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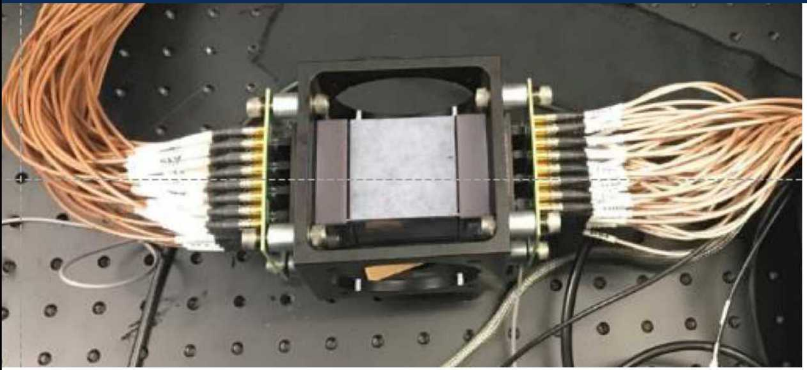

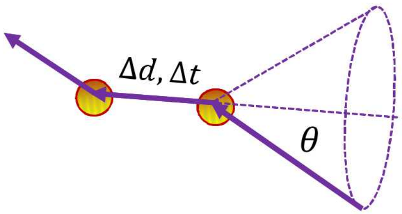

The Single-Volume Scatter Camera Project

Melinda Sweany

October 21st, 2019

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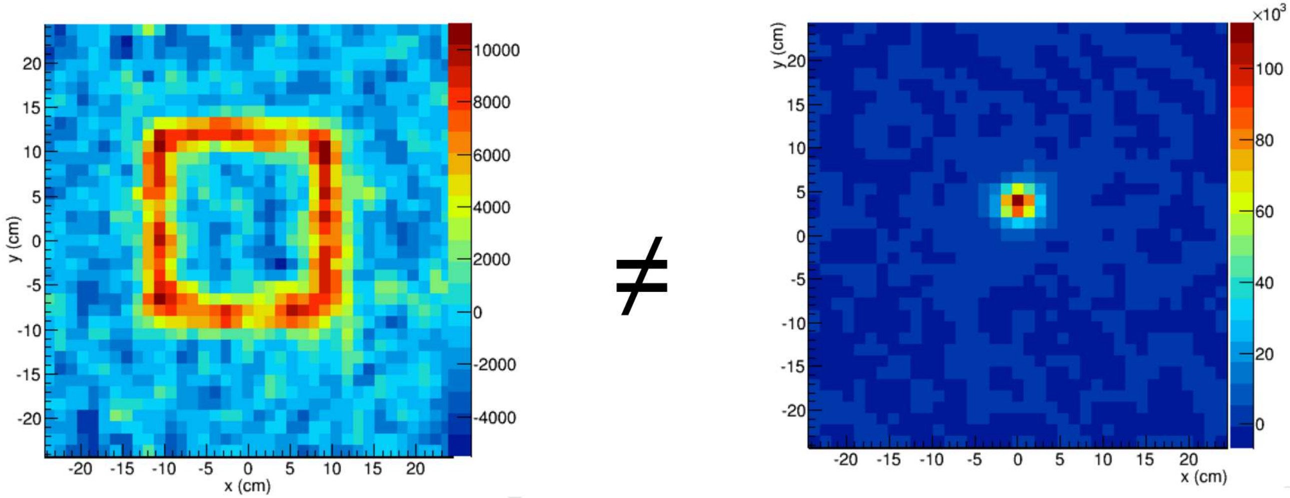
Why neutron imaging?

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:

- kinematic neutron imaging and ~~coded aperture~~

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

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

$$E_n = E'_n + E'_p$$
$$\vec{p}_n = \vec{p'}_n + \vec{p'}_p$$
$$m_n = m_p$$

- square and add:

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

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

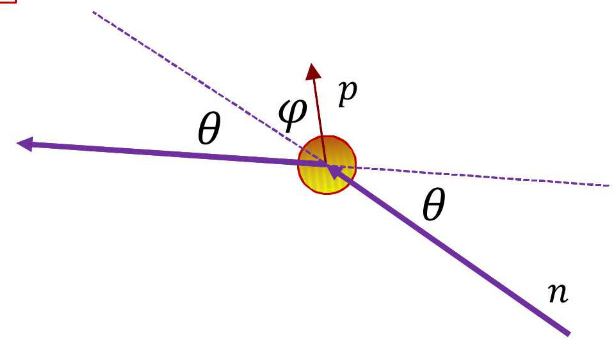
$\sin^2\theta + \cos^2\theta = 1$

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

← COE

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

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



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

How kinematic imaging works - measurement

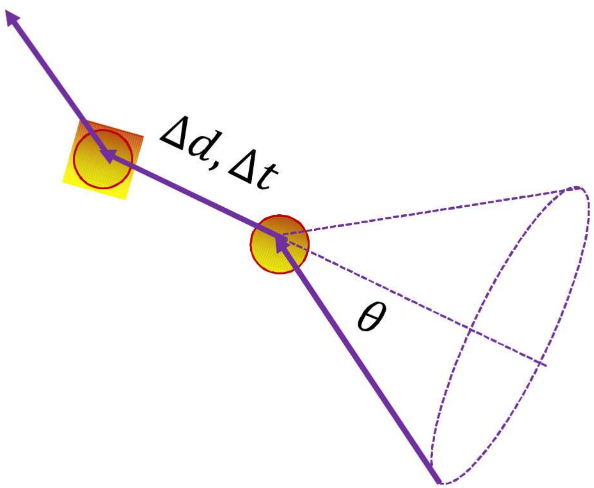
Need the incoming/scattered neutron energy:

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

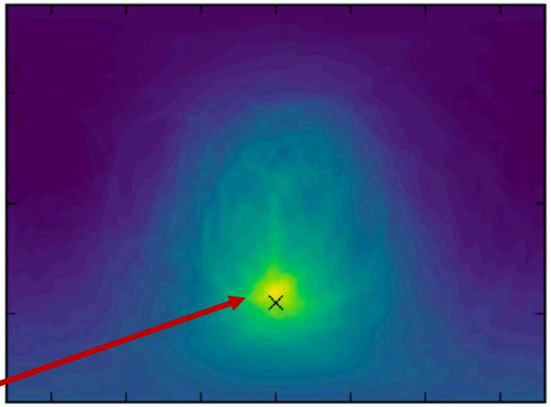
$$E'_n = \frac{1}{2} m_n \left(\frac{\Delta d}{\Delta t}\right)^2$$

