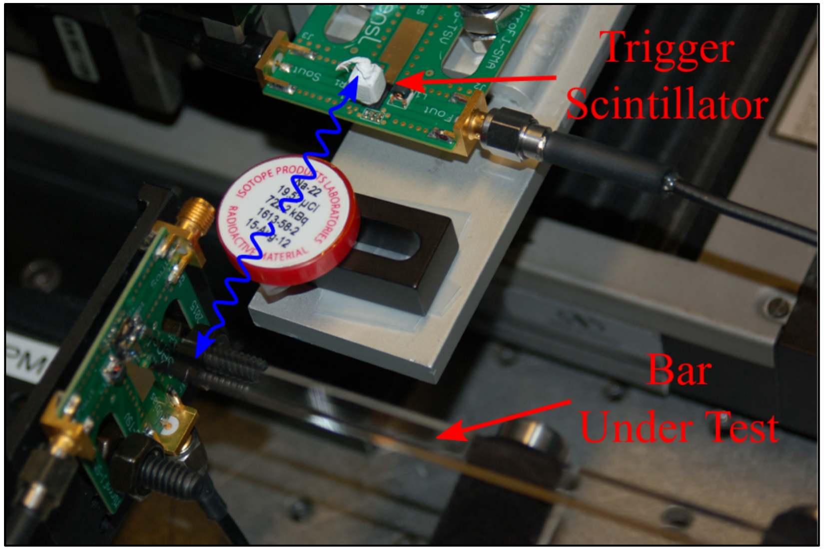
- photodetector: J-series from SensL
  - OS is not overly impacted by high dark noise
  - PDE peaks at 50%
  - TTS ~100 ps
- data acquisition: drs4 evaluation board from PSI
- scintillator/reflector material?
  - top three scintillators based on parameters from Eljen + PSD-capable EJ276
  - choose top two pure diffuse/specular materials: Teflon/ESR

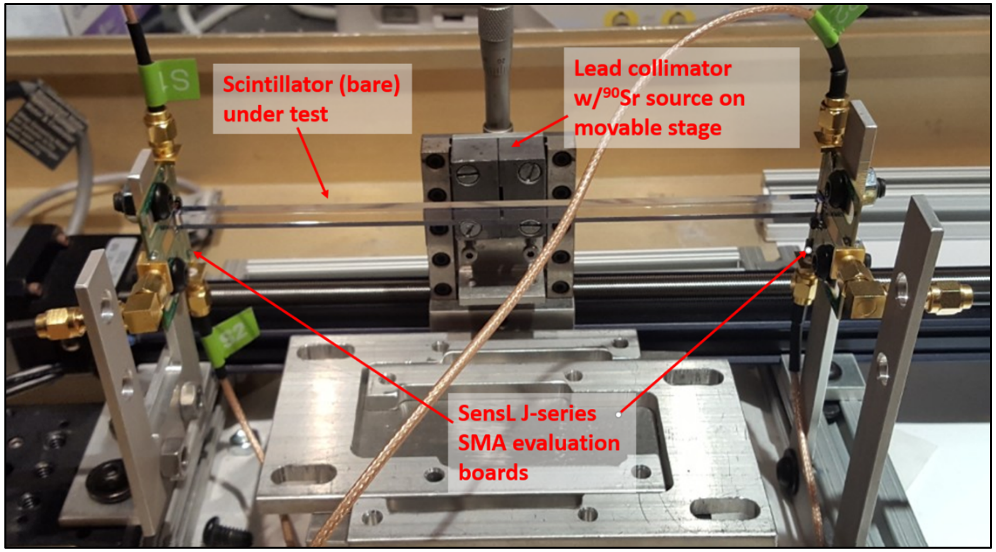
PAUL SCHERRER INSTITUT PSI



Scintillator	t_R (ns)	λ (cm^{-1})	N_e (MeV^{-1})	N_d (MeV^{-1})	
				J-series	C-series
EJ200	0.9	380	10,000	4,905	3,946
EJ204	0.7	160	10,400	5,084	4,103
EJ208	1.0	400	9,200	4,378	3,519
EJ230	0.5	120	10,200	4,557	3,664
EJ232	0.35	-	8,400	3,679	2,924
EJ260	-	350	9,200	3,470	2,767
EJ262	-	250	8,700	3,548	2,835
EJ276	-	-	8,600	4,203	3,381
EJ276G	-	-	8,000	2,991	2,384

Experimental Single-bar testing





@SNL

- tagged Na-22 scan
- trigger is on 5x5x5 mm Stilbene crystal (no threshold effects on test bar)
- provides timing, z-position, and energy resolution measurements

