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Proof of Principle Simulation of a Handheld Neutron Scatter Camera

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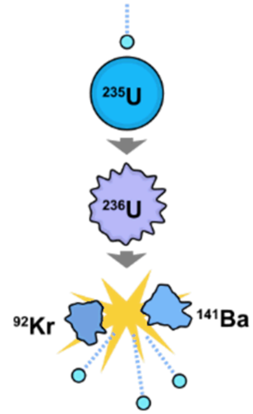
Motivation
The Need for Compact Neutron Imaging Systems

- In certain situations, a human-portable system is needed to identify nuclear warheads
  - Treaty verification
  - Emergency response
- Nuclear weapons have unique shapes of special nuclear material (SNM)
- SNM emit neutrons spontaneously or when interrogated
  - Produced throughout whole volume of SNM
  - Not easily shielded by self or otherwise
- A compact neutron imager can determine the spatial distribution of SNM to identify a nuclear warhead

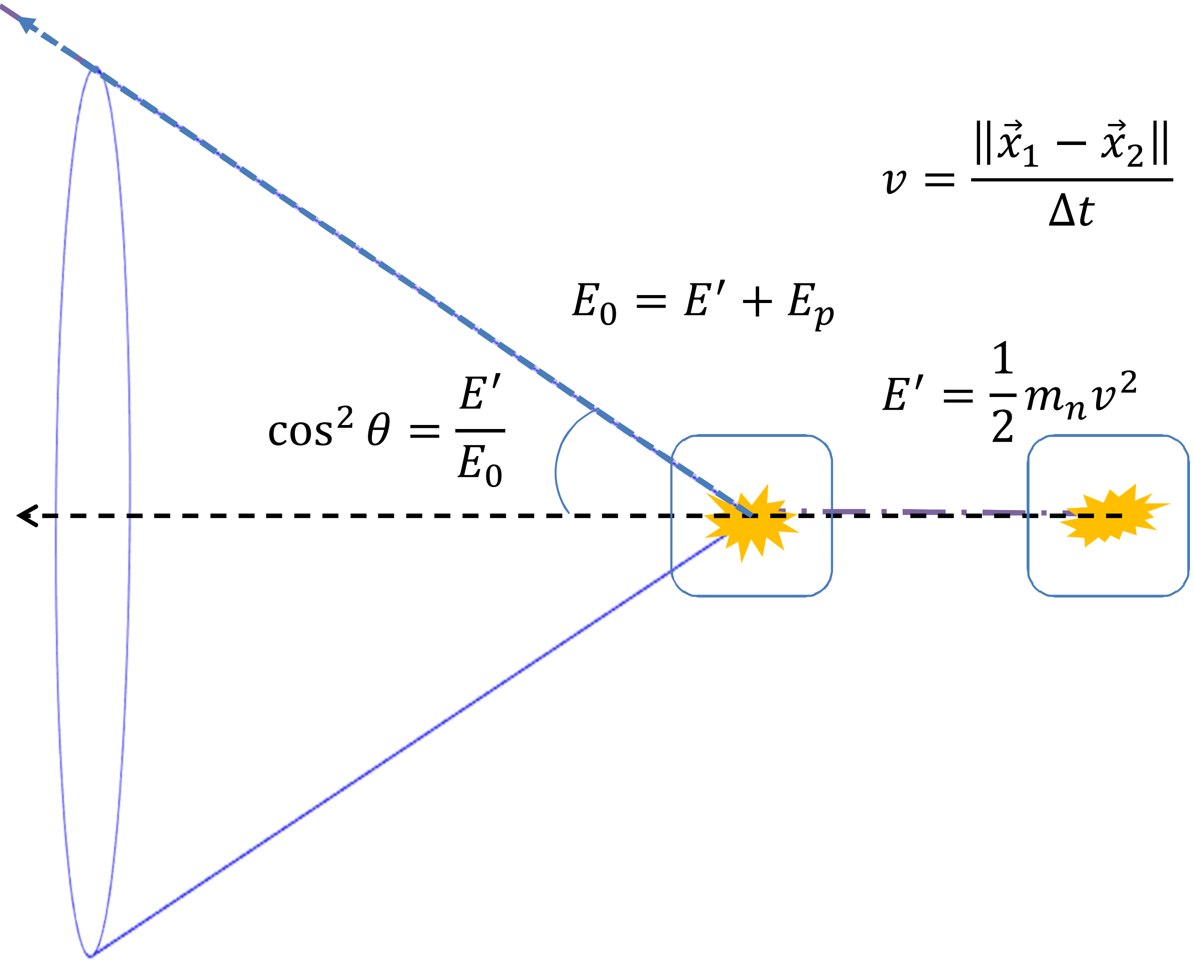


[1]Nuclear fission

[2]Casing of a B83 bomb

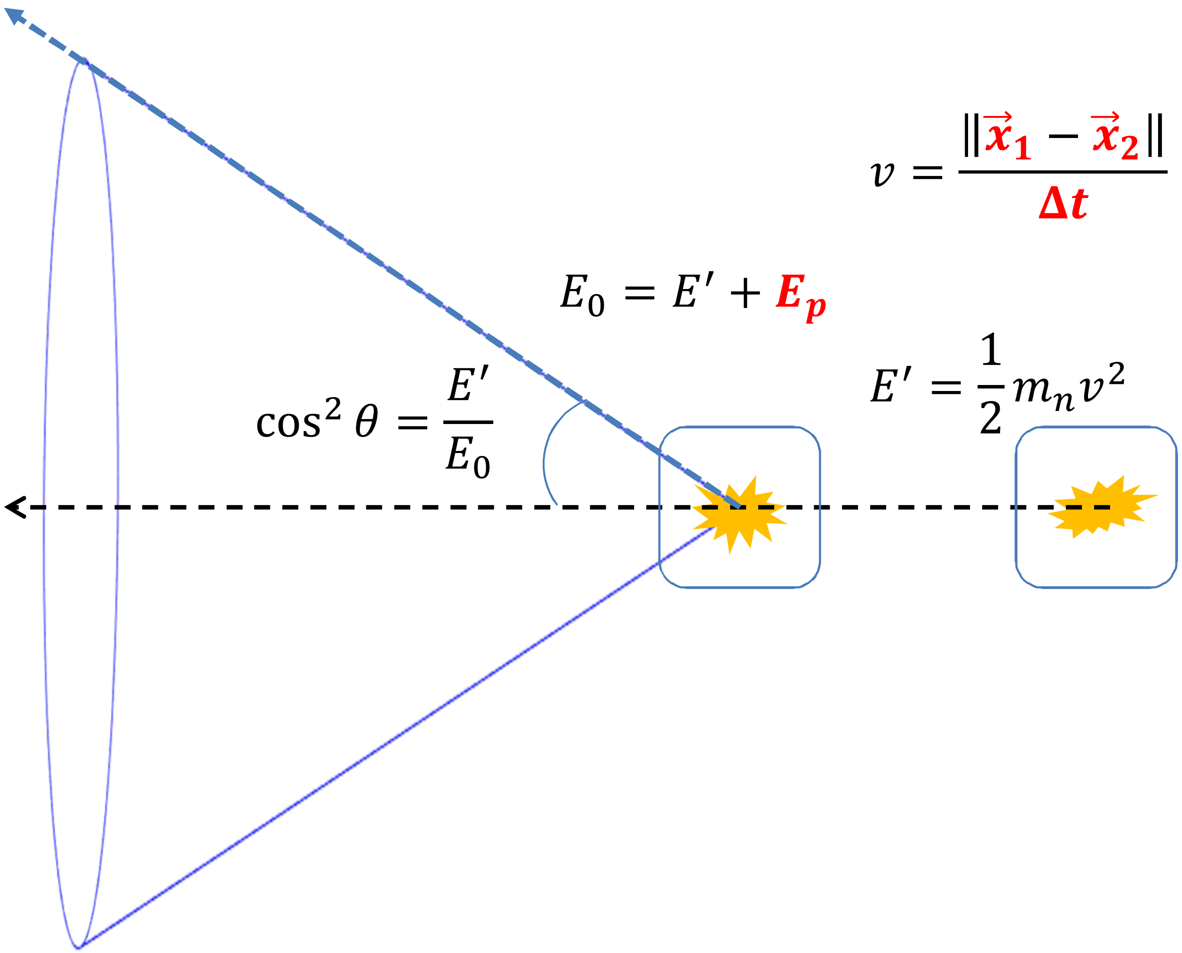
[1]https://commons.wikimedia.org/wiki/File:Nuclear_fission.svg
[2]http://knoxblogs.com/atomiccity/category/y-12/page/181/