- 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

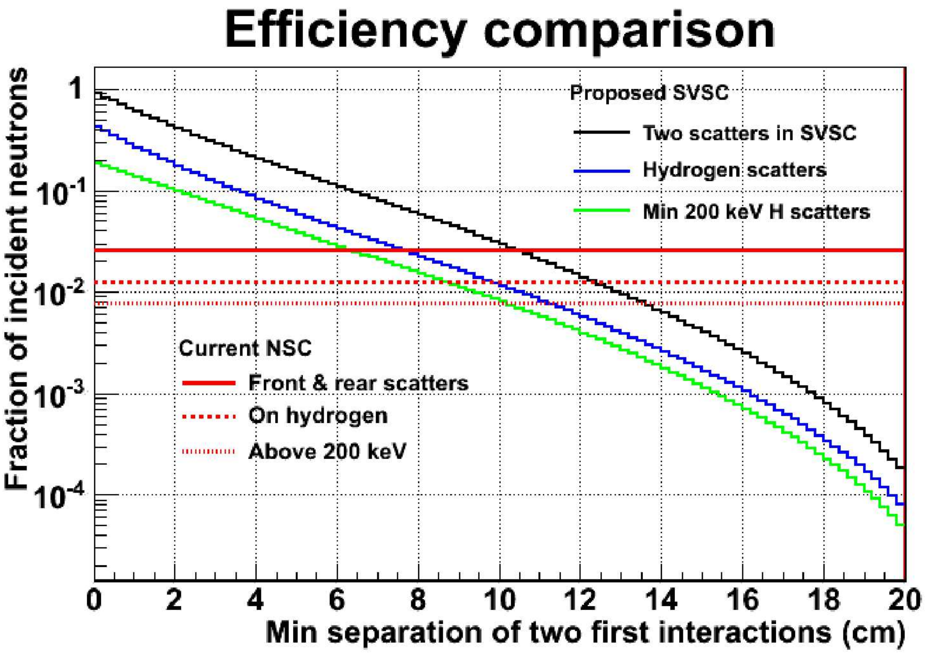
SNL's first neutron scatter camera system:

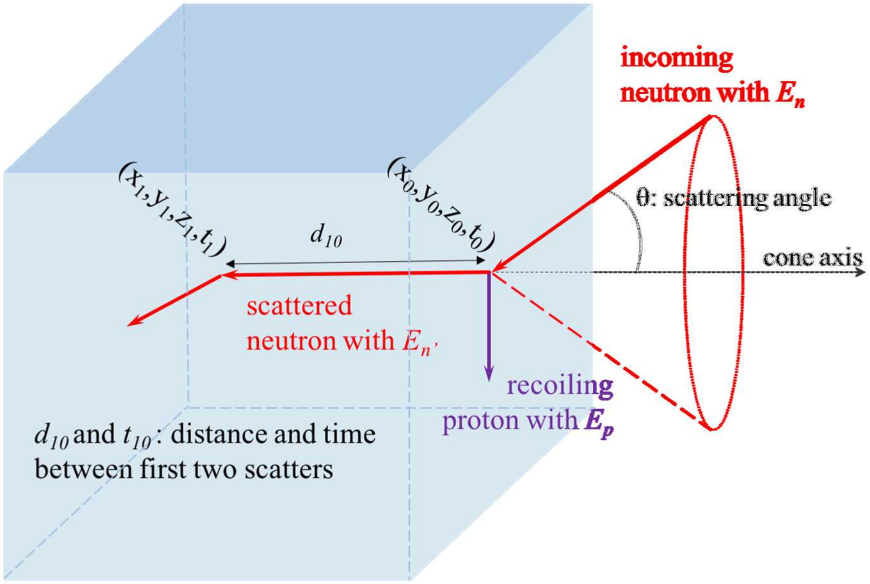
SNL's MINER system with improved SWaP

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!



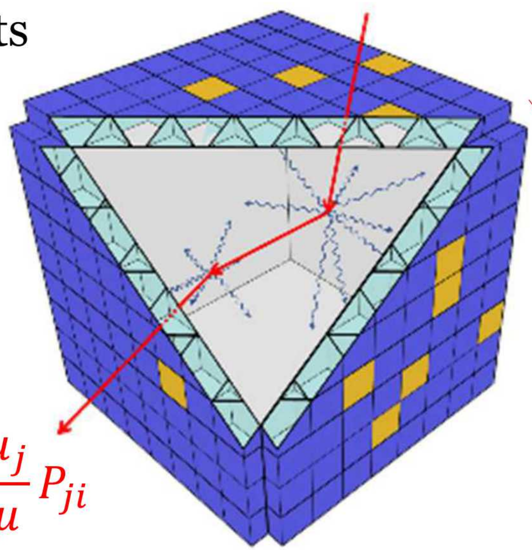


Our two-pronged approach

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

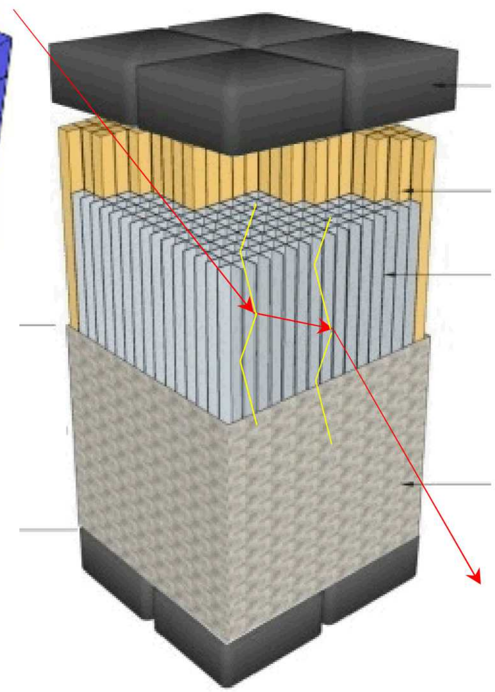
Easy detector, complicated reconstruction



