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MCP-based Detectors for Nuclear Non-proliferation

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Outline

1. Nuclear non-proliferation applications

   - Detection principles & physics

     - How MCP-based detectors fit in

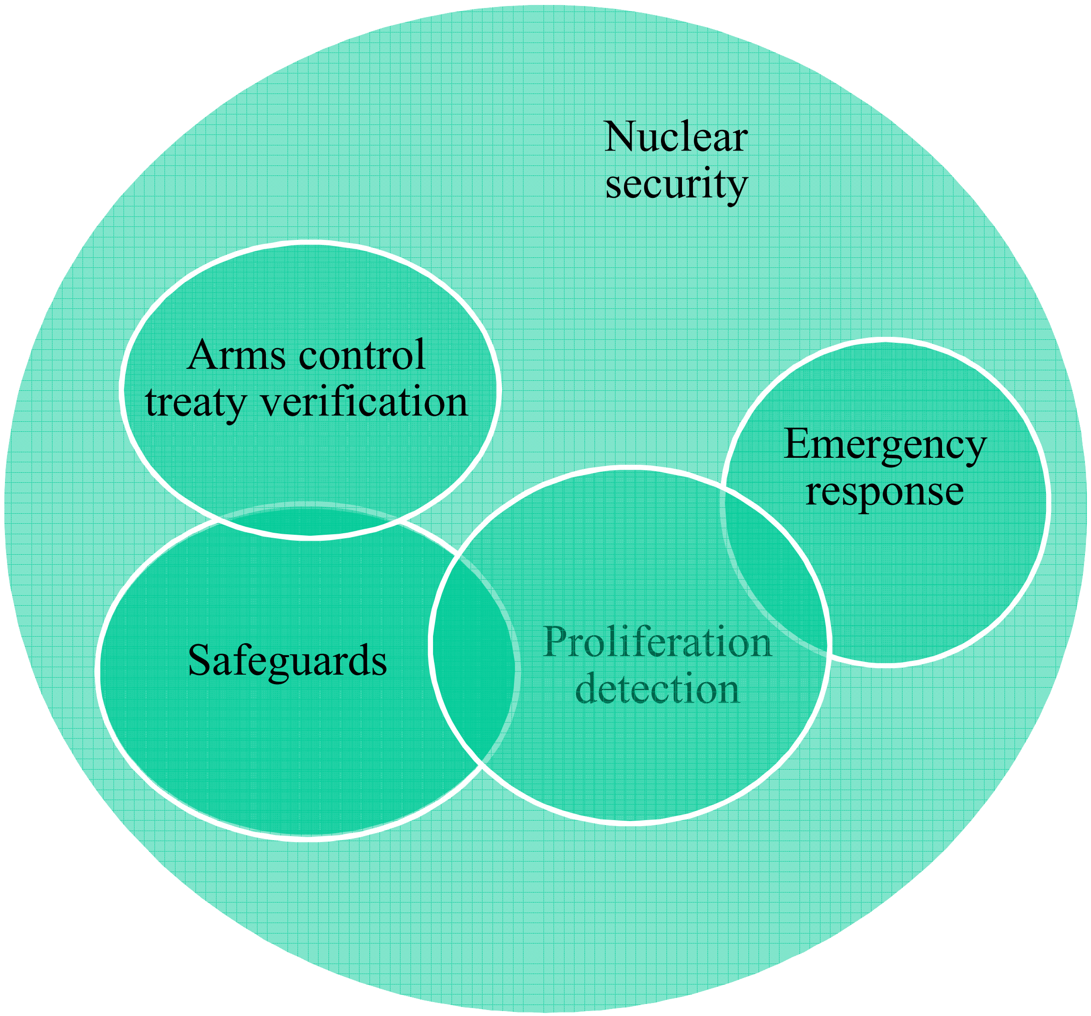
       - Specific example: Single-Volume Neutron Scatter Camera

       - Other ideas for MCP-based detectors

- NB: Acknowledged bias toward
  - Neutrons
  - Imaging
  - Arms control

Nuclear non-proliferation application space

Nuclear security Venn diagram



- Horizontal proliferation: new actors acquiring nuclear capabilities
- Vertical proliferation: existing NWS increasing nuclear capabilities
- Special nuclear material (SNM) is the common element.
    - Detect
    - Locate
    - Characterize
- Radiation detection can help!

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

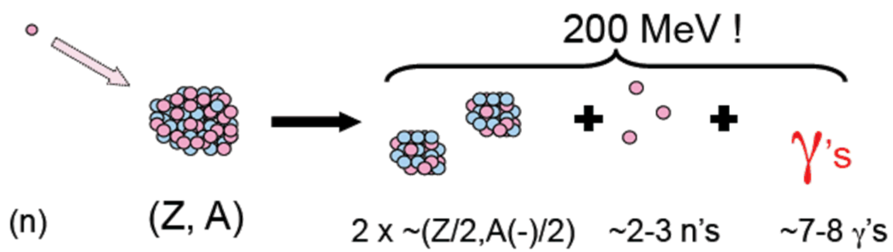
SNM radiation signatures

These physical processes…

- Spontaneous fission
- Induced fission
  - Self-interrogation
  - External interrogation
- Other radioactive decays
  - Gamma
  - (α,n)

… produce these signatures

- Gamma spectrum reflects isotopics
- Neutron fission spectrum
- Time correlations (multiplicity analysis)



Gamma signatures

The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)	Mean Free Path (mm) (High-Z, ρ)	Mean Free Path (mm) (Low-Z, ρ)
^{234}U	120.9	9.35×10^4	0.23	69
^{235}U	143.8	8.40×10^3	0.36	73
	185.7	4.32×10^4	0.69	80
^{238}U	766.4	2.57×10^1	10.0	139
	1001.0	7.34×10^1	13.3	159
^{238}Pu	152.7	5.90×10^6	0.40	75
	766.4	1.387×10^5	9.5	139
^{239}Pu	129.3	1.436×10^5	0.27	71
	413.7	3.416×10^4	3.7	106
^{240}Pu	45.2	3.80×10^6	0.07	25
	160.3	3.37×10^4	0.45	76
	642.5	1.044×10^3	7.4	127
^{241}Pu	148.6	7.15×10^6	0.37	74
	208.0	2.041×10^7	0.86	83
^{241}Am	59.5	4.54×10^{10}	0.14	38
	125.3	5.16×10^6	0.26	70

These materials are dense; self-shielding is not negligible

Ref: "Panda Book"

Slide courtesy of David Chichester, INL

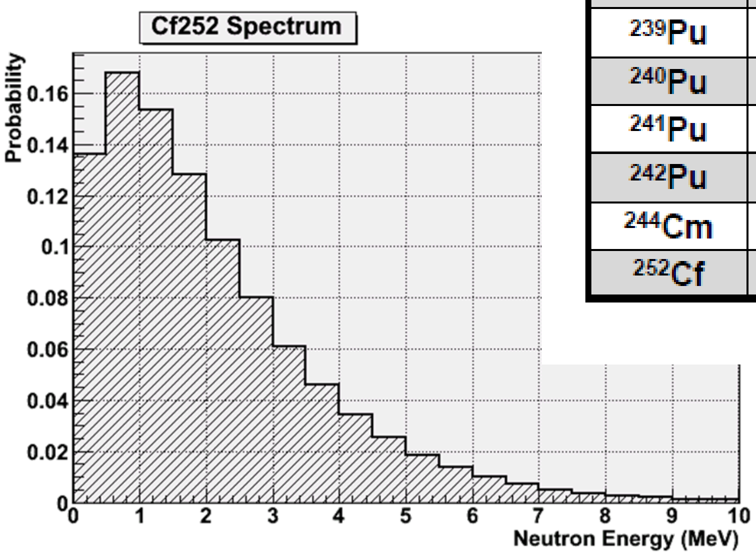
Neutron signatures

The Passive Neutron Signatures

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)	Spontaneous Fission Multiplicity ν	Induced Thermal Fission Multiplicity ν
^{232}U	71.7 yr	1,300	1.71	3.13
^{233}U	1.59×10^5 yr	0.86	1.76	2.4
^{234}U	2.45×10^5 yr	5.02	1.81	2.4
^{235}U	7.04×10^8 yr	0.299	1.86	2.41
^{236}U	2.34×10^6 yr	5.49	1.91	2.2
^{238}U	4.47×10^9 yr	13.6	2.01	2.3
^{237}Np	2.14×10^6 yr	0.114	2.05	2.70
^{238}Pu	87.7 yr	2.59×10^6	2.21	2.9
^{239}Pu	2.41×10^4 yr	21.8	2.16	2.88
^{240}Pu	6.56×10^3 yr	1.02×10^6	2.16	2.8
^{241}Pu	14.35 yr	50 ±	2.25	2.8
^{242}Pu	3.76×10^5 yr	1.72×10^6	2.15	2.81
^{244}Cm	18.1 yr	1.08×10^{10}	2.72	3.46
^{252}Cf	2.65 yr	2.34×10^{15}	3.757	4.06

Ref: "Panda Book", values with ± have significant uncertainty

Table courtesy of David Chichester, INL



Rad detection for detecting SNM

Notional scenarios:

- Sources indicate that a significant quantity of nuclear material is present in X neighborhood. Find it or provide all clear.
- Radiographic/active interrogation of rail cargo: scan rates of 8 to 24 km/h, scan lengths over one kilometer, and a penetration depth of 90 cm of steel

- By definition, interesting/difficult cases have low S:B.
- Active interrogation can increase signal at cost of more/different background
- Radiation detection needs:
  - High efficiency
  - Scalability
  - S:B discrimination

Rad detection for locating SNM

Notional scenarios:

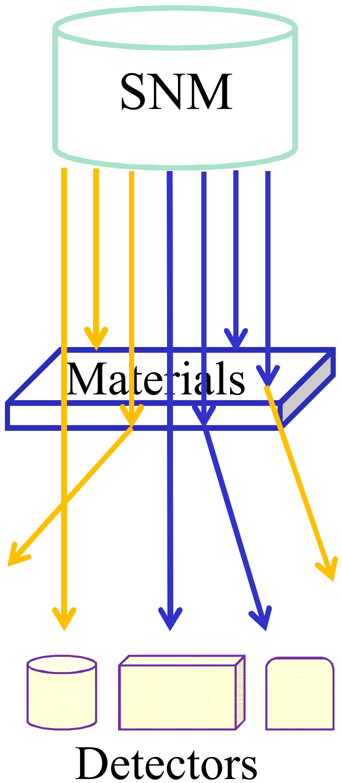
- Nuclear material is present in building X. Determine which floor/apartment.
- Count number of nuclear warheads on an ICBM without visual access.

- Radiation detection needs:
  - Directional information
  - Field of view depends on specific application

Rad detection for characterizing SNM

Signatures (physics)

- **SNM emits** γ, n radiation
  - {Spectrum, rate, vector field, correlations} determined by {SNM mass, isotopics, configuration}
- **Surrounding material** attenuates, scatters, modifies signature
- **Interactions** between SNM, surroundings



Detectors (technology)

- Typically optimized for measuring one aspect of the radiation signature, e.g.
  - Gamma spectrum → good energy resolution
  - Neutron timing correlations → Large effective area for n detection
  - SNM configuration → position, direction resolution
  - Low-rate processes → active stimulation

SNM detection/imaging

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

Standoff detection

Cargo screening

Arms control treaty verification

Emergency response

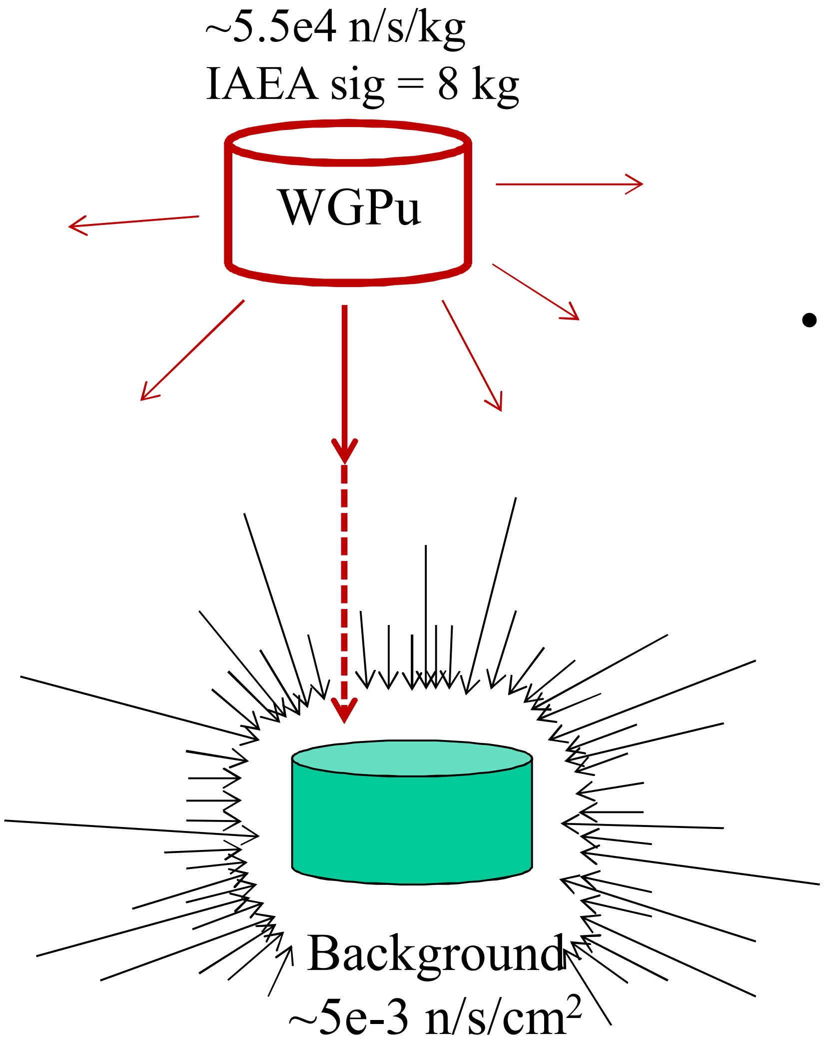
SNM detection applications

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

SNM imaging applications

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

Standoff detection



- Example: Large stand-off application (100 meters)
  - 8 kg WGPu = ~4.4e5 n/s → 4.4e5 *exp(-R/100)/4πR^2 ≈**1.3 n/s/m^2**
  - Background = ~**50 n/s/m^2** (at sea level)
  - 100% efficient, 1 m^2 detector → 5σ detection in **~13 minutes**
  - 10% efficient, 1 m^2 detector → 5σ detection in **~2 hours**
  - 10% efficient, 1 m^2 detector, 3% bg rate systematic → 5σ detection in **never**

Cargo screening

- Extremely challenging problem!
  - Needle in a haystack
  - Flow of commerce
  - Potential for heavy shielding
  - Background variations
- Primary screening, secondary, etc.