Neutron Scatter Camera Principle of Operation



- Neutron scatters twice in hydrogenous medium
- Velocity is determined from time and distance between scatters
- Energy of scattered neutron determined from velocity and neutron mass
- Incident neutron energy determined through energy of scattered proton and energy conservation
- Scatter angle follows from incident and scattered energies
- Net result of scatter axis and angle: cone of possible incident directions

Neutron Scatter Camera Required Measured Quantities



$$v = \frac{\|\vec{x}_1 - \vec{x}_2\|}{\Delta t}$$

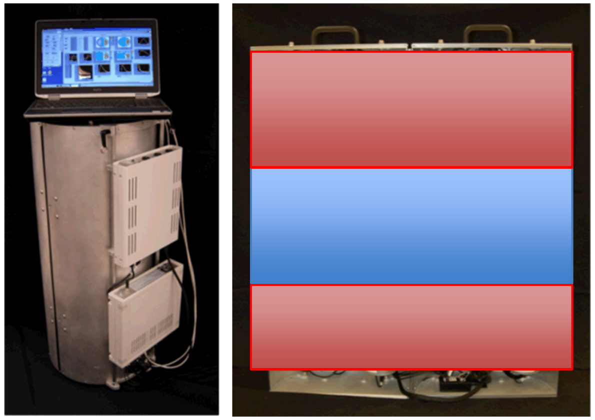
$$E_0 = E' + E_p$$

$$\cos^2\theta = \frac{E'}{E_0}$$

$$E' = \frac{1}{2} m_n v^2$$

- Determine incident particle is a neutron using PSD
- Measure time of flight
- Measure position of each collision
- Measure energy deposited in first collision