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

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

- 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

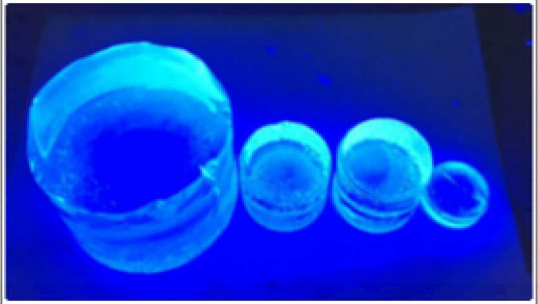
Both systems depend on four main components

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

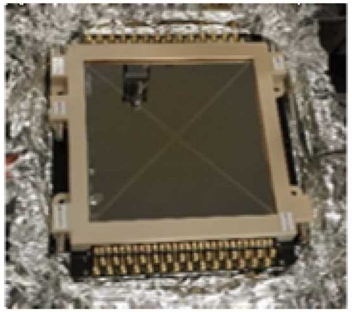
Components

Fast, bright organics, pref. with PSD

Scintillators



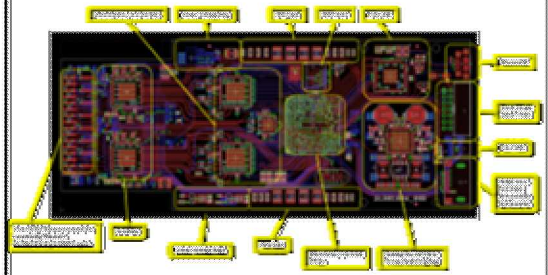
Photodetectors



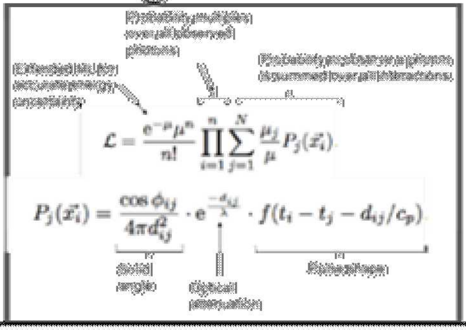
Fast, high PDE, scalable

Fast, scalable

Electronics



Algorithms

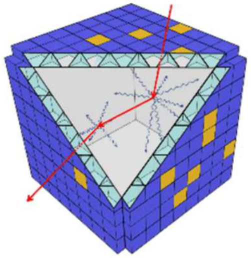


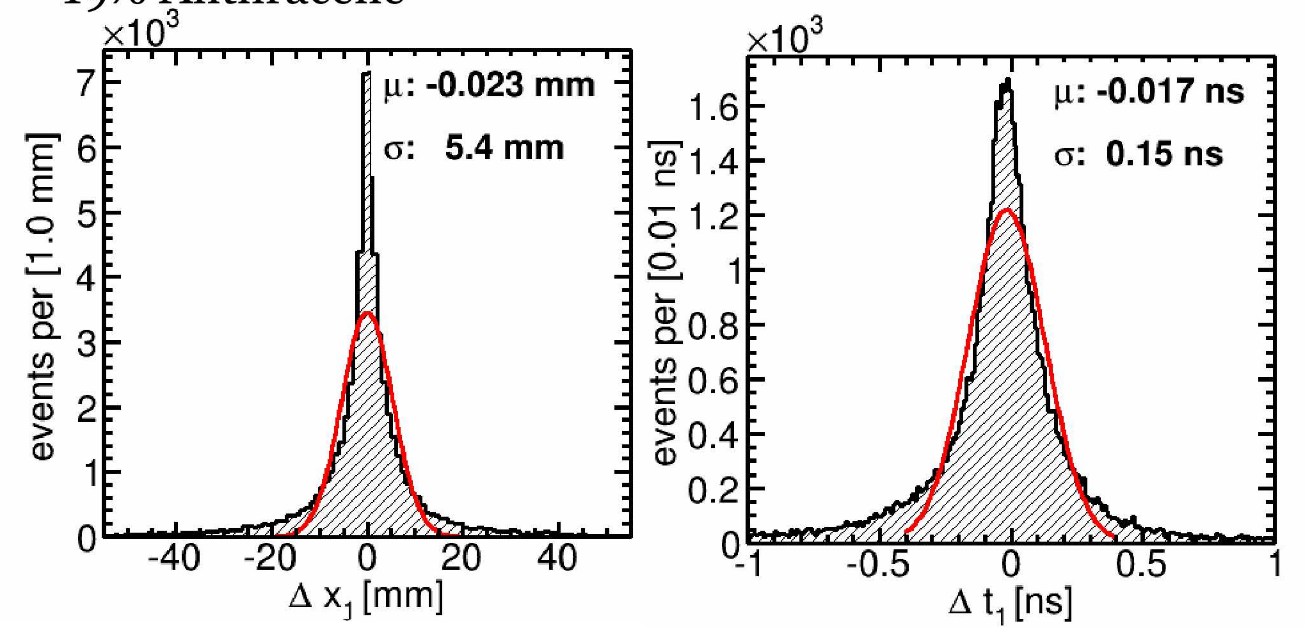
O(1cm/1ns)

Example monolithic reconstruction

Geant4 optical simulation results

- nominal photodetector efficiency, timing, pixelization from Planacon XP85112 MCP-PMT: 25% QE, 35 ps TTS, 6x6 mm
- nominal EJ-232Q0.5% response: 110 ps rise, 360 ps width, LO = 19% Anthracene





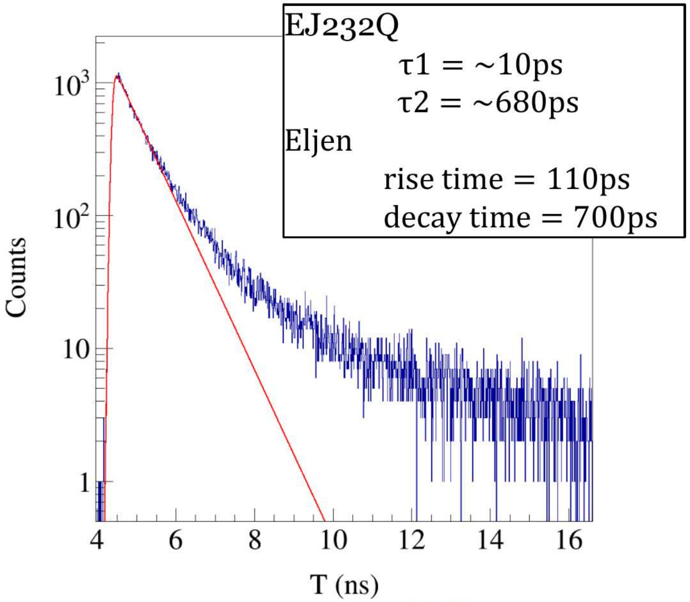
second interaction

J. Braverman, J. Brennan, E. Brubaker, B. Cabrera-Palmer, S. Czyz, P. Marleau, J. Mattingly, A. Nowack, J. Steele, M. Sweany, K. Weinfurther, E. Woods "Single Volume Neutron Scatter Camera for High-Efficiency Neutron Imaging and Scectroscopy" arXiv: 1802.05261 (2018)