@UH

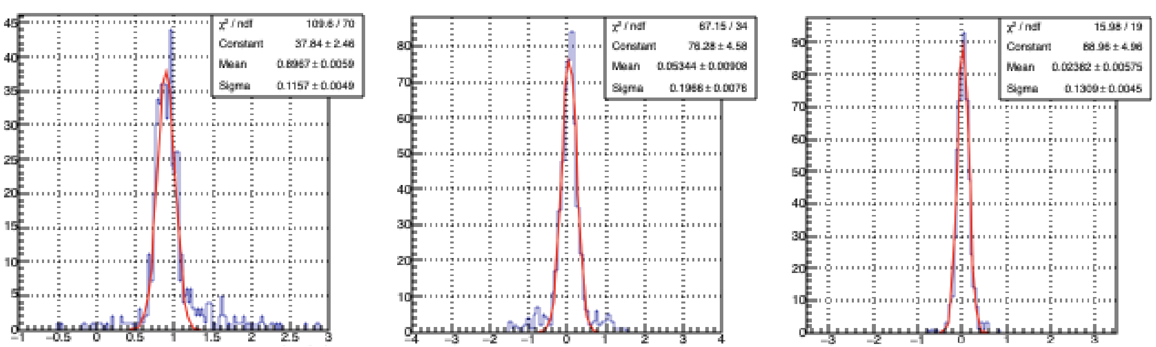
- collimated Sr-90 scan
- trigger is on one end of test bar
- provides z-position and energy resolution measurements
- double bar measurements provides limited timing measurements

Combination provides cross check and critical systematic errors

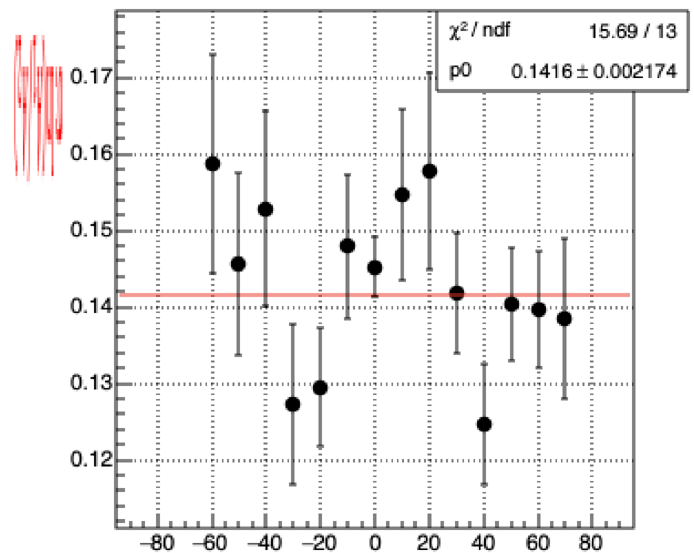
Experimental Single-bar testing

Analysis Details

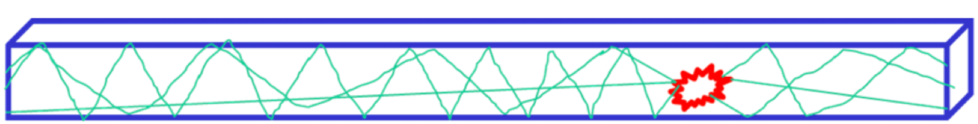
- for each scan position, the responses are fit with Gaussian distribution
- mean (μ) as a function of position fit to 1st-order polynomial
- sigma (σ) as a function position fit to 0th-order polynomial
- resolution defined as the constant of the σ fit divided by slope of μ fit
- measurements combined to form best linear unbiased estimate (*BLUE*)



$(t_1+t_2)/2$ 1 − 2 $\ln(A_1/A_2)$



position (mm)



Experimental Single-bar results - summary

Scintillator	σ_t (ps)	σ_z (mm)		σ_E/E (%)	
		^{22}Na	^{90}Sr	^{22}Na	^{137}Cs
EJ-200, bare	155±2	13.35	14.27	16.7	14.1
Teflon	154±3	10.29	7.65	14.5	15.8
ESR	145±3	11.14	12.09	16.6	12.2
EJ-204, bare	136±3	10.08	10.67	15.7	14.7
Teflon	**142±2**	**8.06**	**6.54**	**13.1**	**14.3**
ESR	125±3	8.59	9.64	17.6	12.2
EJ-230, bare	141±3	9.61	8.86	17.8	15.0
Teflon	142±2	8.39	6.32	22.6	13.9
ESR	156±3	10.17	8.52	23.4	13.0
EJ-276, bare	183±5	12.13	13.51	17.8	14.1
Teflon	171±2	9.29	9.54	16.5	14.1
ESR	177±4	11.65	10.45	15.0	11.3
Syst. error	±7	±0.73	±0.42	±3.5	-

← **Also, highest light output**

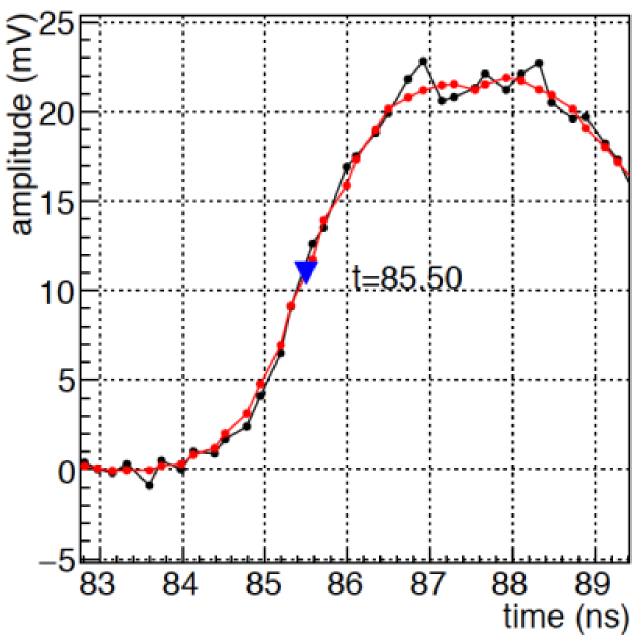
- lowest possible threshold to optimize detection of fission energy neutrons
- estimate 30 keVee with 7 mV electronics threshold