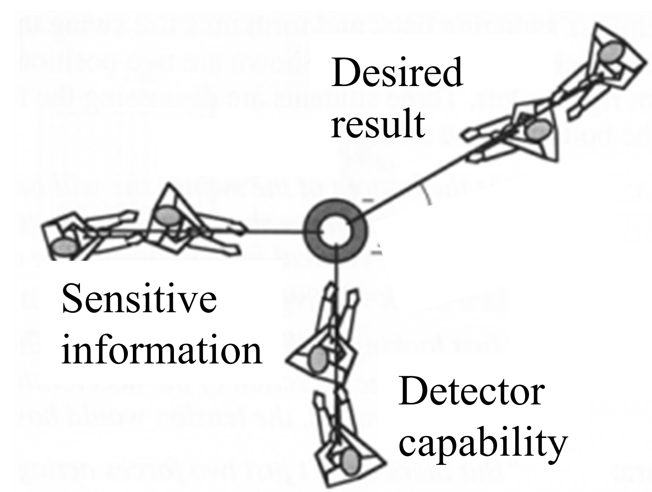
Emergency response

- Learn as much as possible, as quickly as possible, about a package containing SNM.
- All information is potentially useful.

Arms control treaty verification

Treaty needs:

- Warhead counting
  - Verify declarations
- Warhead confirmation
  - Verify it is a warhead
  - Verify warhead type
- Chain of custody
  - Monitored storage
  - Spot check status
- Dismantlement/disposition
  - Maintain perimeter
  - Track item through process



Three-way tug of war!

Signatures/detectors

- 0.1 MeV – 10 MeV gammas
  - High natural backgrounds, many NORM sources
  - Shielded by high-Z materials
  - Energy resolution key to determine isotopics
- 0.1 MeV – 10 MeV neutrons
  - Low natural backgrounds, few benign sources
  - Shielded by low-Z materials
  - Weak spectral information
  - Direct access to fission process: time correlations
- Directional information improves S:B, locates sources, measures spatial configuration of material
- Active interrogation, radiography are wild cards

Signatures/technologies

0.1 MeV – 10 MeV gammas • High natural backgrounds, many NORM sources • Shielded by high-Z materials • Energy resolution key to determine isotopics	• Plastic scintillator/PMT • Inorganic scintillators/PMT (NaI, CsI) • Semiconductors (HPGe, CZT) • Shaping/MCA electronics
0.1 MeV – 10 MeV neutrons • Low natural backgrounds, few benign sources • Shielded by low-Z materials • Weak spectral information • Direct access to fission process: time correlations	• Thermal neutron detectors (He-3 tubes) • Organic scintillators/PMT (plastic, liquid, crystalline) • Pulse height/shape discrimination • Multiplicity analysis
Directional information improves S:B, locates sources, measures spatial configuration of material	• More complex systems—high channel counts, calibrations, data processing, analysis, image reconstruction
Active interrogation, radiography are wild cards	• Gamma sources • Neutron sources

Where does MCP fit in?

- MCPs can detect/amplify
  - Charged particles directly
  - With PC, optical photons (e.g. from scintillator)
- MCP-based detectors have intrinsically
  - Good spatial resolution (10s of um)
  - Good time resolution (10s of ps)
  - Decent scalability
- Not trivial to take advantage of those qualities!
  - Cost/capability tradeoff
- Where in the nuclear security application space is the tradeoff worth it?

Single-Volume Neutron Scatter Camera

Jim Brennan, **Erik Brubaker**, Aaron Nowack,
John Steele, Melinda Sweany, Eli Woods
Sandia National Laboratories, Livermore, CA

John Mattingly, Kyle Weinfurther
North Carolina State University

Cf. mTC…

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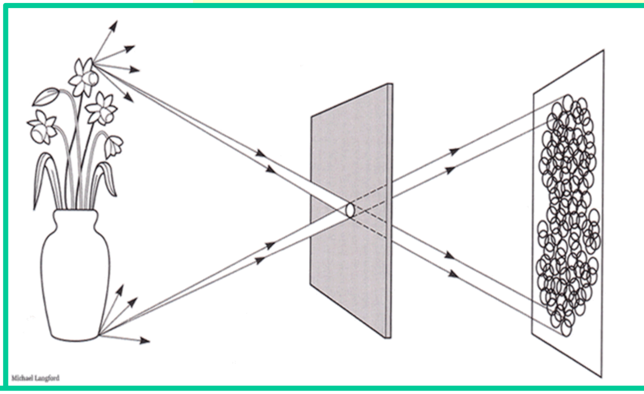
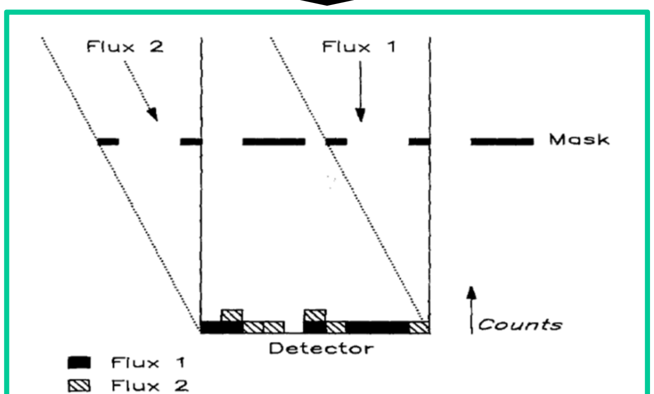
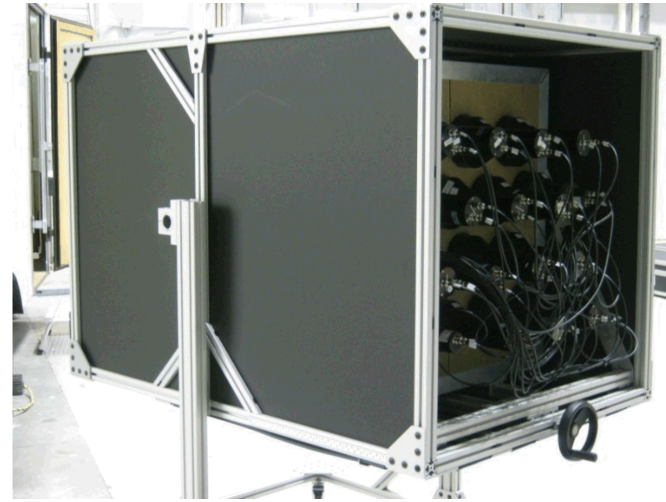
Neutron camera approaches



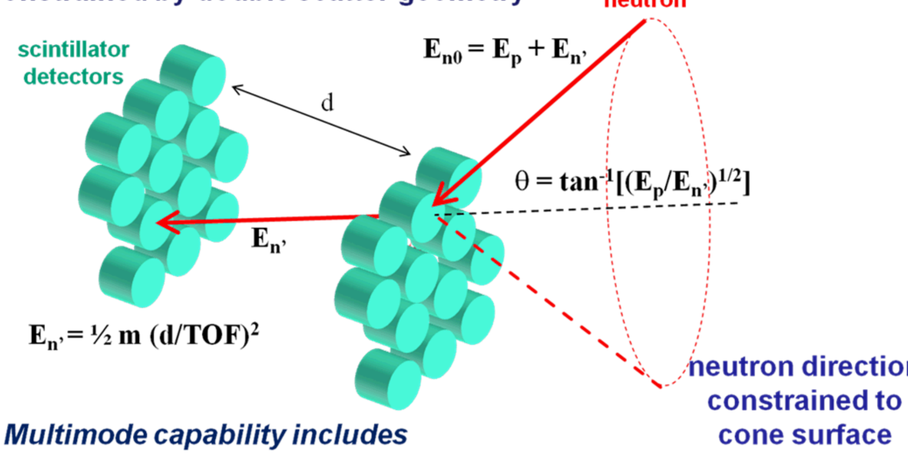
Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput

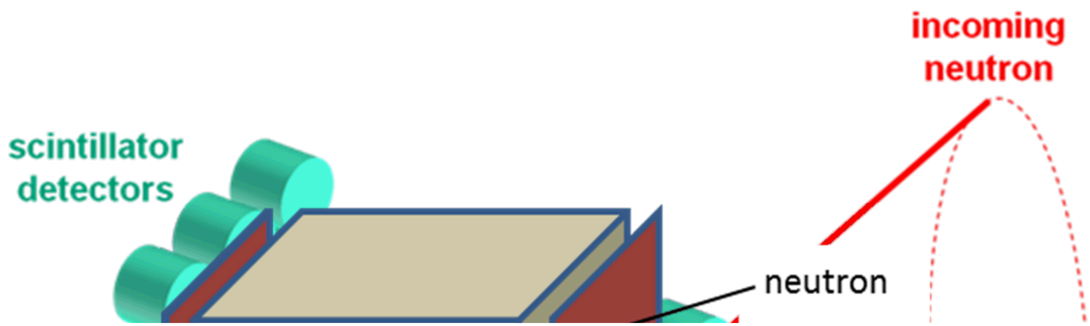


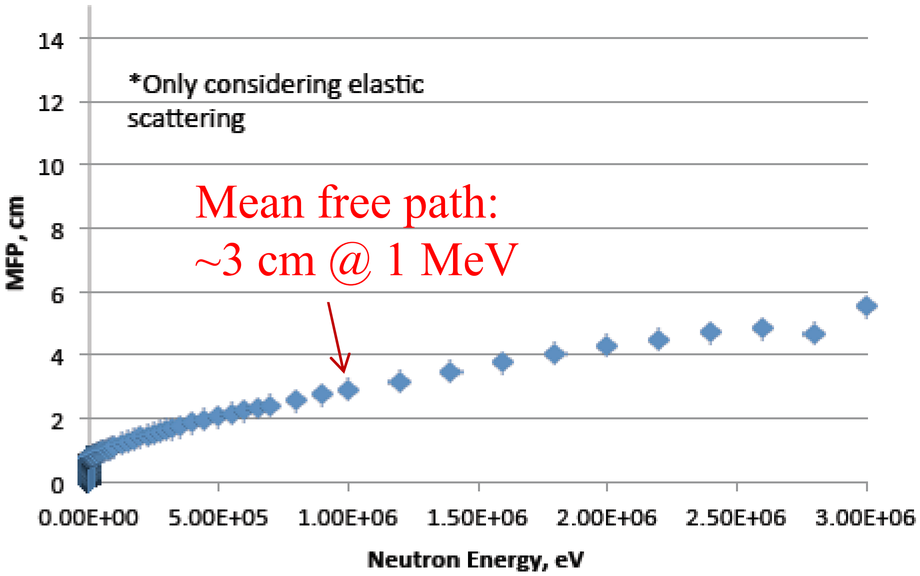
Fast neutron directions and energies constrained by double scatter geometry