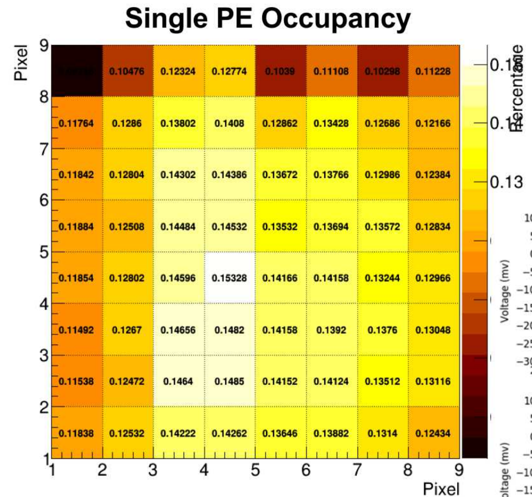
In reality…

Component responses are not always nominal

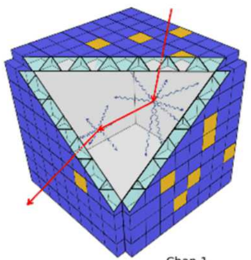
- XP85112 MCP-PMT response
  - QE: variability across pixels ~1%
  - TTS: 80-100 ps (σ)
  - 6x6 mm: not really
- EJ-232Q0.5% response
  - pulse shape, PLY

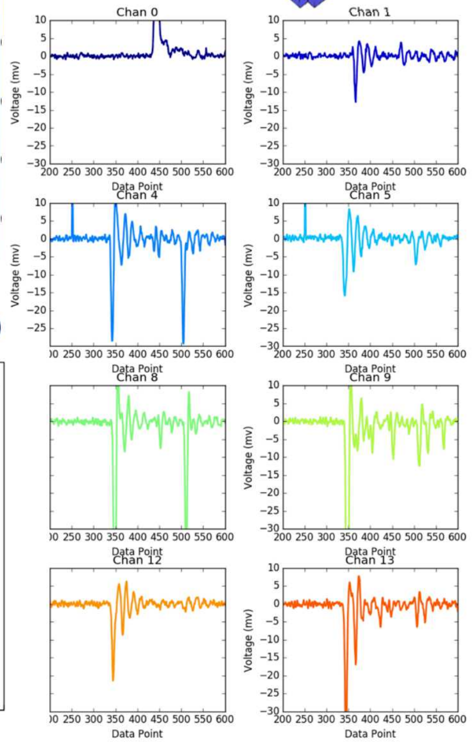


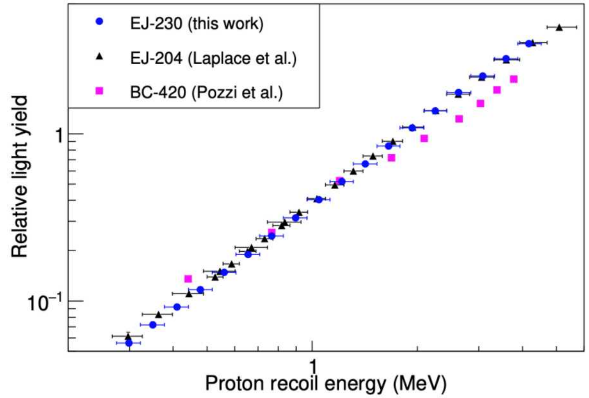
J. Brown



K. Weinfurther (NCSU)







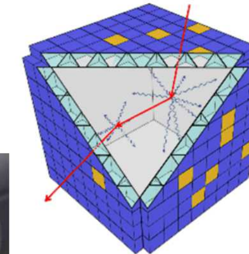
J. Manfredi et al., submitted to TNS

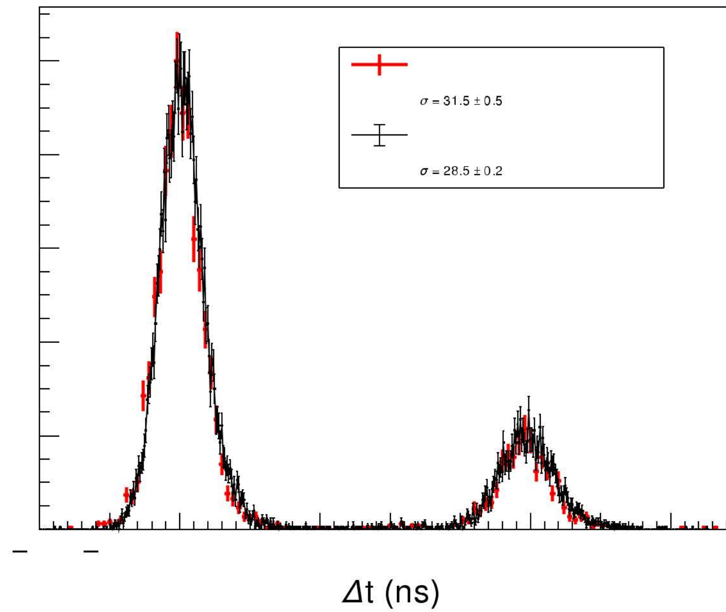
Another large hurdle:

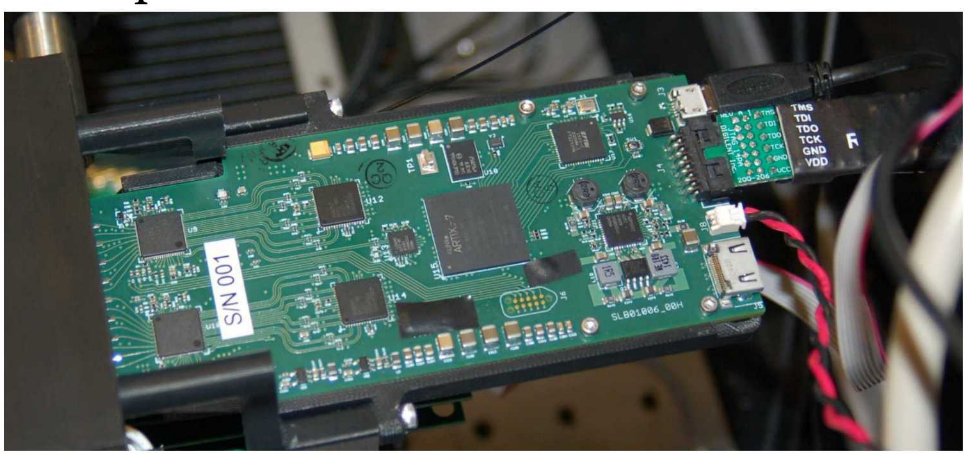
Scalable data acquisition solution?