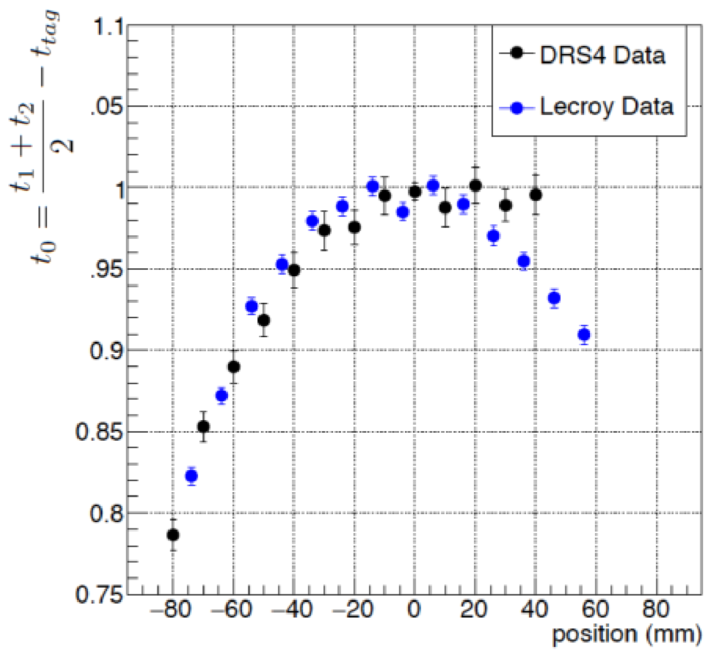
M. Sweany, A. Galindo-Tellez, J. Brown, E. Brubaker, R. Dorrill, A. Druetzler, N. Kaneshige, J. Learned, K. Nishimura, and W. Bae. "Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout" *Nucl. Instr. And Meth. A 927 (2019) 451-462*

Experimental Single-bar results - event time

~100ps difference in event time for edge/center:

example trace with time pick-off





event time bias with interaction location

M. Sweany, A. Galindo-Tellez, J. Brown, E. Brubaker, R. Dorrill, A. Druetzler, N. Kaneshige, J. Learned, K. Nishimura, and W. Bae. "Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout" *Nucl. Instr. And Meth. A 927 (2019) 451-462*

First OS prototype @UH

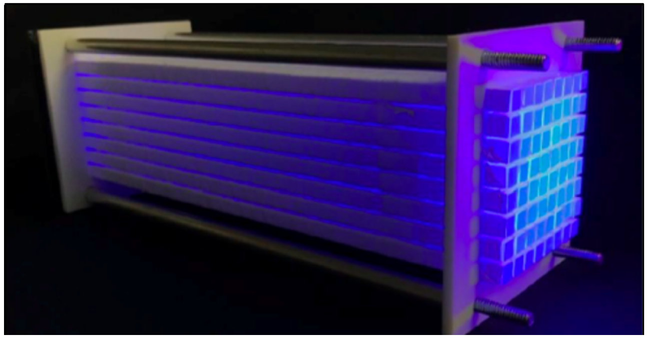
calibration shows decreased performance compared to single bar results

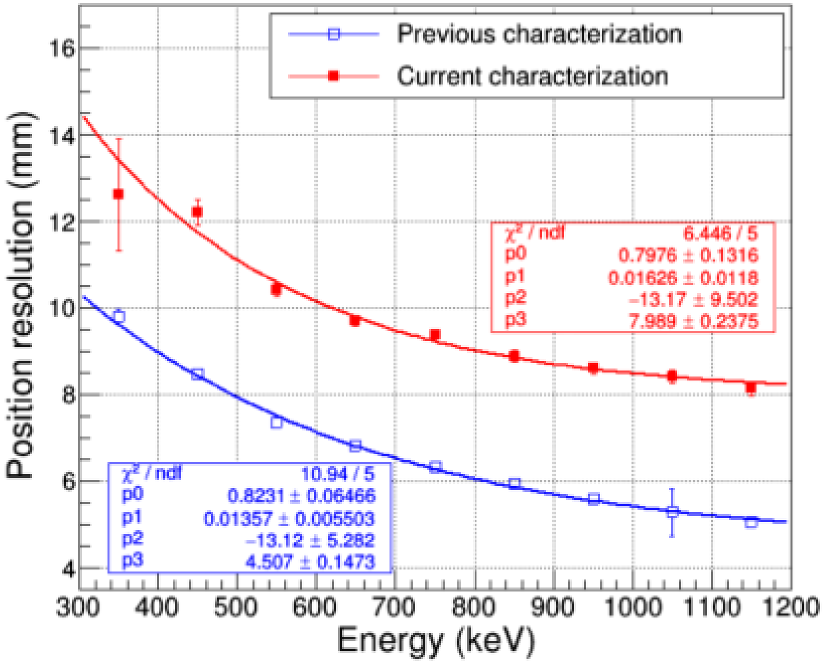
Several possibilities may account for this:

- different electronics, sampling at 2.7 GHz rather than 5 GHz
- silicone coupling pads between scintillator/SiPM rather than optical grease
- electronic cross talk in J-series array
- non-uniform bar spacing/Teflon-wetting due to mechanical instability

Bar ID	σ_z^A (mm)	σ_z^t (mm)	σ_z (mm)
16	15.67 ± 0.08	37.49 ± 0.34	14.46 ± 0.10
24	14.32 ± 0.07	43.58 ± 0.38	13.60 ± 0.11
32	16.25 ± 0.13	21.99 ± 0.25	13.07 ± 0.05
40	12.35 ± 0.06	41.41 ± 0.45	11.83 ± 0.12
48	8.34 ± 0.06	31.56 ± 0.59	8.06 ± 0.14
56	8.91 ± 0.07	33.28 ± 0.56	8.61 ± 0.14
64	8.63 ± 0.07	27.09 ± 0.41	8.23 ± 0.11

A. Galindo-Tellez, K. Keefe *et al.*
***arXiv:2102.02951* (2021)**

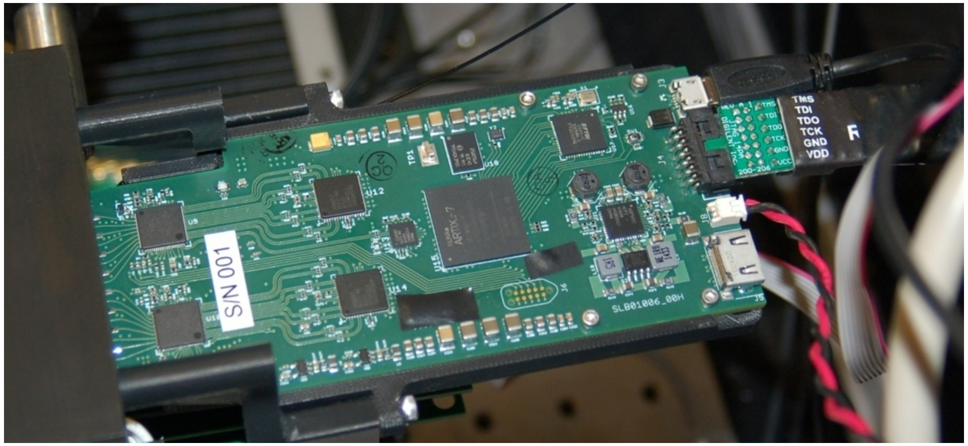


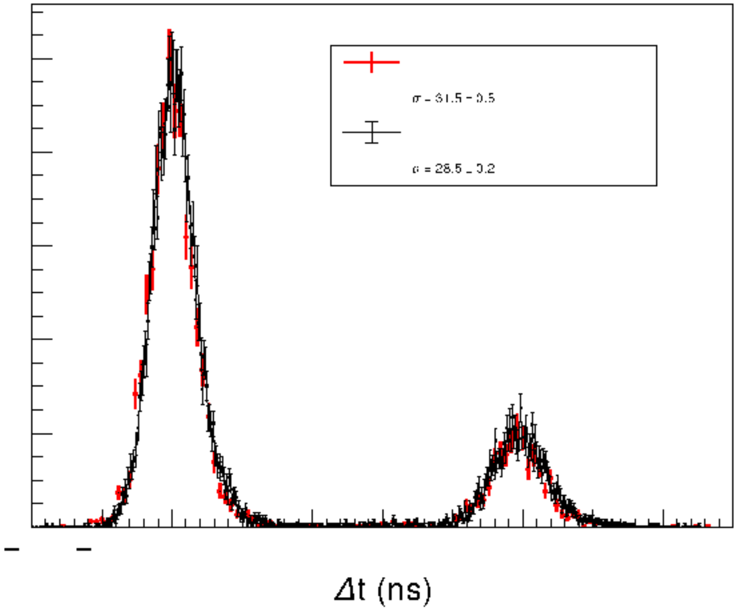


Electronics solution?

SCEMA digitizer board

- drs4 chip from PSI capable of 700 MS/s - 5 GS/s waveform sampling: e-kit provides 4 channel solution
- multi-year effort to develop 16-channel drs4-based data acquisition board for monolithic
- comparison of single photon time distribution from PMT-210 (TTS =28 ps) with LeCroy Waverunner 40 GS/s scope acquisition