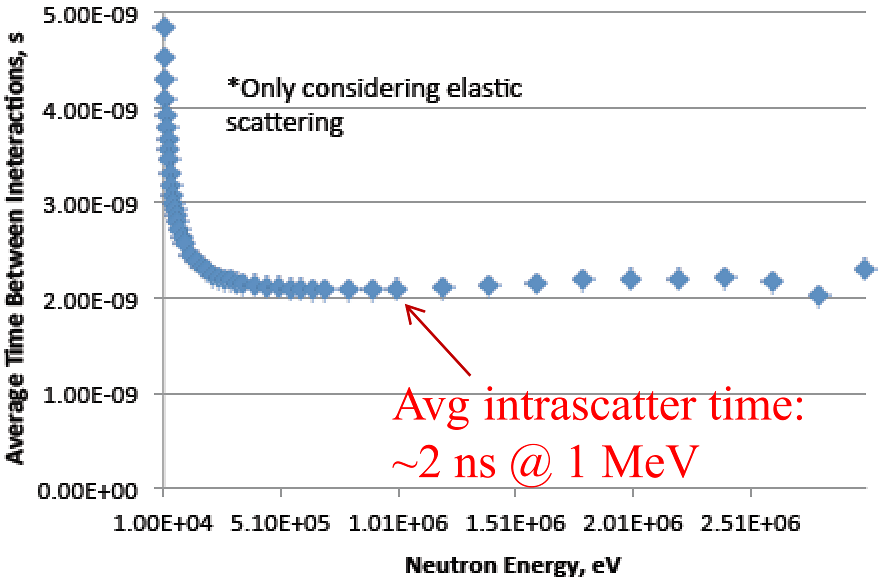


Multimode capability includes
- *Neutron energy spectrum.*
- *Compton imaging.*

Single-Volume Neutron Scatter Camera

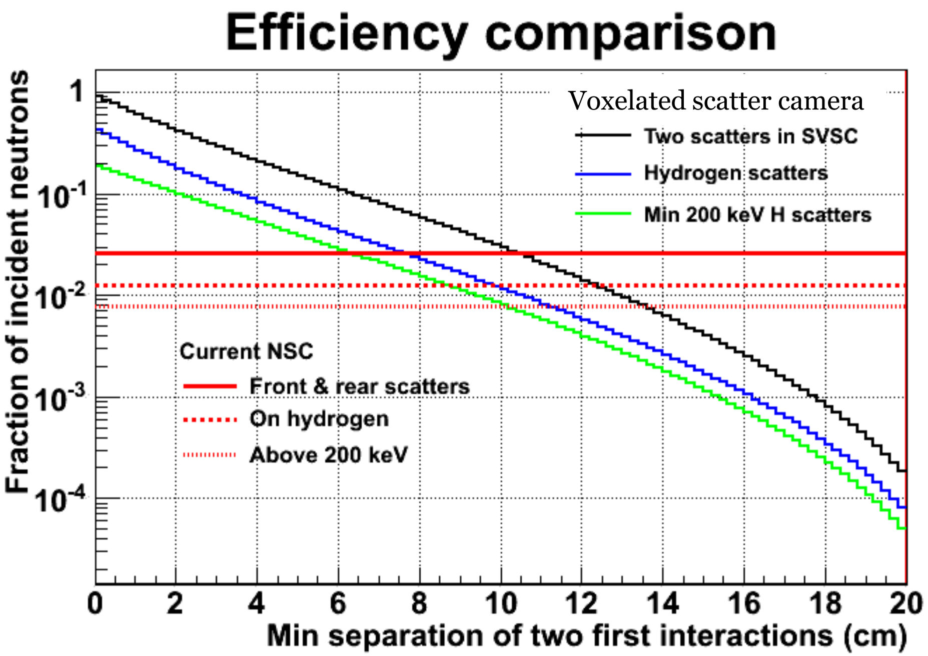


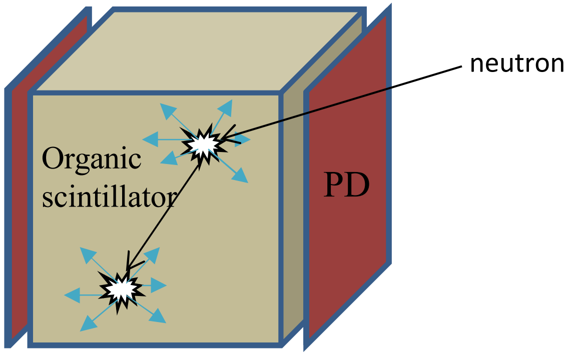




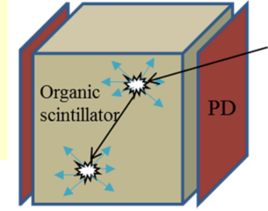
Single-Volume Neutron Scatter Camera

- A scatter camera built from a highly voxelated volume can recover more than an order of magnitude of efficiency if nearby interactions can be resolved.
- Additional advantages of compact form factor.
- Resolving multiple interactions of a neutron separated by O(cm) and O(ns) in a bulk scintillator is difficult!
- Excellent spatial and temporal resolution of photodetectors based on microchannel plates is the key enabling technology.

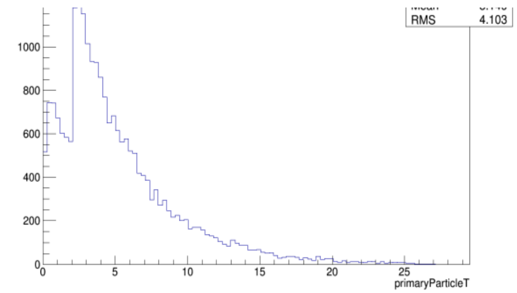




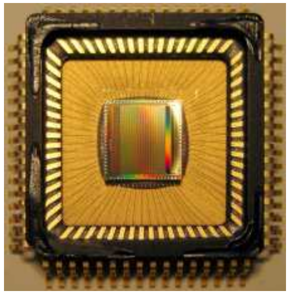
System Components



- Active material
  - Fast organic scintillator
  - Plastic vs crystalline
- Photodetector
  - MCP-PMT, e.g. Planacon
  - Position resolution depends on anode structure
  - 35 ps transit time spread
    - Equals 8 mm photon travel
- Electronic readout
  - Switched capacitor array
    - e.g. DRS4 (5 GS/s, 950 MHz, 11.5 enob)
  - Need careful board design—bandwidth, noise
  - Long reset time



Photonis



PSI

\+ Simulation
\+ Event reconstruction algorithm
\+ Image reconstruction algorithm

Simulation/Reconstruction

Probability multiplies over all observed photons

Extended ML for accurate energy uncertainty

Probability to observe a photon is summed over all interactions

$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!} \prod_{i=0}^{n} \sum_{j=0}^{N} \frac{\mu_j}{\mu} P_j(x_i)$$

$$P_j(x_i) = \left[\frac{\cos\phi_{ij}}{4\pi|\vec{x}_i - \vec{x}_j|^2} e^{\frac{-|\vec{x}_i - \vec{x}_j|}{\lambda}} f(t;\mu,\sigma,\lambda) \right]$$

Solid angle

Pulse shape

Optical attenuation

Event reconstruction via likelihood maximization.
Input is a list of photon arrival positions and times.

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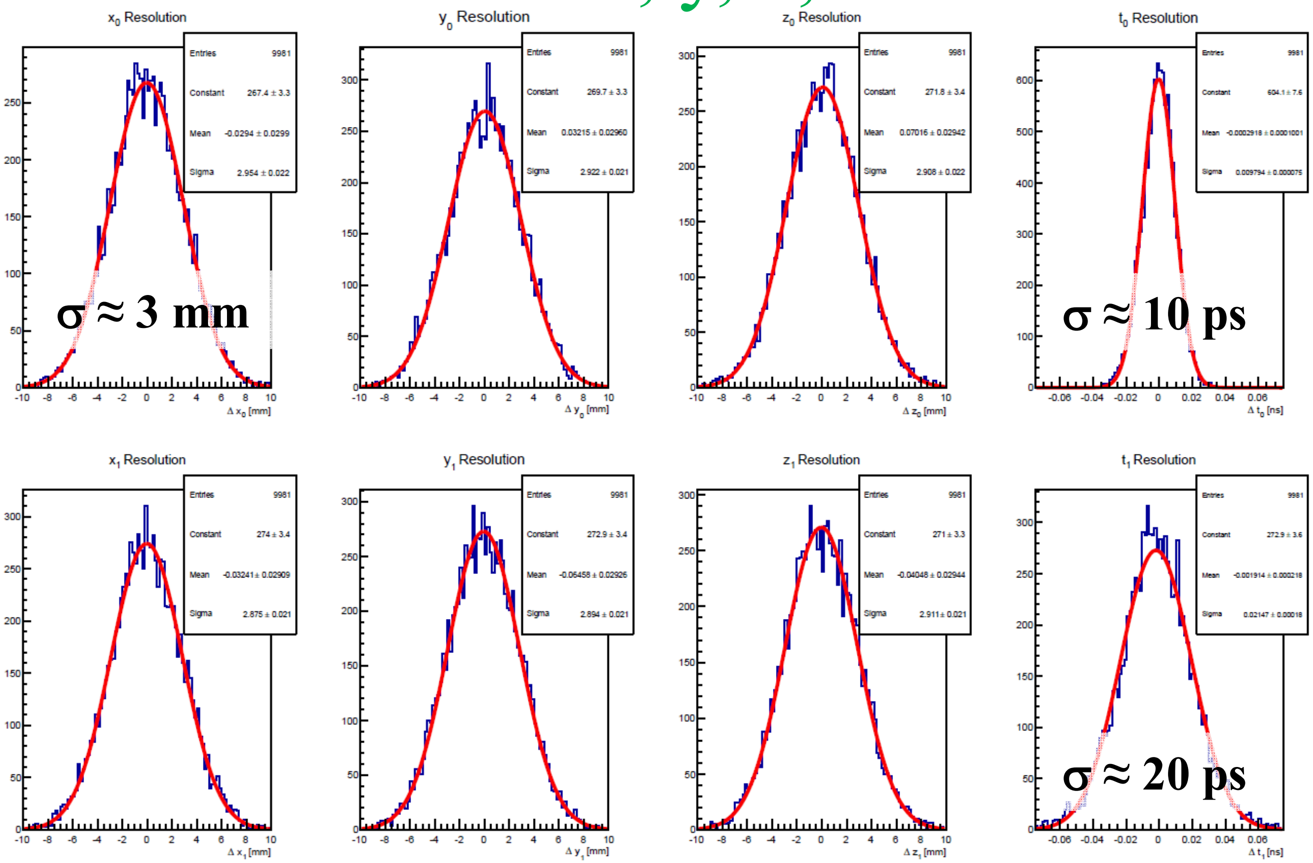
Simulation/Reconstruction

- GEANT4 simulation incl optical photons
- (10 cm)^3 detector, PD on all six sides
- Fixed event: 3 cm/2 ns separation, ~1 MeVee each recoil
- Stilbene pulse shape (0.1 ns rise, 4.5 ns decay)
- Idealized PD response/resolution

First Interaction x, y, z, t



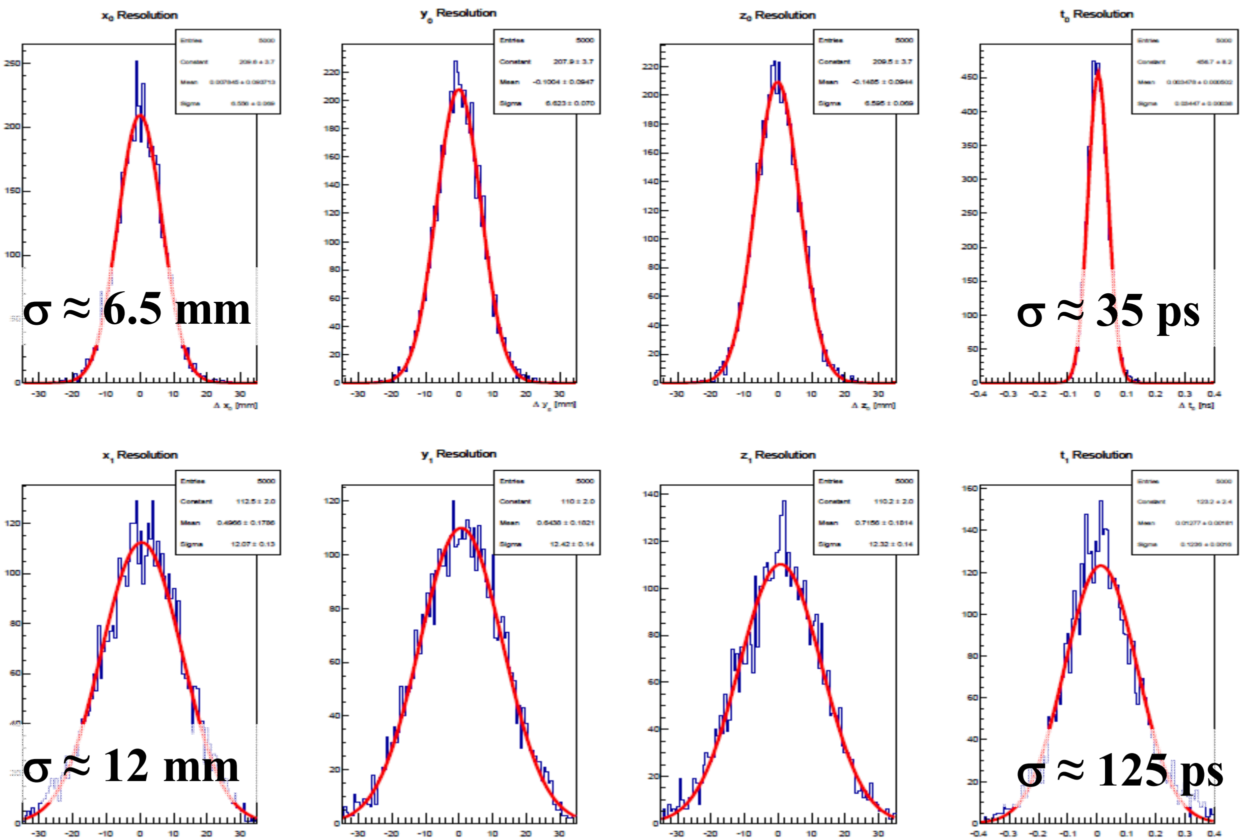
Second Interaction x, y, z, t

Ideal case, **NOT** predictions of experimental resolutions!

More realistic

- GEANT4 simulation incl optical photons
- (10 cm)[3] detector, PD on all six sides
- Fixed event: 3 cm/2 ns separation, 1.5 MeV, 0.75 MeV proton recoils
- BC-422 pulse shape (fast plastic)
- Idealized PD response/resolution

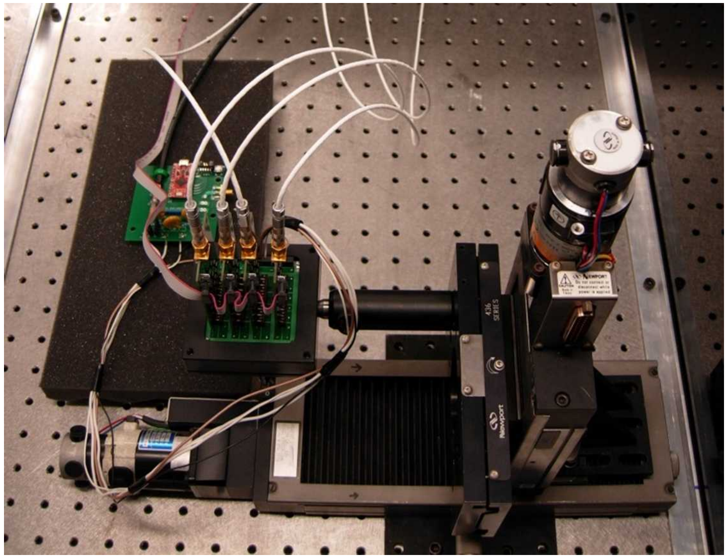
First Interaction x, y, z, t

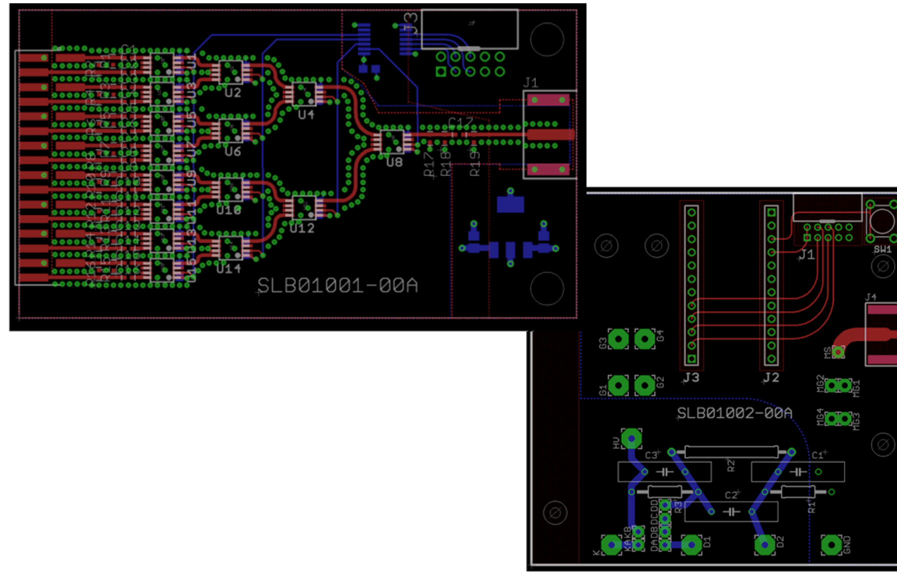


Second Interaction x, y, z, t

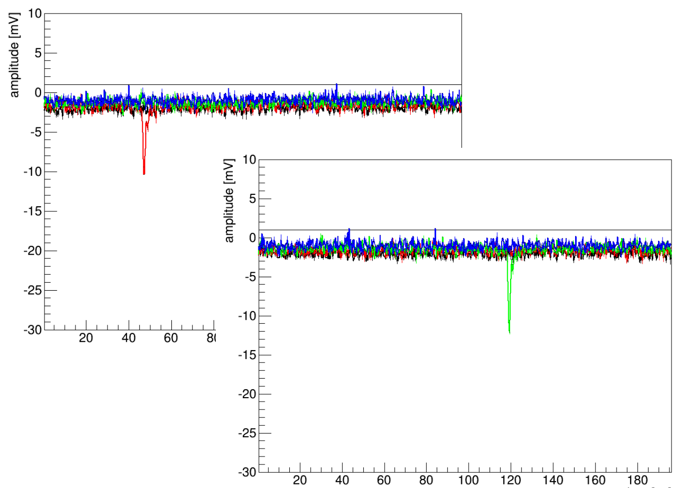
Ideal case, **NOT** predictions of experimental resolutions!