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

PAUL SCHERRER INSTITUT



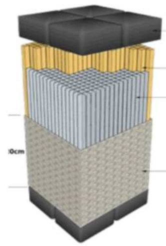




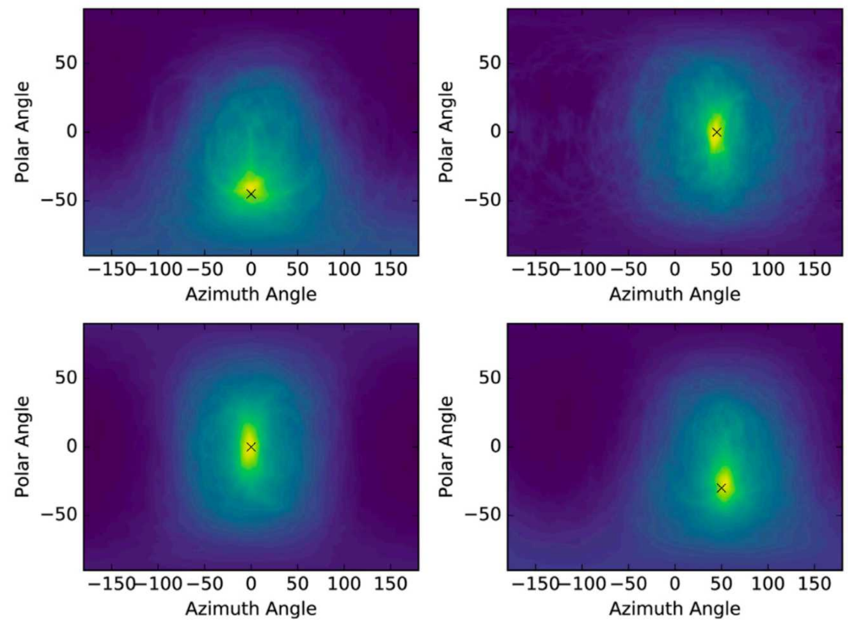
J. Steele, J.A. Brown, E. Brubaker, K. Nishimura. "SCEMA: a high channel density electronics module for fast waveform capture" ***Journal of Instrumentation*** **14 (2019) P02031.**

Example optically-segmented reconstruction

Geant4 optical simulation results



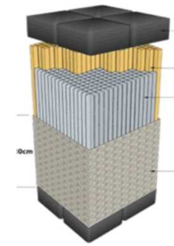
- Geant4 optical transport for several different combinations of photodetector, scintillator, and reflector materials
  - air gap gives best results
  - absolute values likely best case (mostly due to polish): ~5 mm
- particle transport in MCNPX/Polimi with smearing of timing, position
  - ^{252}Cf, 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

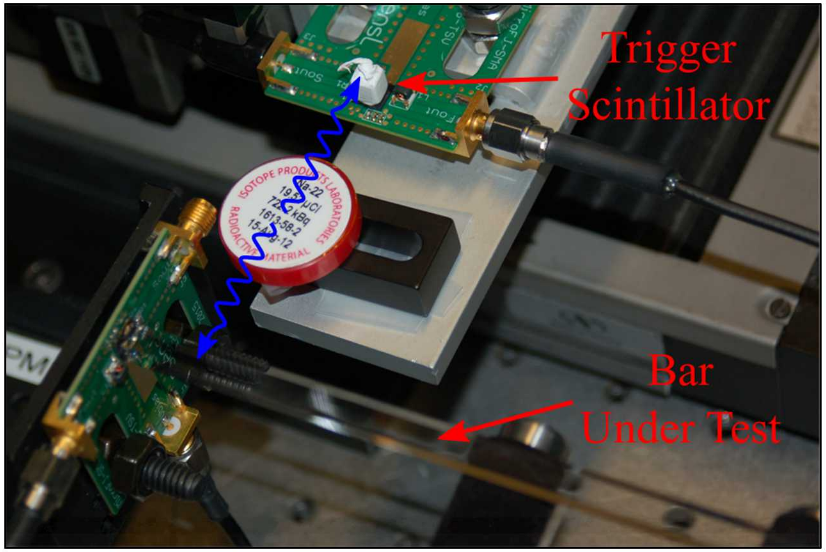
What components to use in prototype?

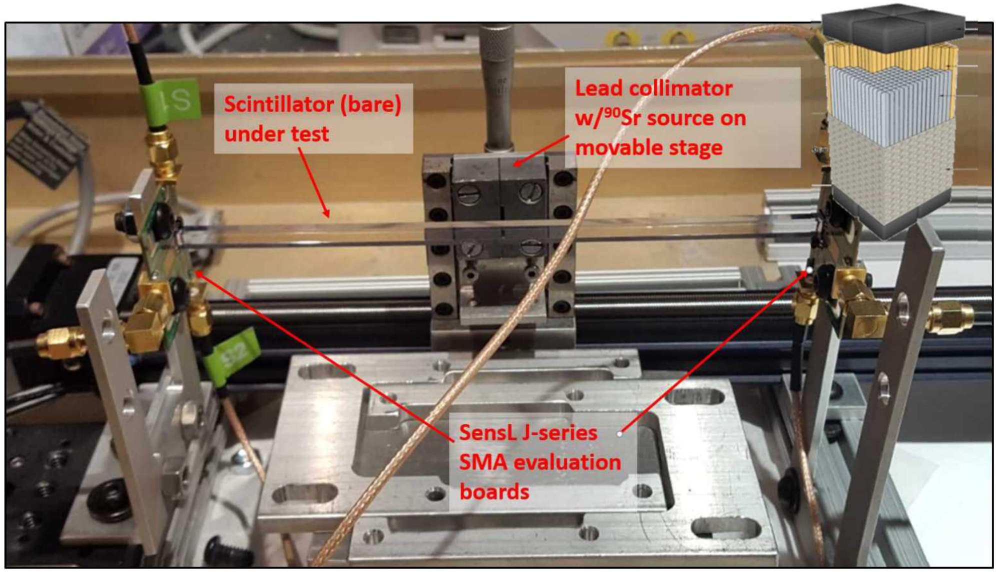


- photodetector: J-series from SensL
  - OS is not overly impacted by high dark noise
  - PDE peaks at 50%
  - TTS ~100 ps
- data acquisition: drs4 evaluation board from PSI
- scintillator/reflector material?
  - top three scintillators based on parameters from Eljen + PSD-capable EJ276
  - choose top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