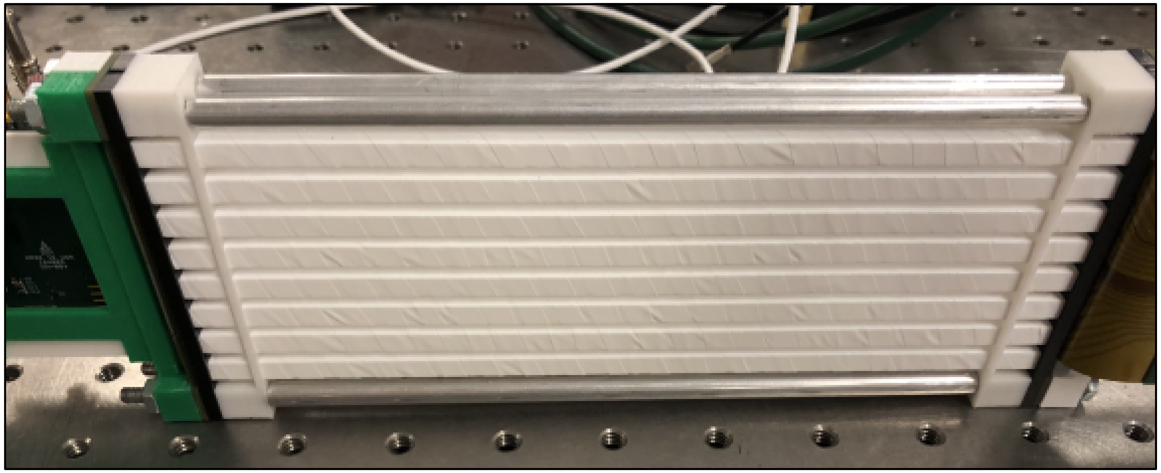


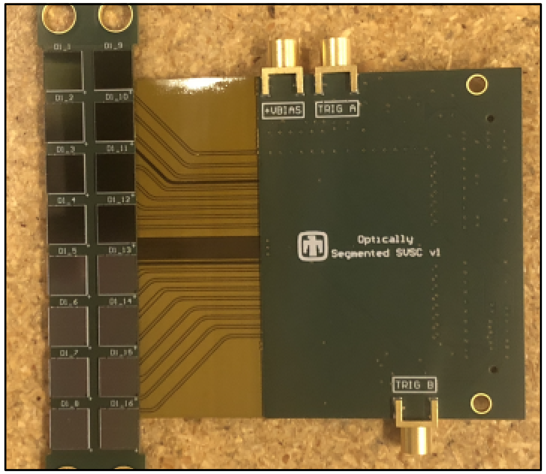
J. Steele, J.A. Brown, E. Brubaker, K. Nishimura. "SCEMA: a high channel density electronics module for fast waveform capture" *Journal of Instrumentation* 14 (2019) P02031.

Second OS prototype @ SNL

Modular design solves many if not all of 1st prototype issues

- 2x8 array allows access to each bar for ^{22}Na calibration scans
- custom 2x8 SiPM array couples to SNL developed 16-channel SCEMA electronics utilizing 5 GHz DRS4 digitizers used in single bar scans[6]
- improved mechanical stability reduces potential for mis-alignment and non-uniform Teflon wetting
- final system will consist of 4 modules, for a complete 8x8 array
- reduced electrical cross talk

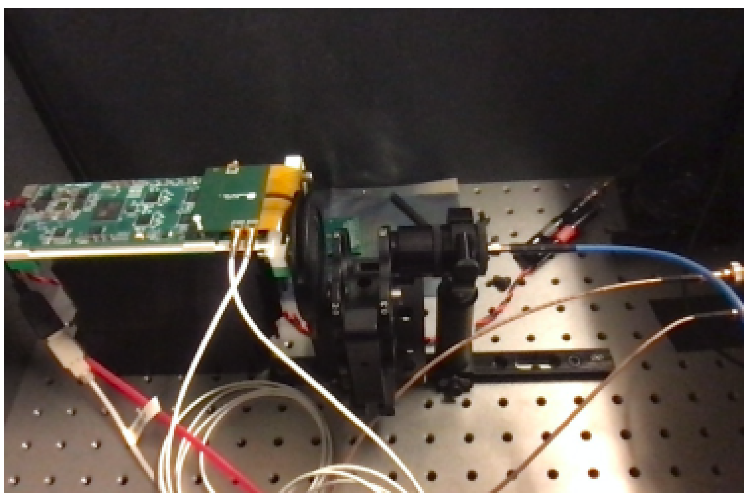


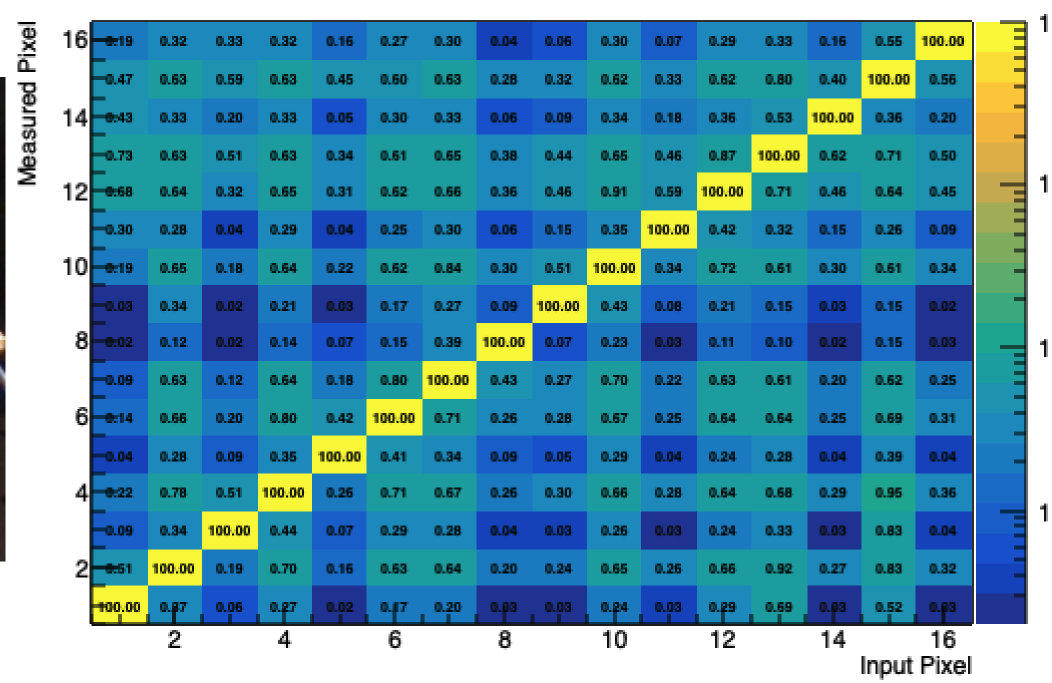


Second OS prototype @ SNL

Electrical cross talk:

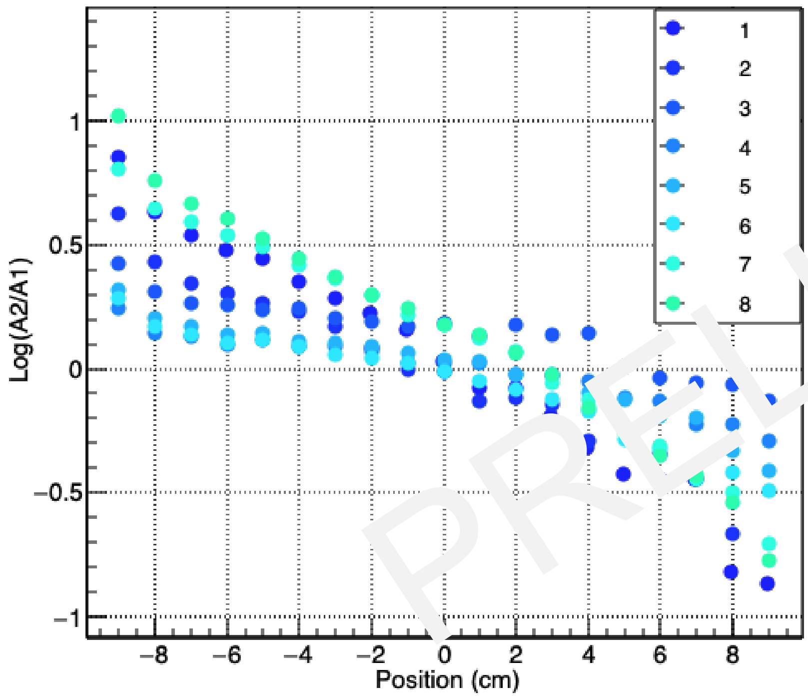
- Laser scan indicates up to 1% of input pixel pulse height measured in other pixels, compared to up to 16% for first prototype
- No obvious dependence dictated by wiring in connector