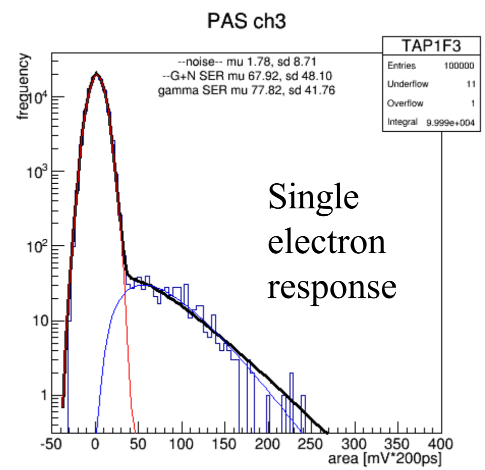
Experimental Status





Pulsed LED
Planacon XP85012
Multiplexer
DRS4 eval board (4 ch)
C++ DAQ

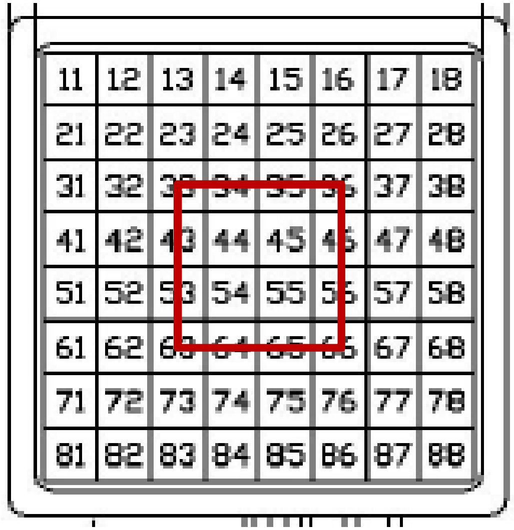




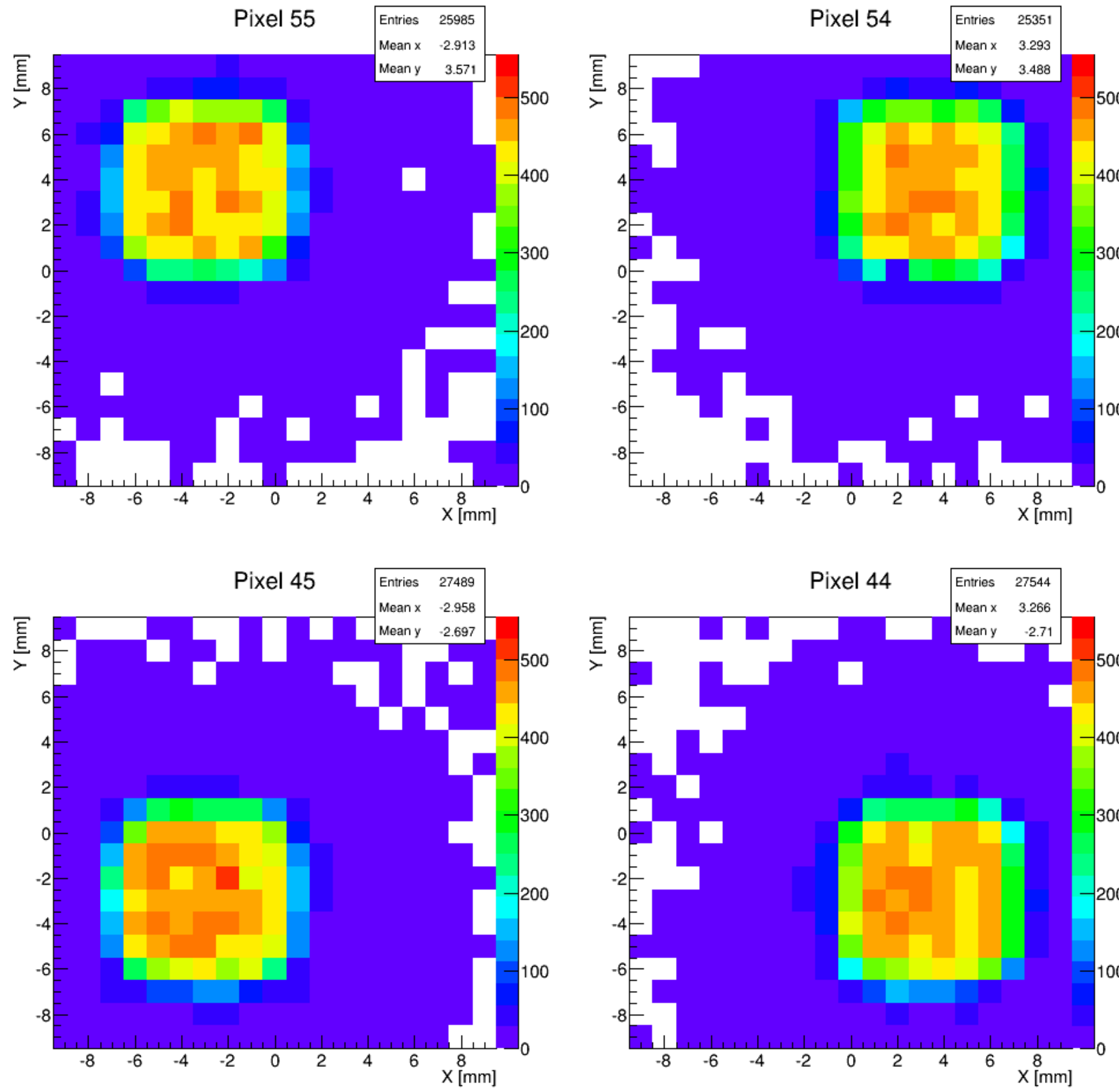
Photodetector characterization

- Complex PD/electronics requires significant effort to **characterize and calibrate**.
- Use LED with 1 mm pinhole aperture; scan Planacon in x,y
- Determine position response of Planacon
  - $N_{pe} \propto$ QE
  - Pulse height $\propto$ gain
  - Also see anode response, charge sharing
- Ultimately feed back to simulation for increased realism & systematic studies.

Collimated LED scan

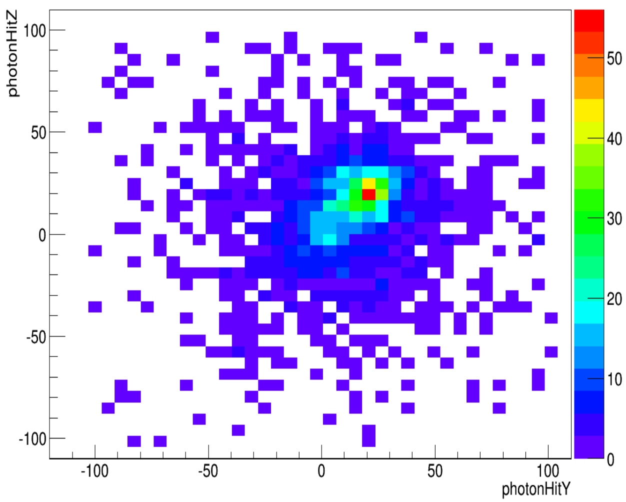


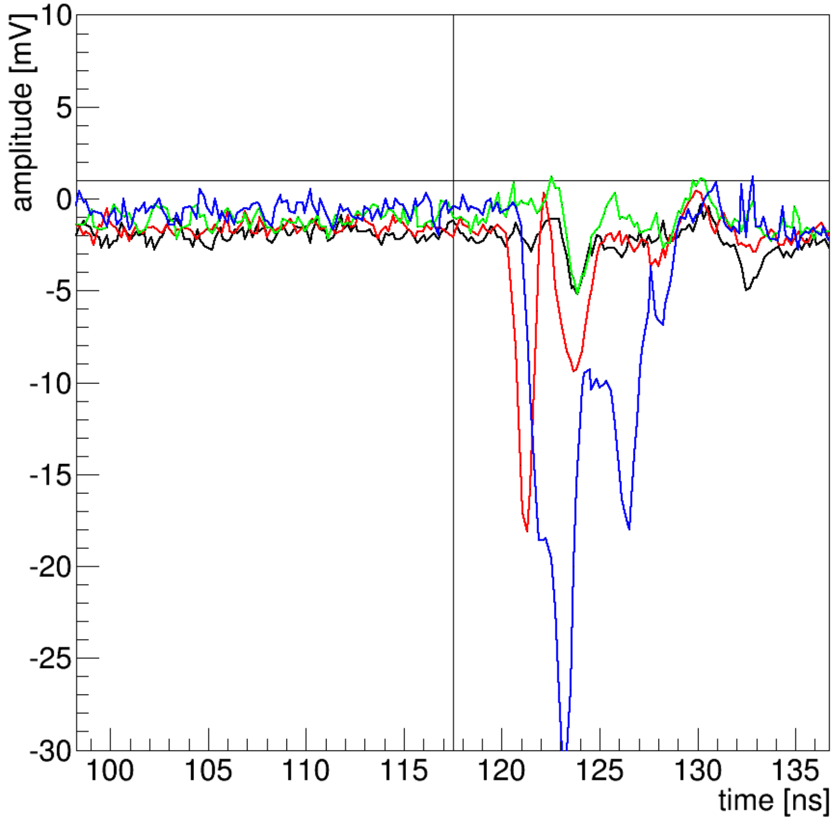
- QE quite flat (over small region)
- Sharp anode pixel boundaries
  - 1 mm collimation
- Some PE scatter



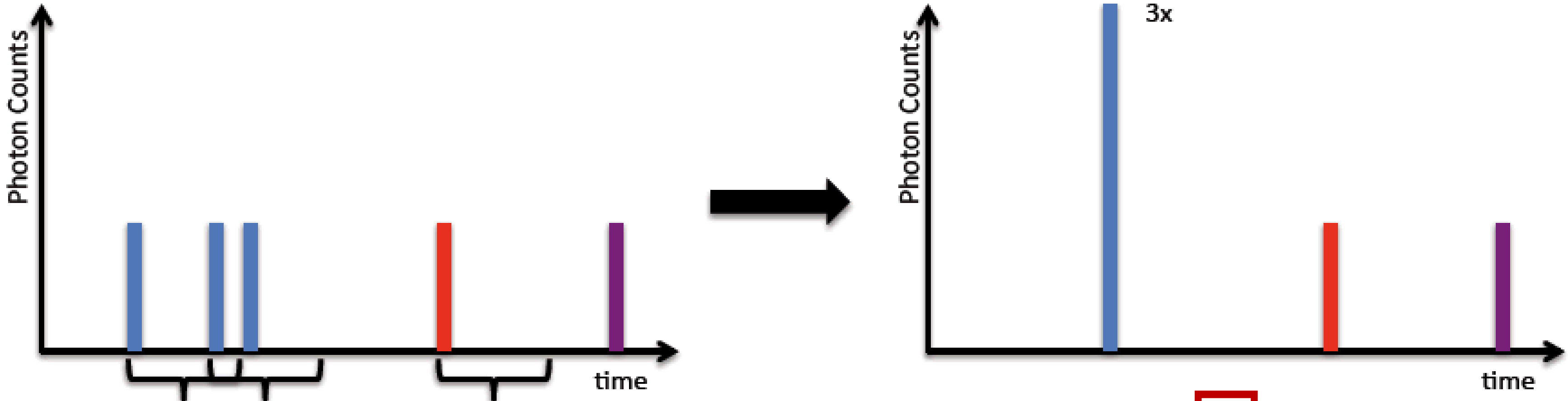
Signal readout/processing

- Not all pixels see well separated single photons.
- Reconstruction algorithm assumes it is handed a list of photon arrival positions & times.
- How to analyze signal trace?