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

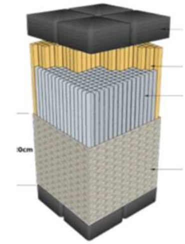
- collimated Sr-90 scan
- trigger is on one end of test bar
- provides z-position and energy resolution measurements
- double bar measurements provides limited timing measurements

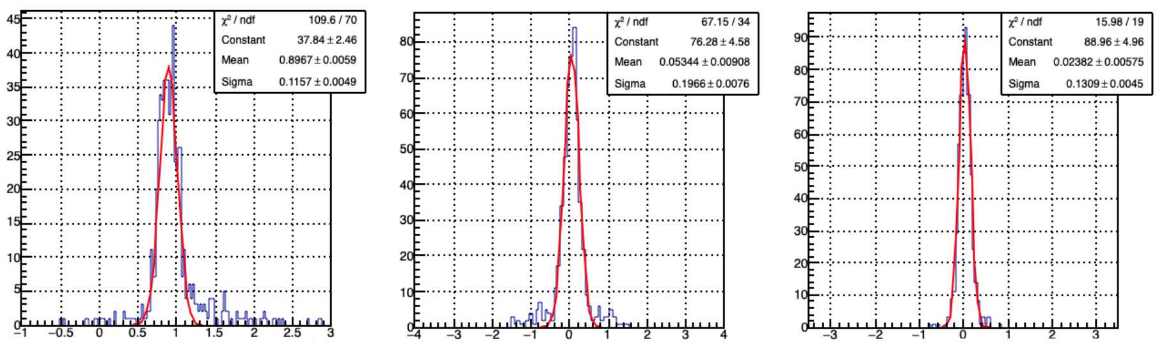
Combination provides cross check and critical systematic errors

Experimental Single-bar testing

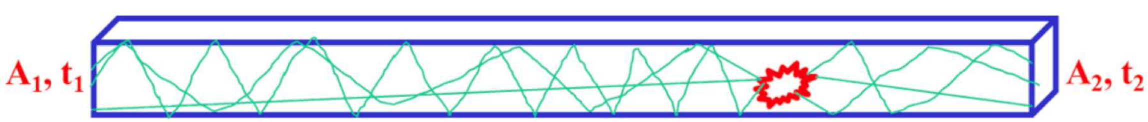
Analysis Details

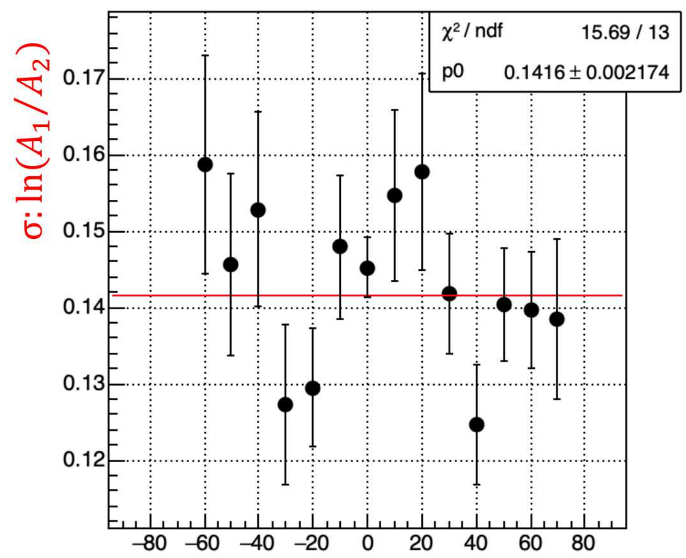
- for each scan position, the responses are fit with Gaussian distribution
- mean (μ) as a function of position fit to 1st-order polynomial
- sigma (σ) as a function position fit to 0th-order polynomial
- resolution defined as the constant of the σ fit divided by slope of μ fit
- measurements combined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





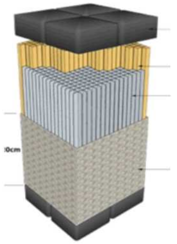
$(t_1+t_2)/2$ $\quad t_1 - t_2$ $\quad \ln(A_1/A_2)$





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	-

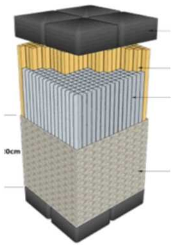
← **Also, highest light output**

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

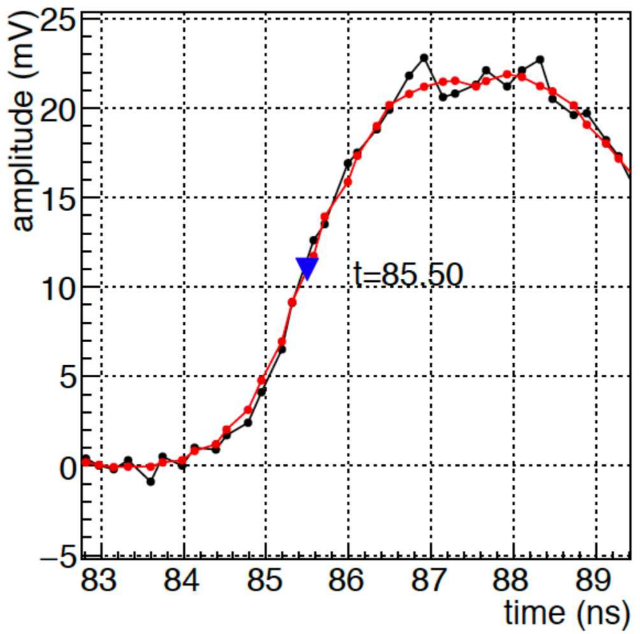
M. Sweany, A. Galindo-Tellez, J. Brown, E. Brubaker, R. Dorrill, A. Druetzler, N. Kaneshige, J. Learned, K. Nishimura, and W. Bae. "Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout" ***Nucl. Instr. And Meth. A 927 (2019) 451-462***