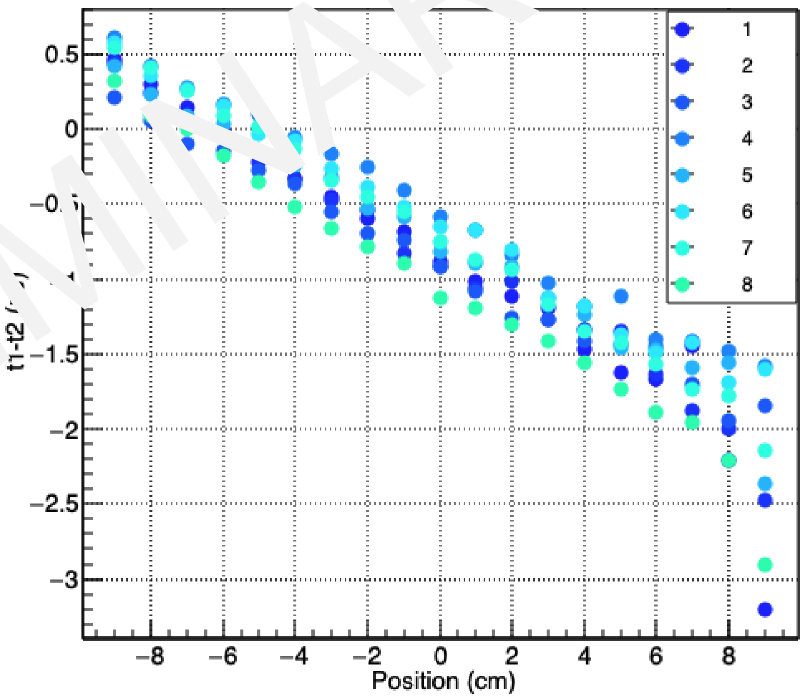




Preliminary calibration data, 300-400 keVee

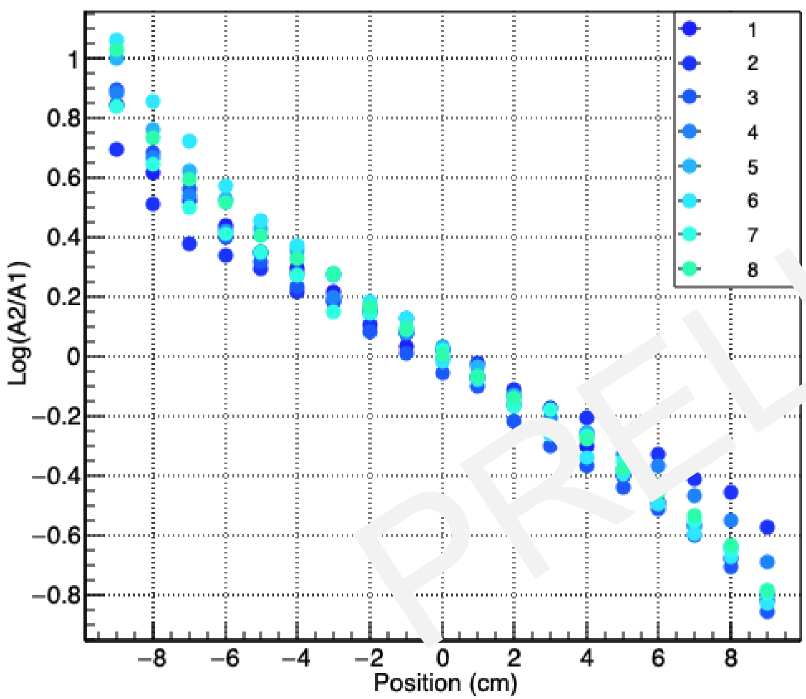
0.5 mm thick silicone optical coupling sheets