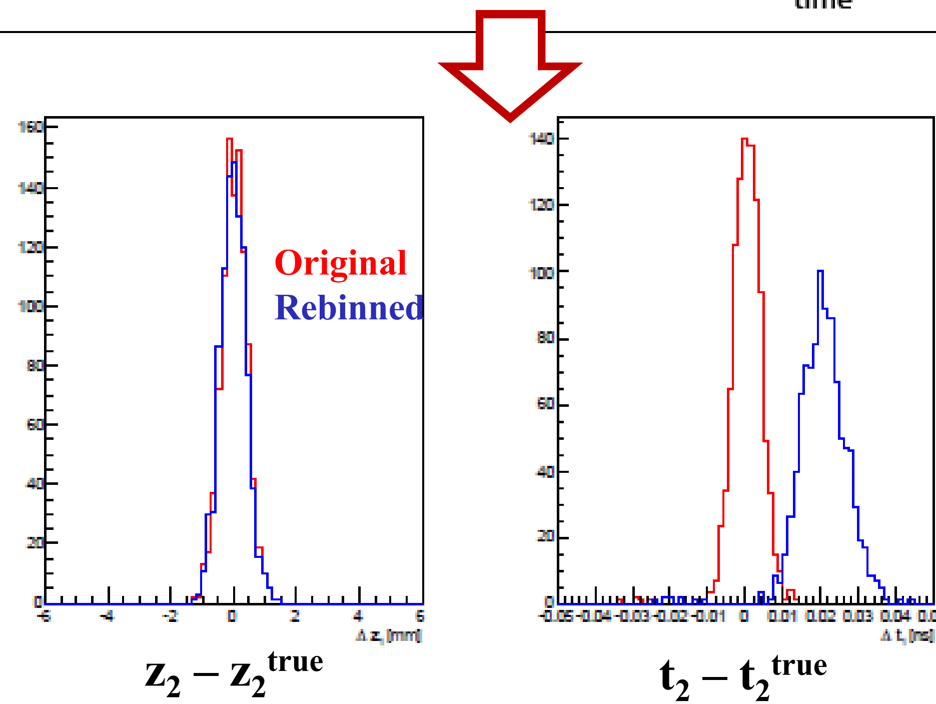




Signal readout/processing



- What if the best we can do for overlapping photons is count them?
- Check in simulation study.
- For t_{window} = 300 ps, time is shifted but reconstruction still reasonable.



SVSC MCP/readout concerns

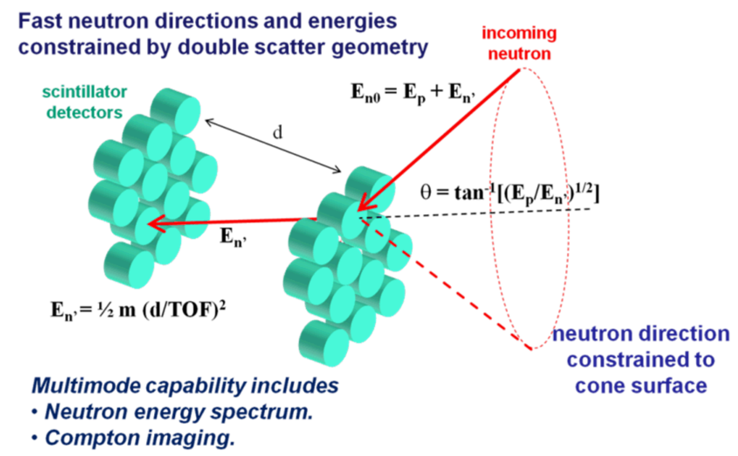
- MCP-PMT lifetime
  - Limited by back-propagating ion bombardment of photocathode, \propto integrated charge through MCP.
  - We want single-photon sensitivity → run at high gain → reduce lifetime.
  - Need to use ALD MCPs.
- Tradeoff between anode segmentation, system cost/complexity.
  - Segmentation driven by occupancy, not resolution!
  - Strip readout saves channels, but disambiguation problem may be intractable.
- Inherent dead time of SCA readout.
  - Need separate trigger pathway, possibly complex trigger analysis.
- Even a $(5\text{ cm})^3$ prototype w/ pixelated anodes has 128–384 channels.
  - Need significant effort to build full readout system.

Bright scintillators, high rates

Other non-proliferation applications

Traditional neutron scatter camera

- MINER system: Mobile Imager of Neutrons for Emergency Responders
(a compact, portable, low-power neutron scatter camera)
- Shorter distance between cells means TOF resolution is more of a limiting factor on spectral & angular resolution.
- Interested in 3” *single-anode* MCP-based photodetectors for improved hit timing resolution.



Detect, Locate, Characterize

Crystal Compton Imager

K.-P. Ziock, J. Braverman, ORNL

- Use coded aperture technique on *optical photons* to reconstruct interaction positions.
- Time resolution not important for gamma imaging, but need good spatial resolution, large area.

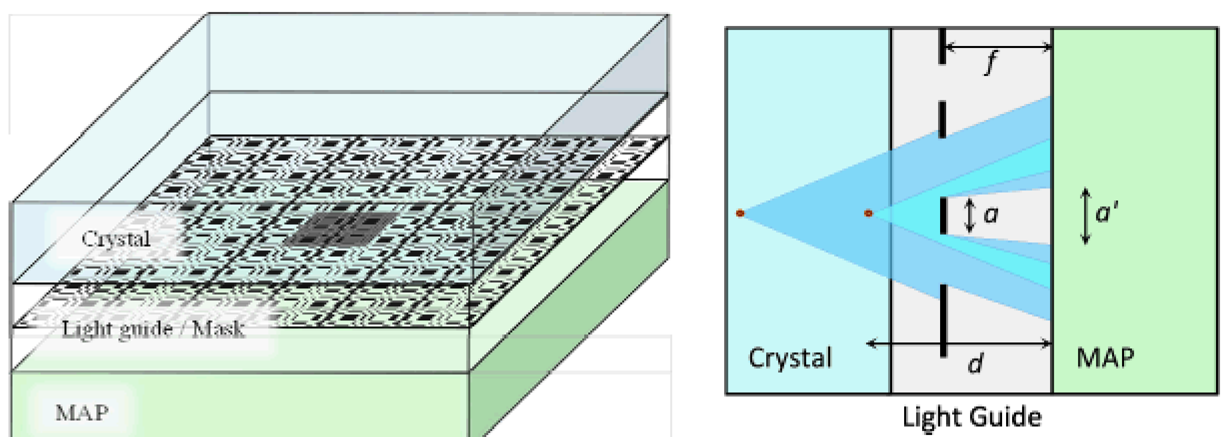


Fig. 2. Schematic of the overall concept (left) showing the scintillator crystal mounted to a light pipe with a shadow mask between the crystal and the MAP. The darker region of the mask represents one base MURA pattern. A close-up of the magnification of a few mask pixels at the MAP input for two events at different depths.

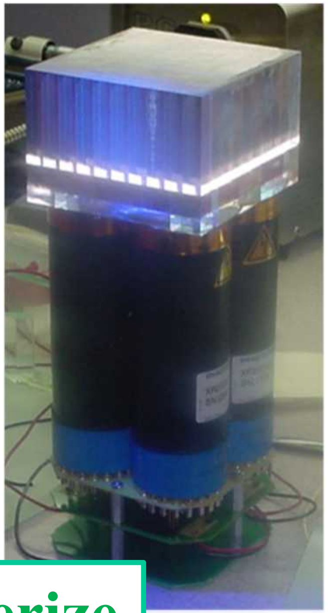
Proc. SPIE 8542, 854210 (November 19, 2012); doi:10.1117/12.979787

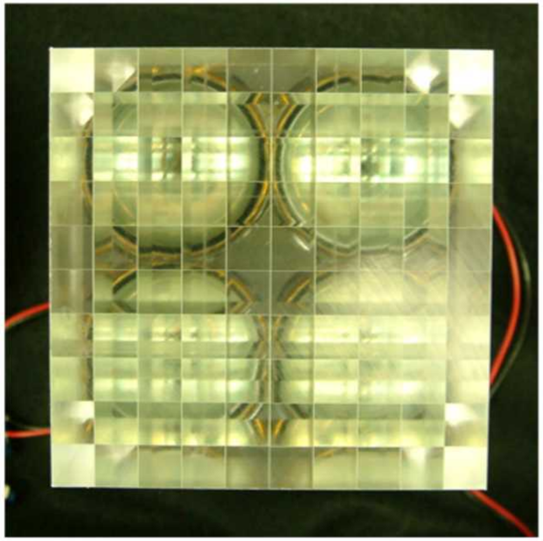
Locate
Characterize

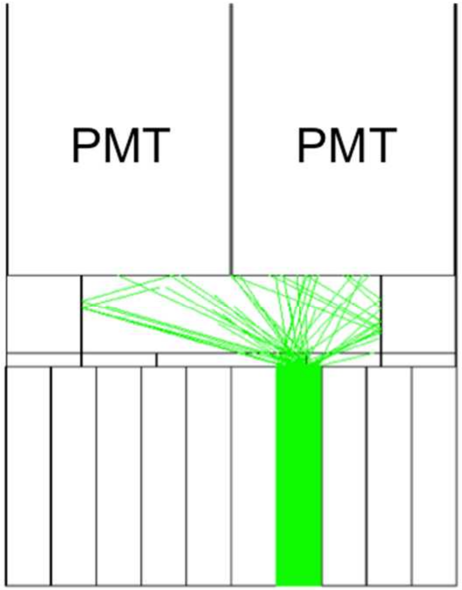
PSD scintillator block detector

P. Hausladen et al., ORNL

- Anger logic allows 4 PMTs to locate an interaction in 100 optically isolated pixels.
  - No sub-pixel resolution.
  - Confused by multiple interactions.
- Used in multiple neutron imaging systems.



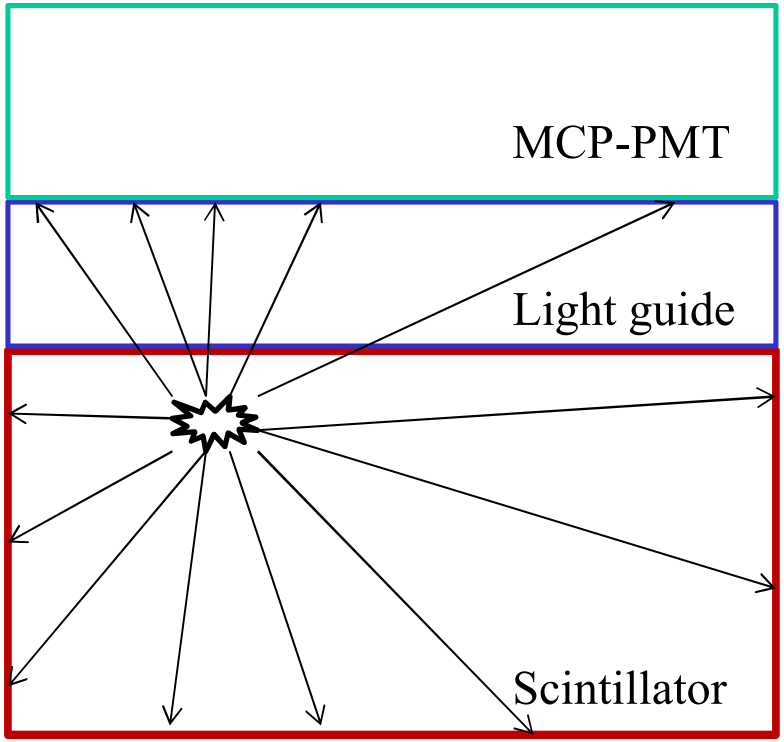




Locate, Characterize

Next-gen scintillator block detector

- With MCP-based photodetector, determine interaction location in continuous scintillator.
  - Like SVSC, but lower coverage; goal is to locate 1st interaction.
  - Resolution not limited by scintillator pixelation.
  - Timing can determine/resolve first interaction.
- Building block for position-sensitive detector plane for energetic neutrons, gammas.
  - ➢ Pinhole imager
  - ➢ Coded aperture imager
  - ➢ Double-scatter imager



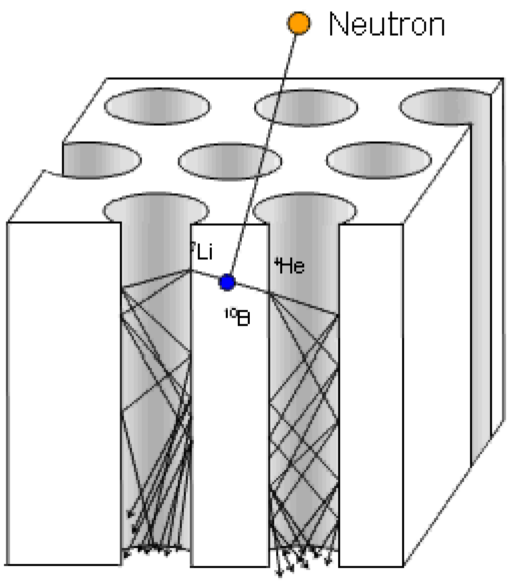
- Significant overlap with medical imaging.
  - E.g. Hunter et al., "Multiple-Hit Parameter Estimation in Monolithic Detectors," *Medical Imaging, IEEE Transactions on* , vol.32, no.2, pp.329,337, Feb. 2013

Locate, Characterize

Direct position sensing for thermal n

- Instead of photocathode, add thermal neutron capture agent to MCP itself.
- Makes high efficiency, high resolution position-sensitive thermal neutron detector.
- Use with coded aperture for thermal neutron imaging, or with thermalized neutron source for radiography.

Nova Scientific



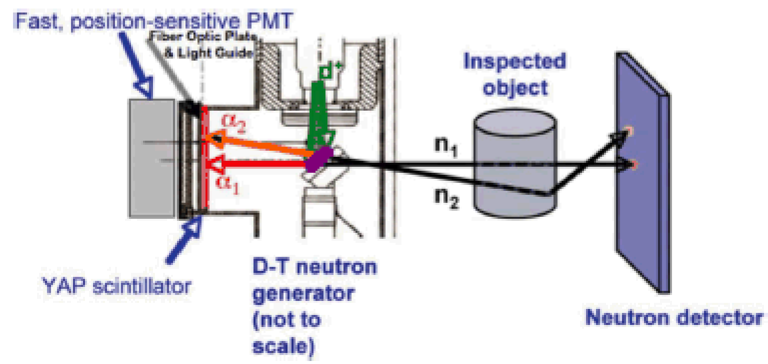
http://www.novascientific.com/neutron.html

Characterize

API alpha detector

- Associated particle imaging technique for 14 MeV neutron transmission imaging.
  - D + T → α + n
  - Detect α to determine neutron direction, t_0.

P. Hausladen et al., ORNL



- Cates, J.W., et al., "Timing Resolution Study of an Associated Particle Detector for Fast Neutron Imaging," Nuclear Science, IEEE Transactions on , vol.59, no.4, pp.1750,1756, Aug. 2012

"… a significant improvement in reconstructed image quality is achievable if the system timing resolution can be reduced below 500 ps, while ideal imaging reconstruction is possible with a timing resolution of 200 ps."