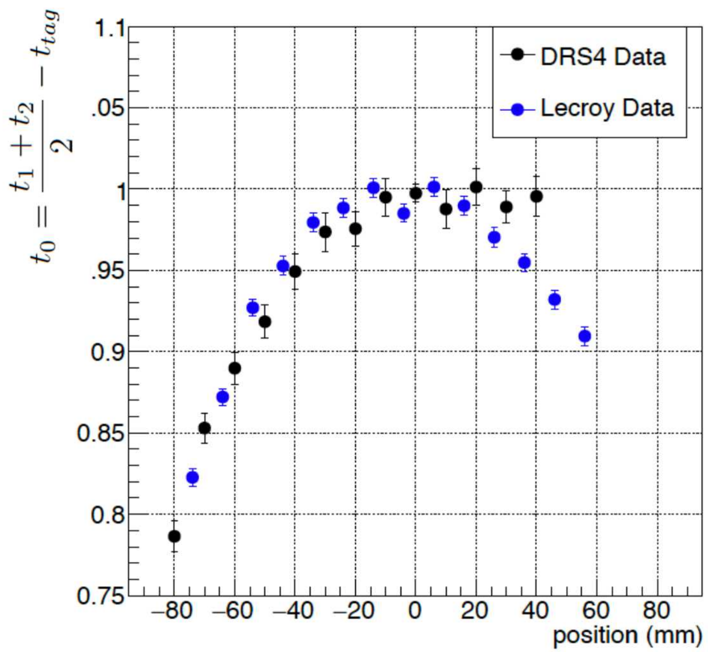
Experimental Single-bar results - event time

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



example trace with time pick-off





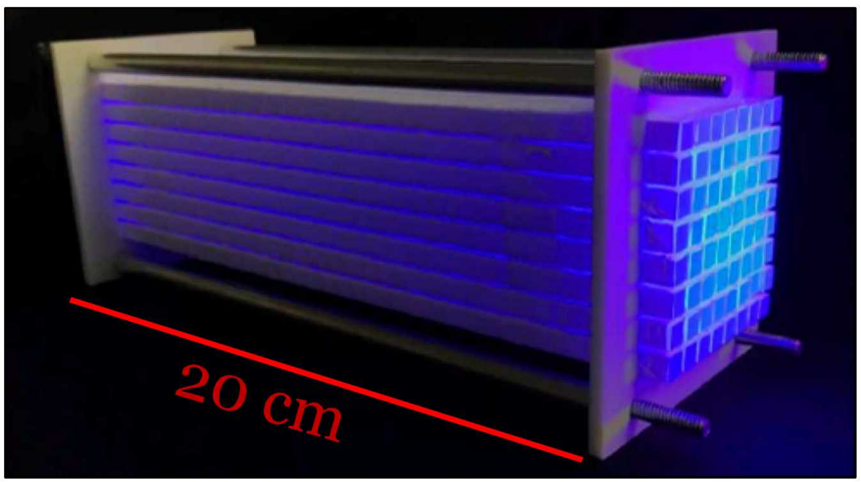
event time bias with interaction location

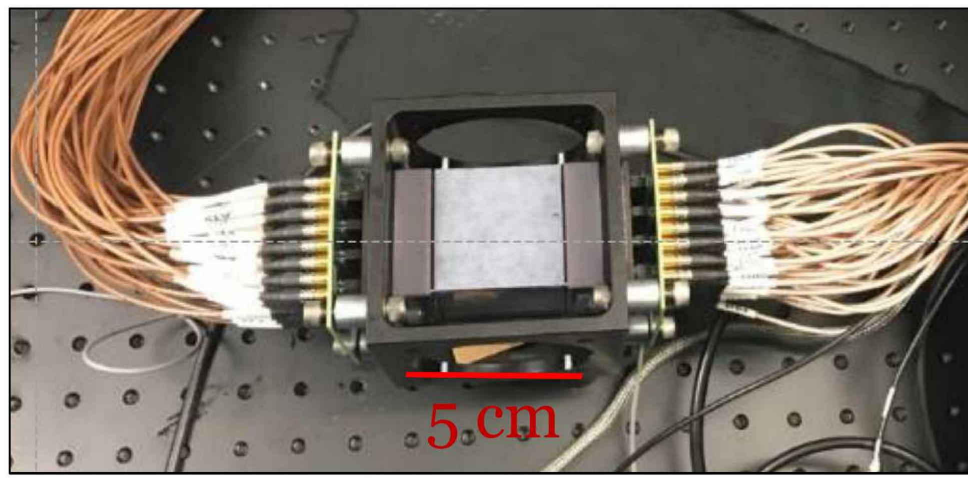
M. Sweany, A. Galindo-Tellez, J. Brown, E. Brubaker, R. Dorrill, A. Druetzler, N. Kaneshige, J. Learned, K. Nishimura, and W. Bae. "Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout" *Nucl. Instr. And Meth. A 927 (2019) 451-462*

Current status

Both prototypes are built and undergoing characterizations

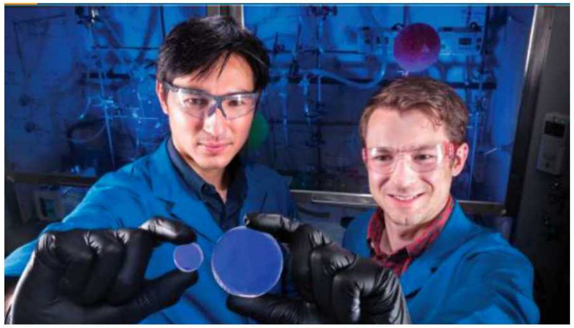
- assembly completed late CY2018
- physics measurements pending electronics characterizations and calibrations
- upgrade path being pursued for both based on component improvements
- upgrades planned for early CY2020