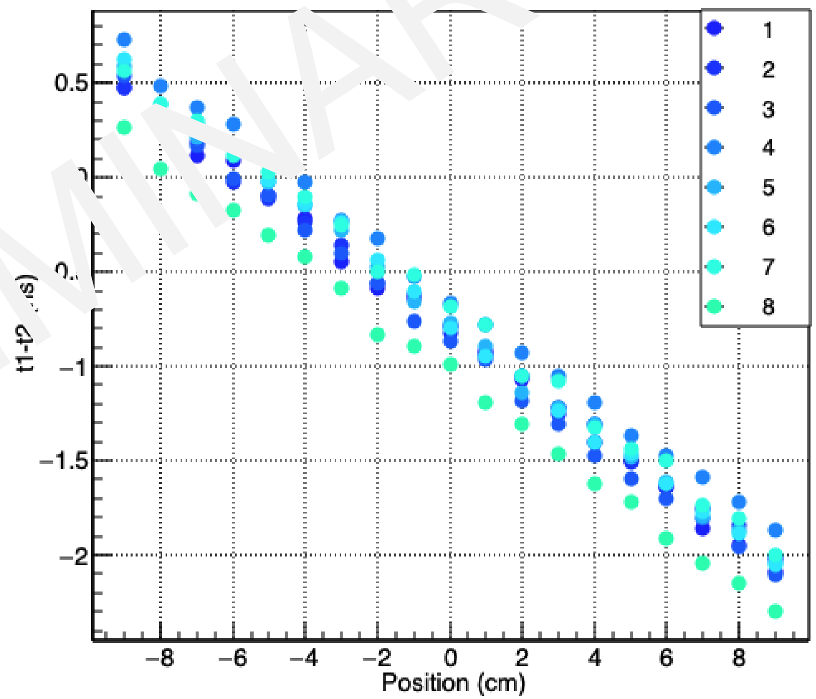




Preliminary calibration data, 300-400 keVee

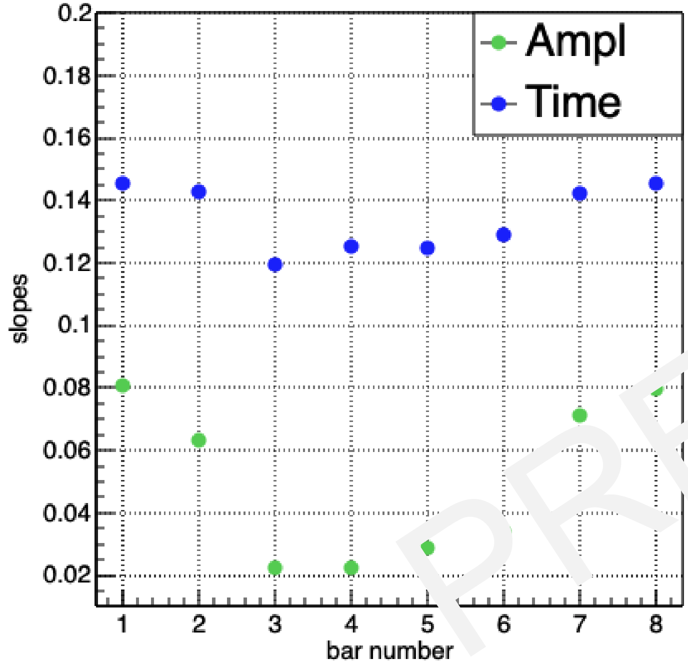
Optical grease



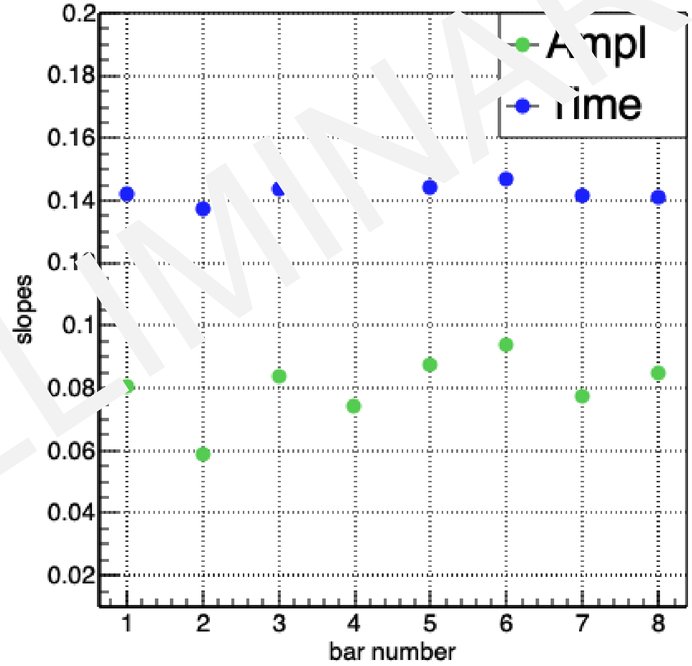


Preliminary calibration data, 300-400 keVee

optical pads



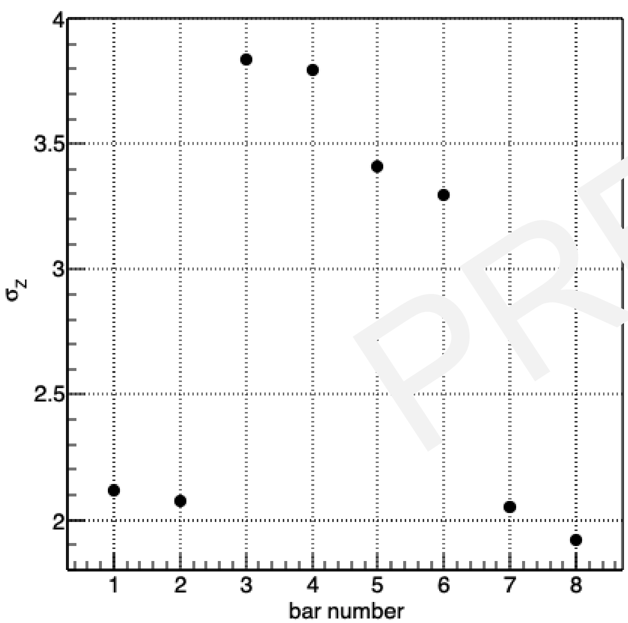
optical grease



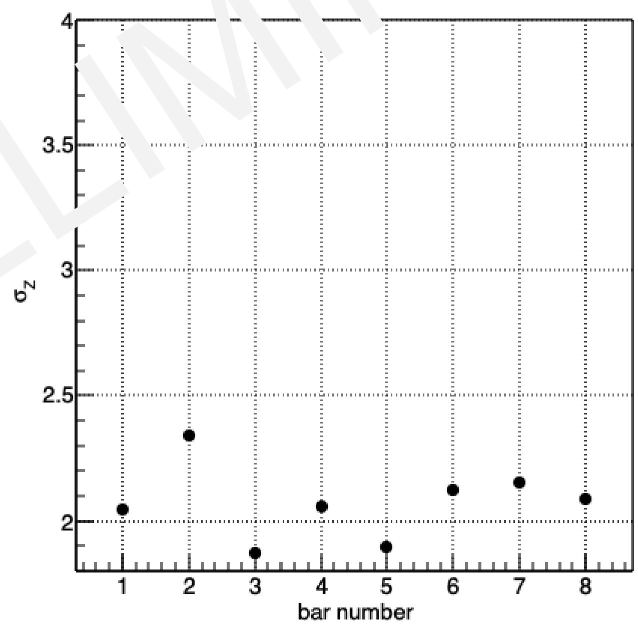
Preliminary calibration data, 300-400 keVee

Some interesting features

- Two populations in position resolution with optical pads
  - Larger slopes in LAR, indicating greater attenuation?
  - Larger σ, indicating less light overall?
- Position resolution using time difference is much larger than single bar result
- Optical grease results in more uniform performance



optical pads



optical grease

Summary

- neutron kinematic imaging can provide improved radiological localization capabilities in unknown background environments, and provide spatial characterization of SNM
- the Single Volume Scatter Camera promises to address the SWaP and detection efficiency drawbacks of current neutron kinematic imaging systems
- required technical capabilities of detector components has recently been achieved
- we are conducting detailed characterizations of components, implementing into two prototype systems
- the two systems have been assembled, undergoing further system-wide characterizations
- second prototypes undergoing characterization now

Thank you!

The authors would like to thank the US DOE National Nuclear Security Administration, Office of Defense Nuclear Non-proliferation for funding this work.

Questions?

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: https://doi.org/10.1016/j.nima.2017.11.025
- SCEMA: A high channel density electronics module for fast waveform capture: https://doi.org/10.1088/1748-0221/14/02/P02031
- Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout: https://doi.org/10.1016/j.nima.2019.02.063
- Low energy light yield of fast plastic scintillators: https://doi.org/10.1016/j.nima.2018.10.122
- Proton Light Yield of Fast Plastic Scintillators for Neutron Imaging: https://doi.org/10.1109/TNS.2019.2959979
- Design and Calibration of an Optically Segmented Single Volume Scatter Camera for Neutron: https://arxiv.org/abs/2102.02951)
- Simultaneous measurement of organic scintillator response to carbon and proton recoils (Phys Rev C: accepted)