Characterize

Neutrinos

- Non-proliferation application of neutrino detection is to monitor or discover nuclear reactors.
  - Neutrino presence determines reactor on/off status
  - Neutrino spectrum sensitive to diversion (Pu/U ratio)
  - Neutrino direction improves detectability of weak sources relative to background
- Detection concepts not different from reactor neutrino physics experiments.
  - For ease of deployment, high desire for above-ground detection system → need exquisite background rejection.

Detect, Characterize

Sandia National Laboratories

MCPs for non-proliferation

- Everything (except neutrinos) in this survey of MCPs for non-proliferation applications relates to γ or n imaging.
  - Takes advantage of good intrinsic spatial resolution.
  - Timing resolution used to extract information from detected particles; not from source itself.
- Primarily interested in detection of optical photons from scintillator.
- Advantages of MCP-based detectors include improved efficiency, resolution, and form factor.

Sandia National Laboratories

Conclusions

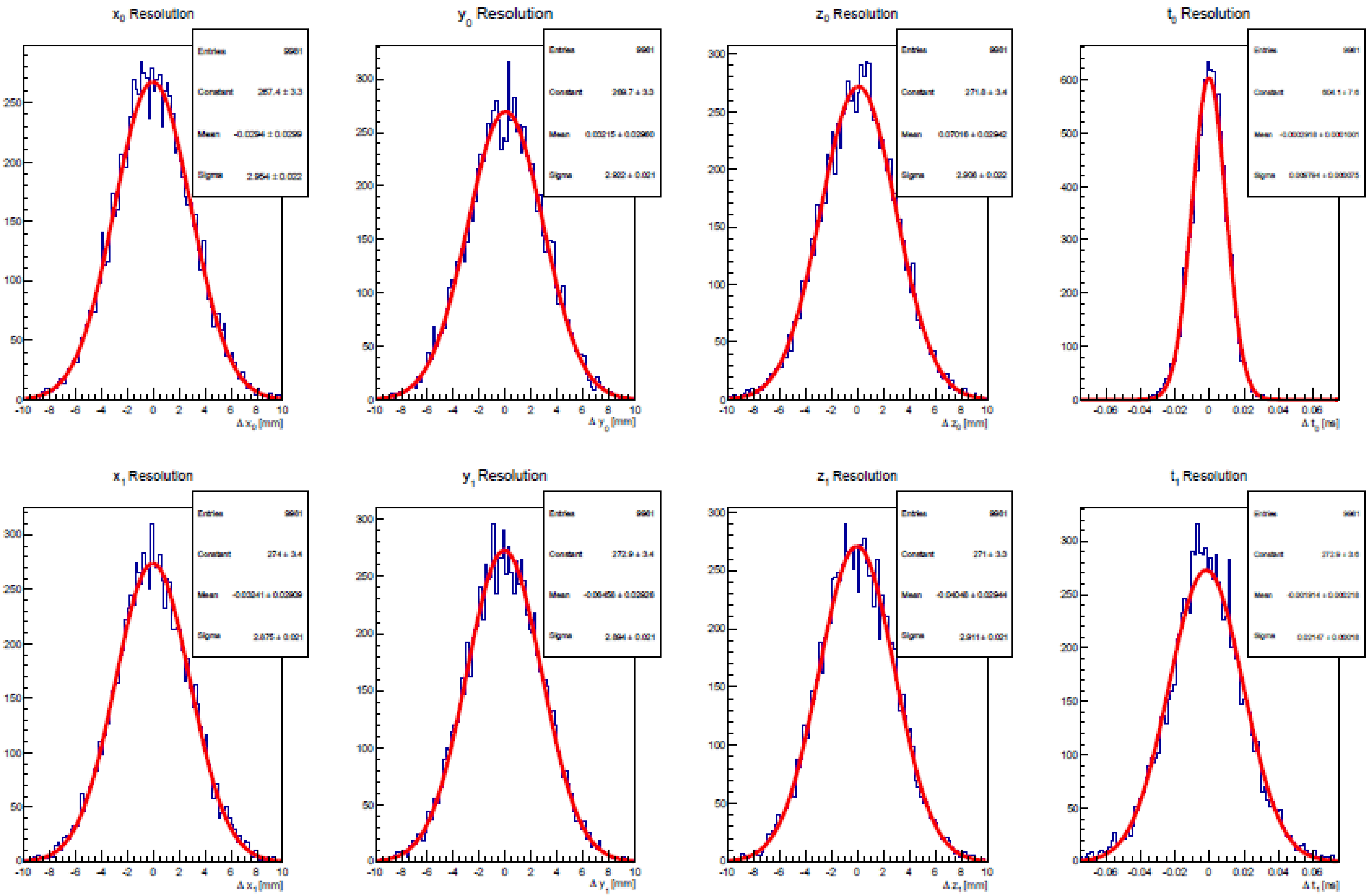
- Overview of non-proliferation application space
  - Detect, locate, characterize SNM
- Single-Volume Neutron Scatter Camera
  - Motivation, goals, progress, issues
- Other non-proliferation MCP-based detection concepts
  - Spatial/temporal resolution of MCP valuable for imaging applications.
  - Increased adoption will depend on price, scalability, ease of use.

Additional Slides

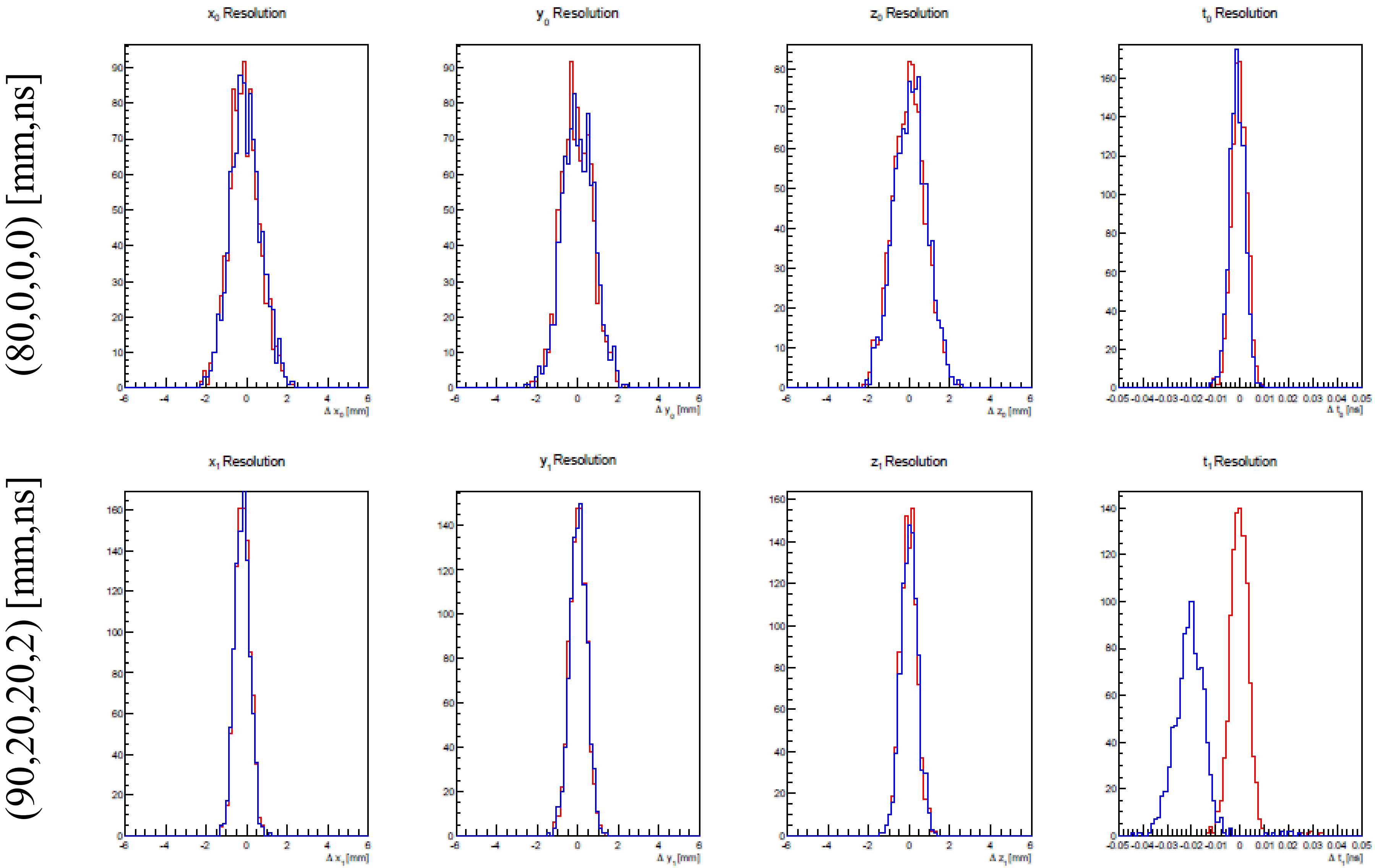
Central event

(10,0,0,0,0) [mm,ns]

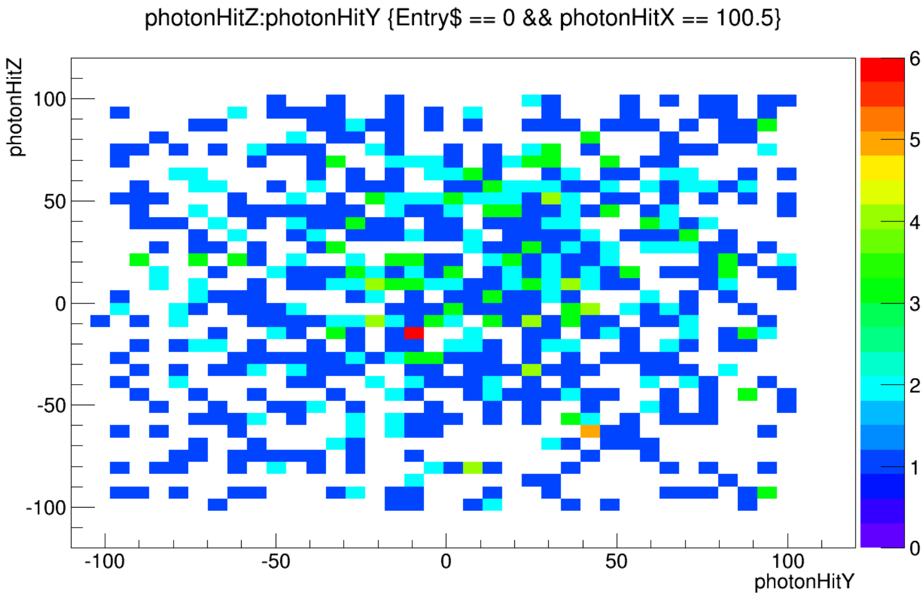
(20,20,20,2) [mm,ns]