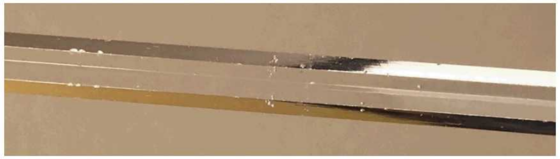


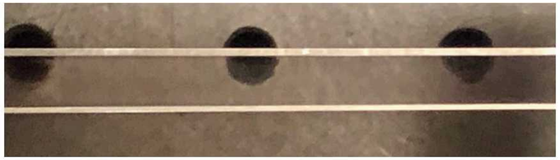
Looking ahead to next prototypes

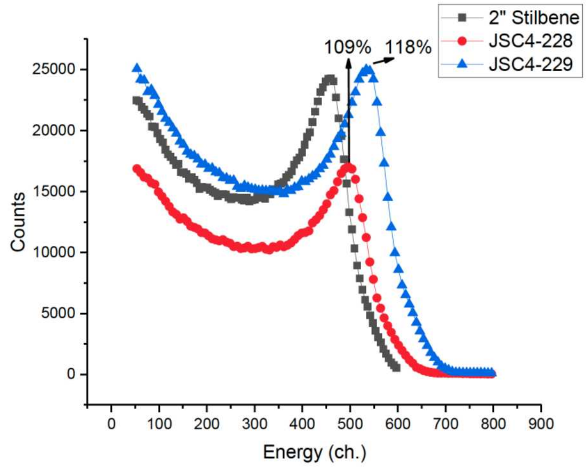
One possibility: using organic glass scintillator

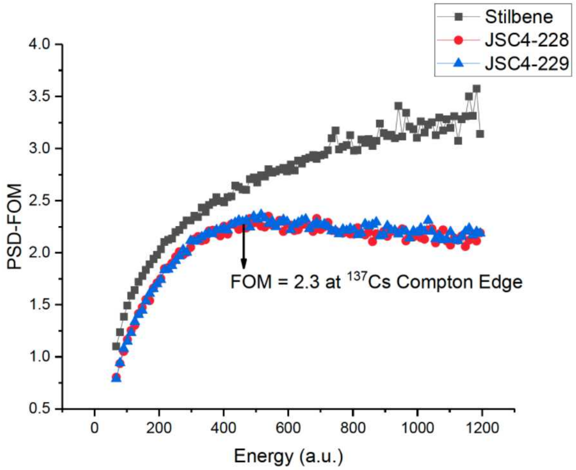


- new scintillator material from SNL scientists (P. Feng and J. Carlson) is very promising alternative
- pure glass material has good LY/PSD/timing
- casting/machining for high aspect ratio is a challenge
- in ~7 months, SNL chemists have solved many machining and bubble problems, re-evaluating PSD in new formulations







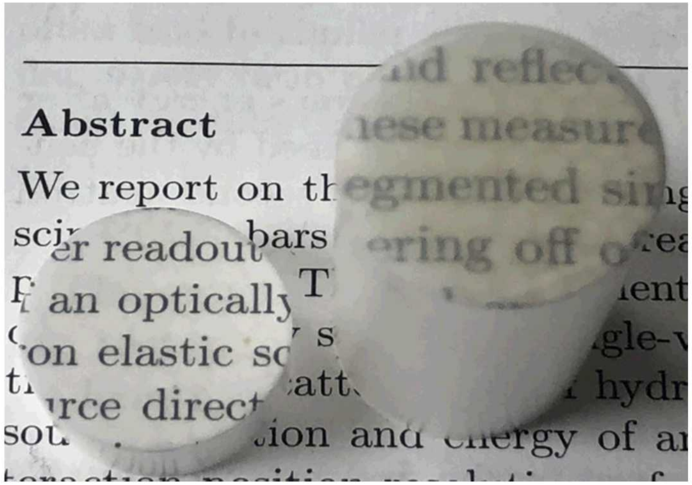


J. Carlson and P. Feng. "Melt-cast organic glasses as high-efficiency fast neutron scintillators" ***Nuclear Instruments and Methods in Physics A*** **832 (2016) 152-157**

Looking further ahead

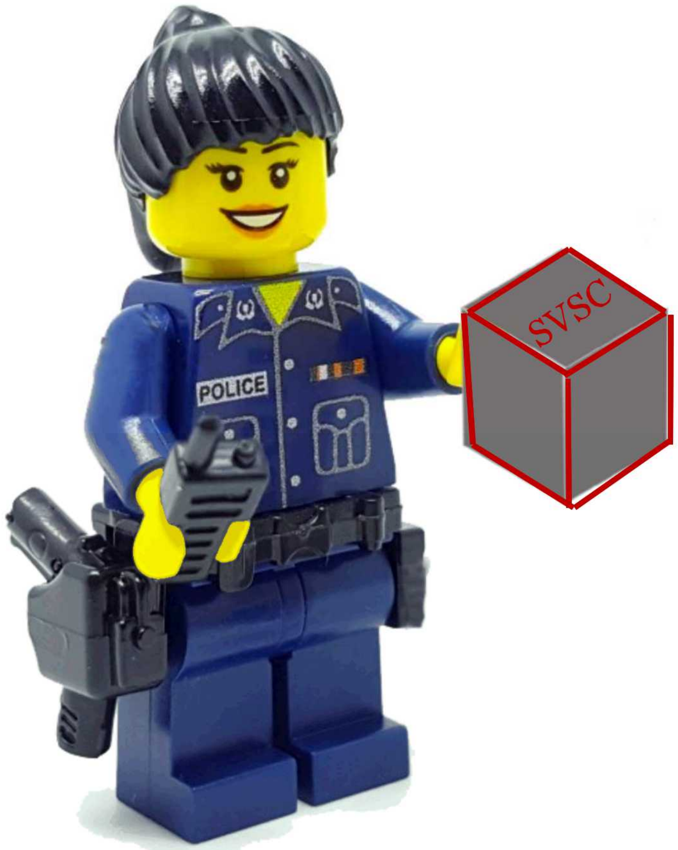
Easy detector, easy reconstruction with Scintillating Nanoguide?

- theory says (paraphrase): diffusive-less light propagation is possible through a disordered scattering medium
- translation: if we randomly distribute the index of refraction in two dimensions, light will propagate without diffusion in the third
- scintillating Nanoguide from Paradigm/Incom is being tested for light transportation effects
- potential to greatly reduce mechanical instability of OS prototype, simplify reconstruction
- only limit to position resolution due to photodetector pixelization



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 recently assembled, undergoing further system-wide characterizations
- next prototypes will be constructed by early CY20



Thank you!

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Questions?