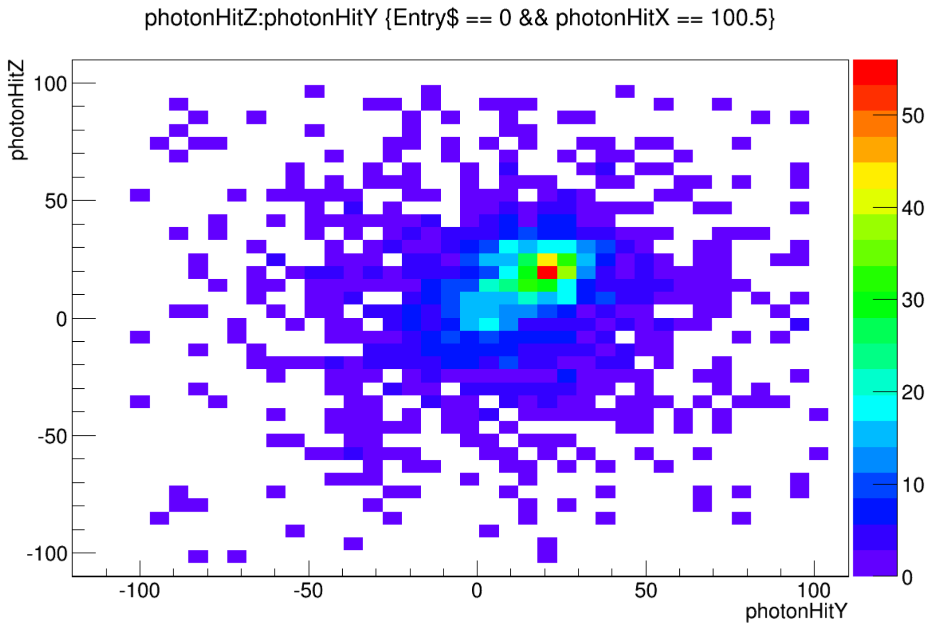


Shifted event



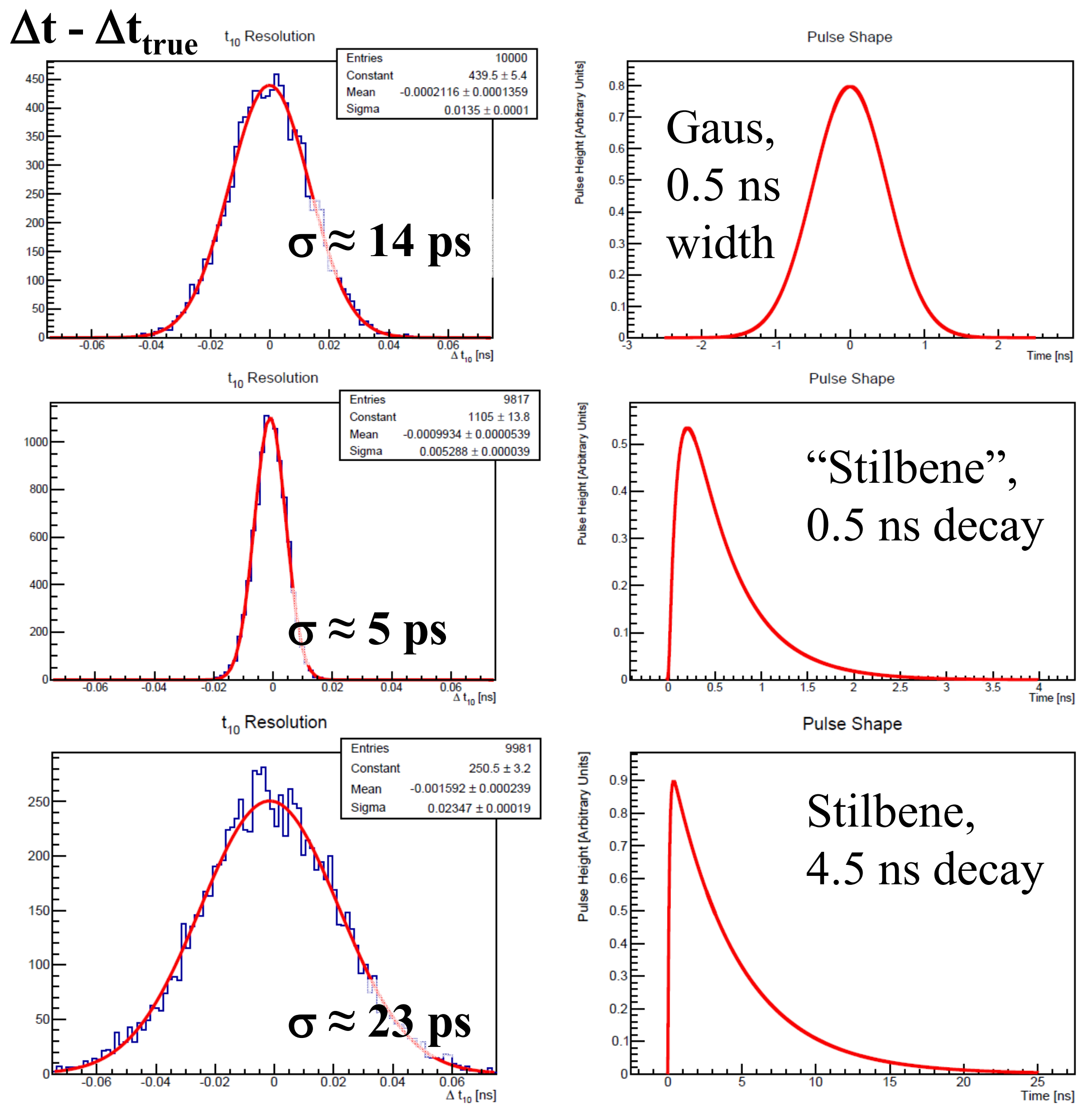
Pixel populations





Active material studies

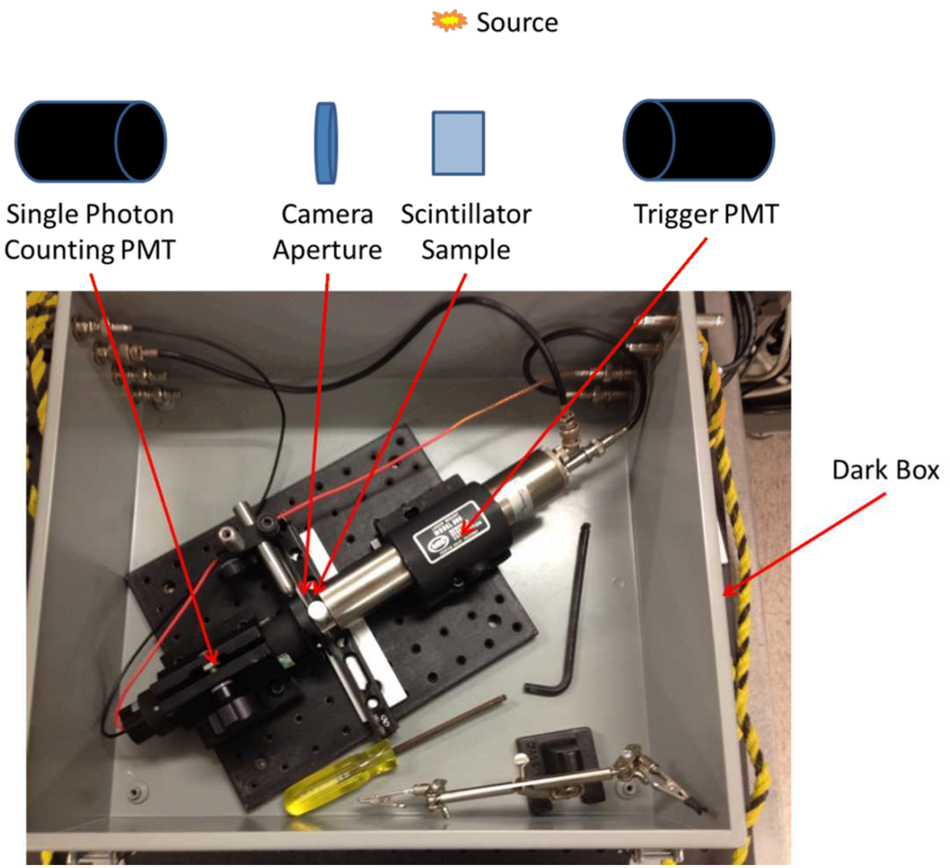
- Study effect of pulse shape on Δt resolution
- Same default event as earlier slide
- Pulse width important, especially rise time
- Quenched plastics?
  - Short decay
  - But slower rise
  - Low light output



Active material studies

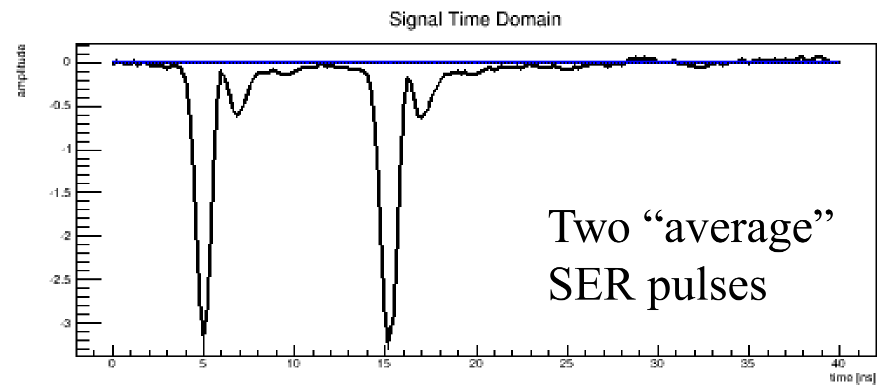
- Use single-photon time-delay method to measure pulse shape of
  - 3 quenched plastics
  - Stilbene single crystal
  - EJ-309 (reference)
- System time resolution is comparable to pulse width!

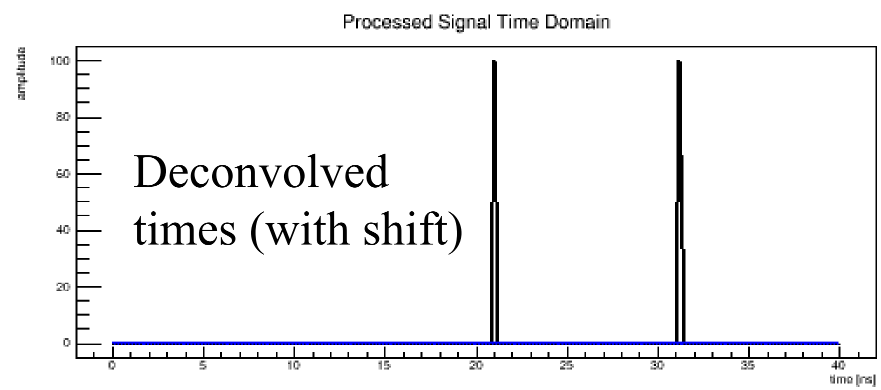
➢ Use Planacon/DRS4 in place of PMTs?



Signal readout/processing

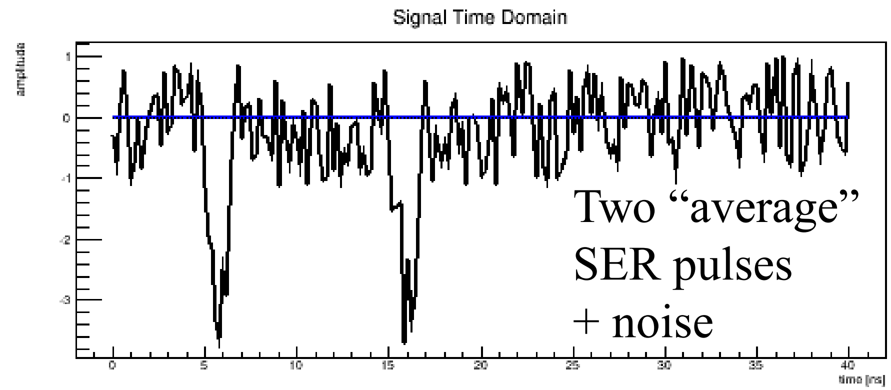
- Not all pixels see well separated single photons.
- Reconstruction algorithm assumes it is handed a list of photon arrival positions & times.
- How to analyze signal trace?
- Use deconvolution with average pulse shape?
- Works great with no noise!

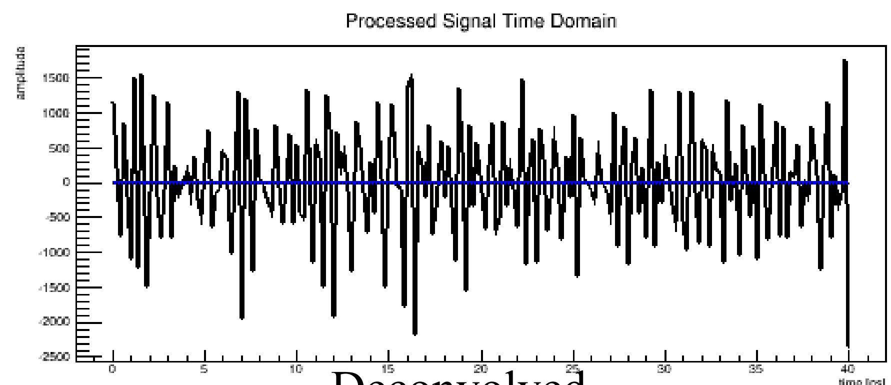




Signal readout/processing

- Not all pixels see well separated single photons.
- Reconstruction algorithm assumes it is handed a list of photon arrival positions & times.
- How to analyze signal trace?
- Use deconvolution with average pulse shape?
- Broken with noise!

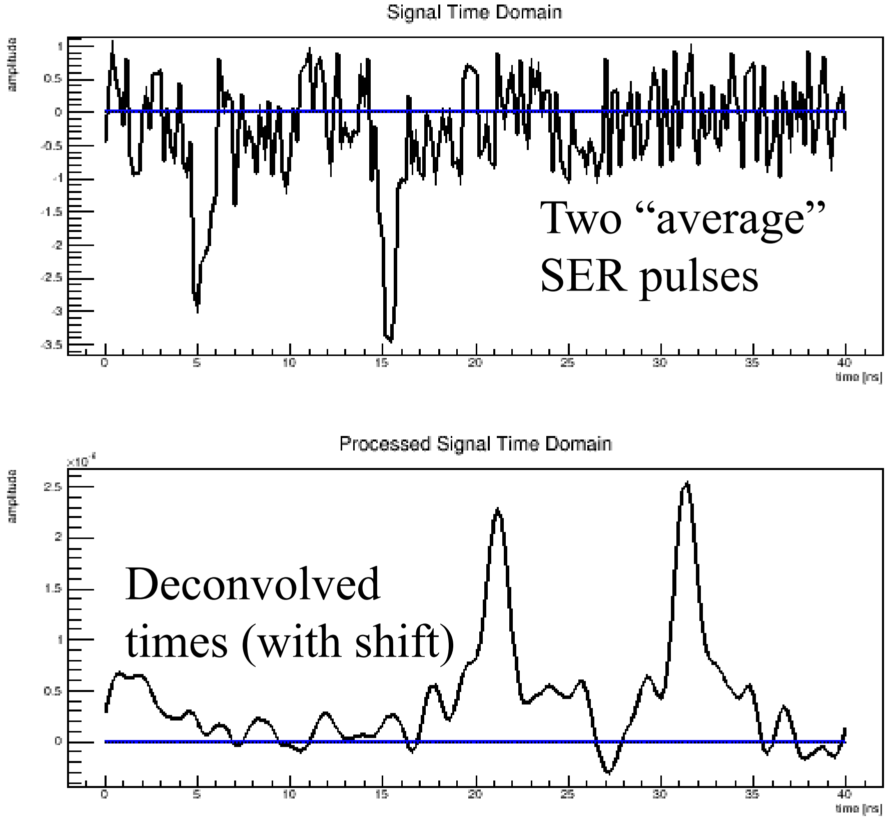




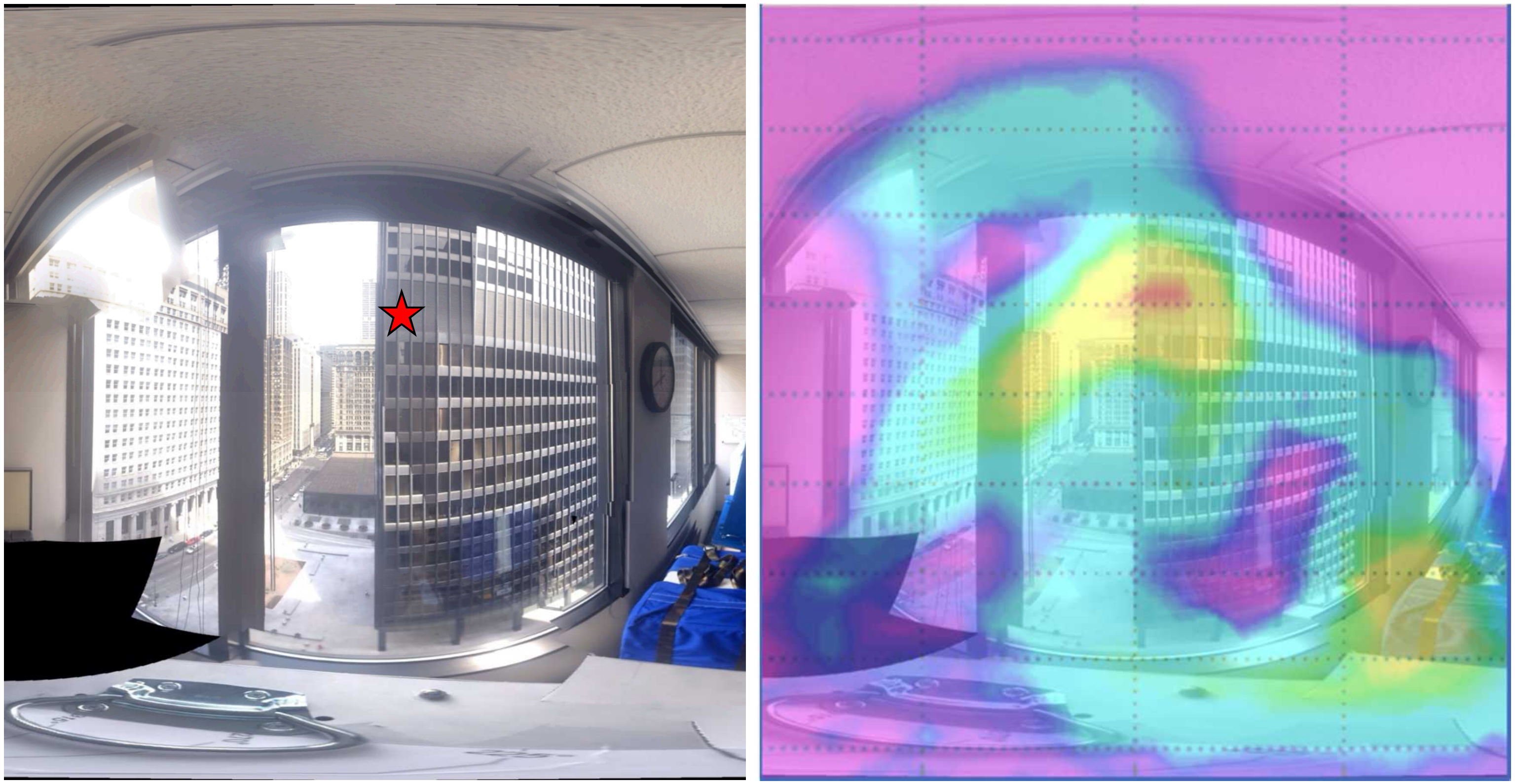
Deconvolved times (with shift)

Signal readout/processing

- Not all pixels see well separated single photons.
- Reconstruction algorithm assumes it is handed a list of photon arrival positions & times.
- How to analyze signal trace?
- Use Wiener deconvolution with average pulse shape?
- Better, but not great…



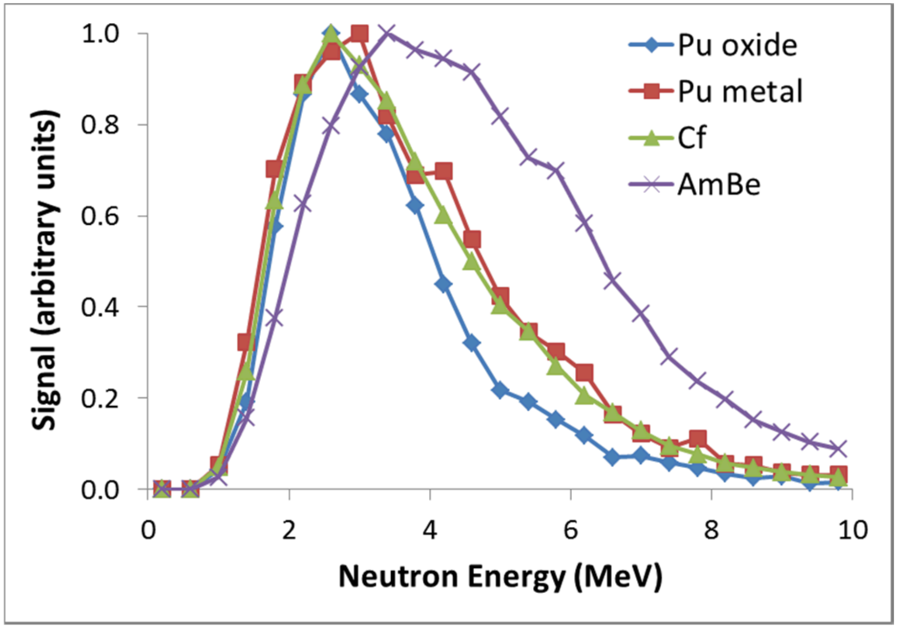
MINER: Building to Building Imaging

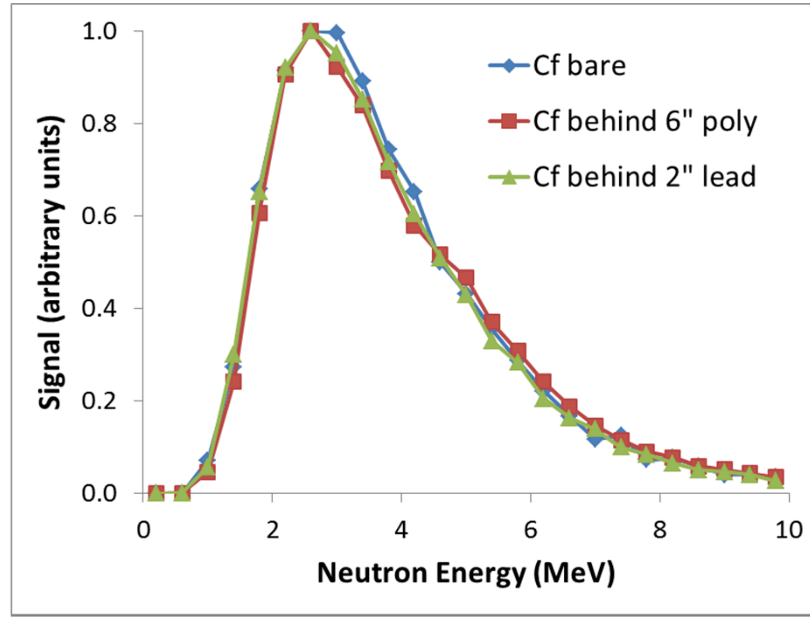


Left: source location (red star) in adjacent high-rise (28 m distance).

Right: neutron image overlaid on photograph

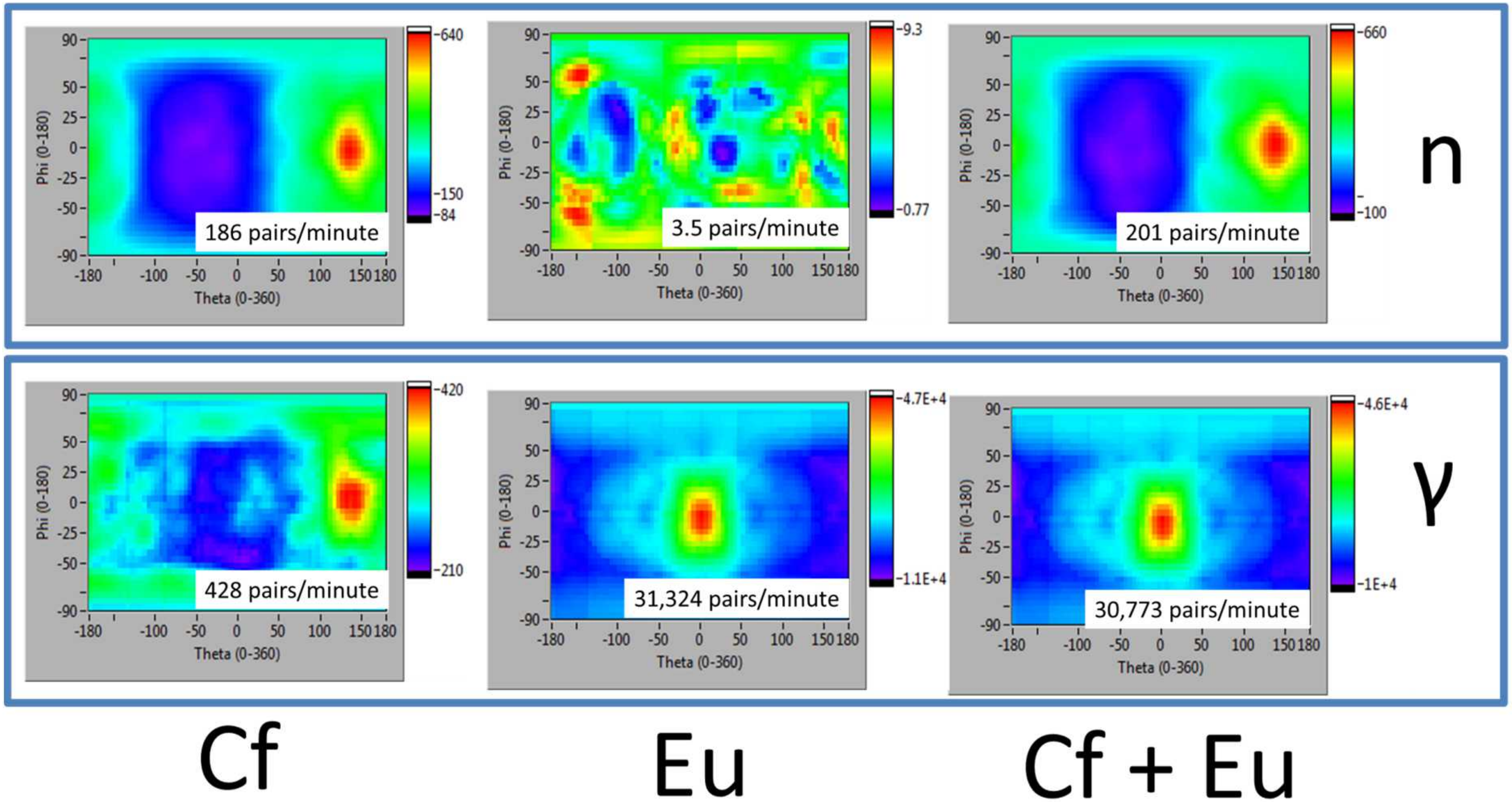
MINER: Neutron Spectroscopy





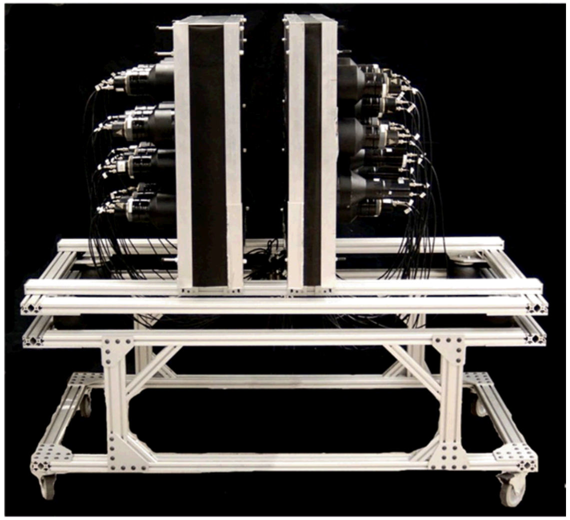
Left – peak-normalized spectra as measured using MINER. Right – insensitivity of Cf spectrum to intervening material as measured by MINER.

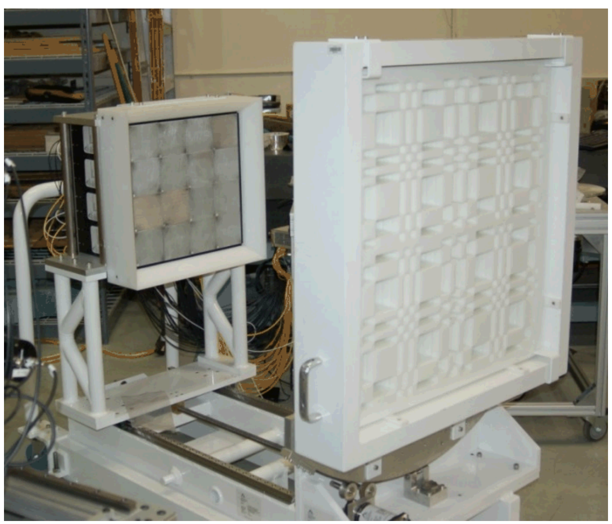
MINER: Gamma Insensitivity for Neutron Imaging



The images above were recorded using a ^{252}Cf source 2 m from MINER at a relative angle of 135°, a strong ^{152}Eu source 1 m from MINER at a relative angle of 0°, and both sources together. This demonstrates the robustness of the neutron image reconstruction process in the presence of gamma fields. (Background neutron rate: ~1.5 pairs/minute.)

Fast neutron imagers @ SNL/CA





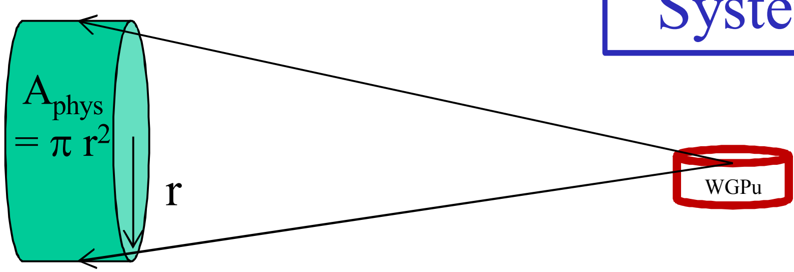
Cast:
P. Marleau
S. Kiff
N. Mascarenhas
J. Brennan
M. Gerling
A. Nowack
J. Steele
S. Mrowka
P. Schuster
K. McMillan
J. Lund
J. Goldsmith
C. Tewell

Fast neutron directional detectors

Common features

- N-P elastic scattering
- Sensitivity to direction
  - Event by event (kinematics)
  - Statistical (many events form a pattern)
- Liquid scintillator based.
  - Gamma discrimination
- Shielding is hydrogenous material.

System attributes



- ***Effective area***: area over which the detector would be 100% efficient.
  - Physical cross-sectional area times the detection efficiency.

$$A_{eff} = A_{phys} * \varepsilon$$

- ***System angular resolution***: resolution of the reconstructed image in the far field.
- ***Event angular resolution:*** resolution on the direction of a single event.