Previous Neutron Scatter Camera Designs



Photos curtesy of John Goldsmith

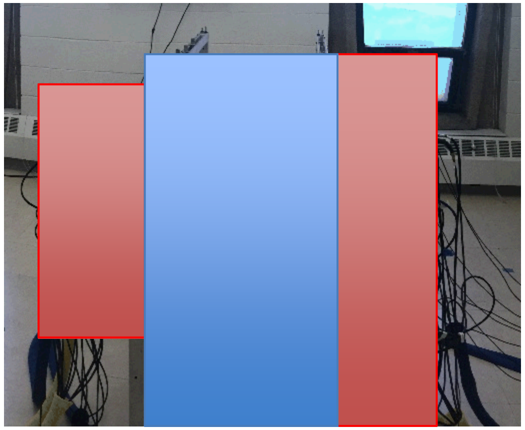
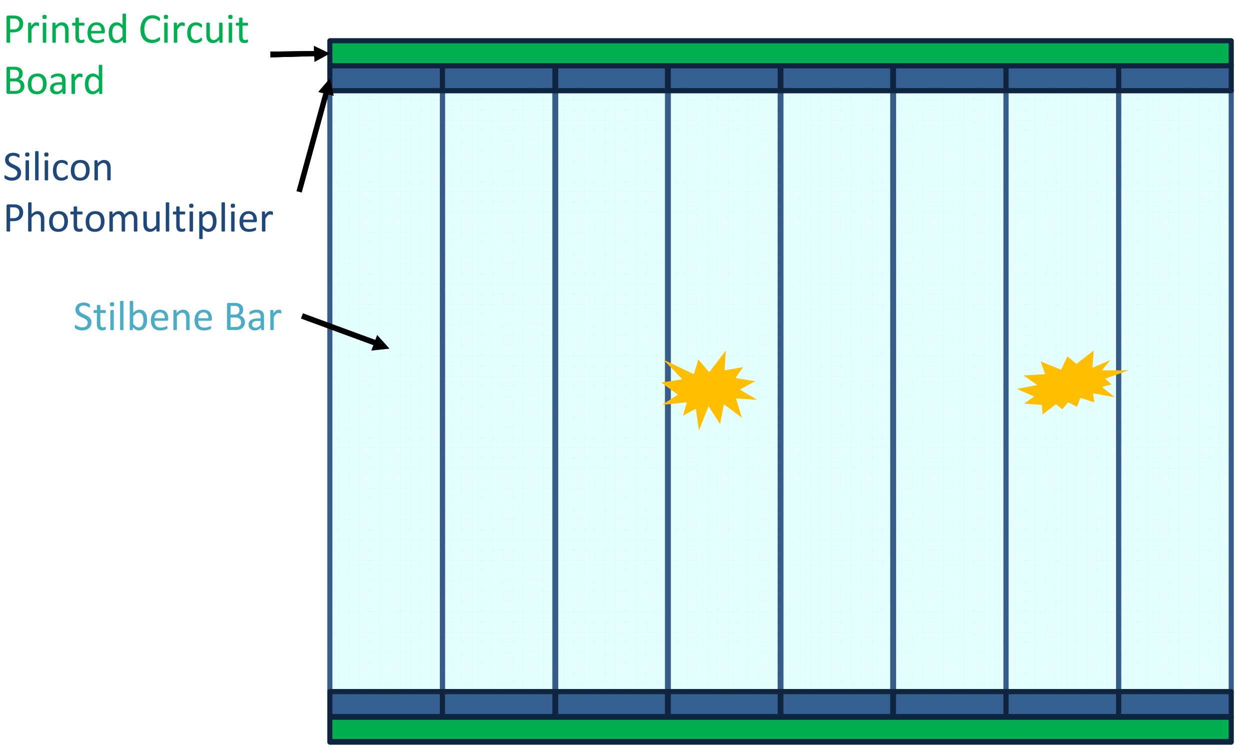
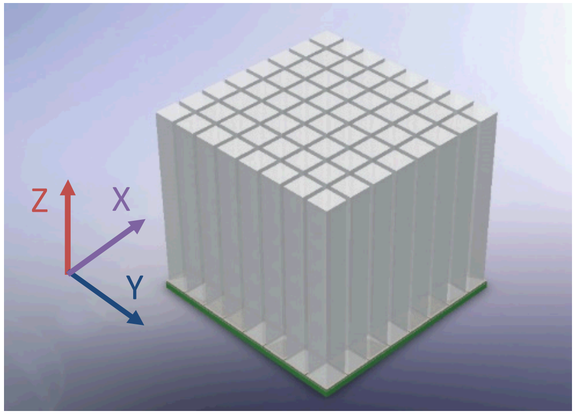


Photo curtesy of Kyle Polack

Multi-Pillar Scatter Camera

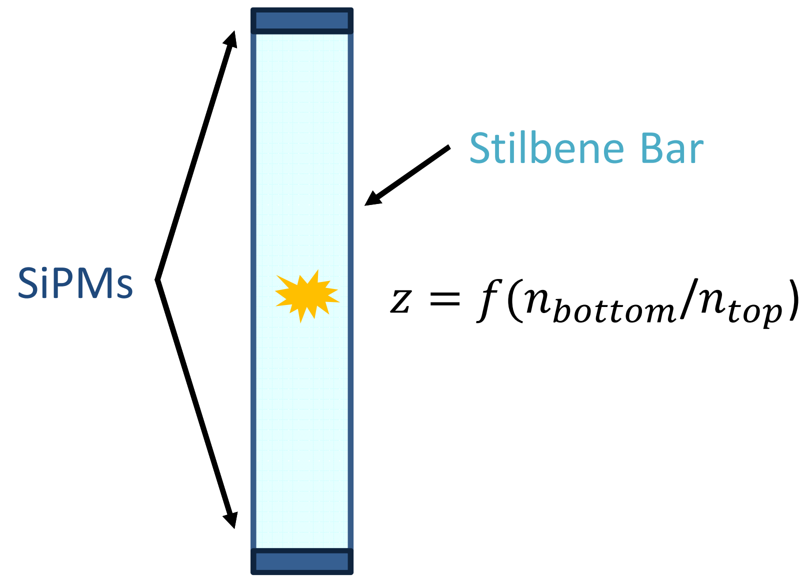


- X, Y position determined by channel
- Z position determined by relative amount of light reaching top and bottom sensor



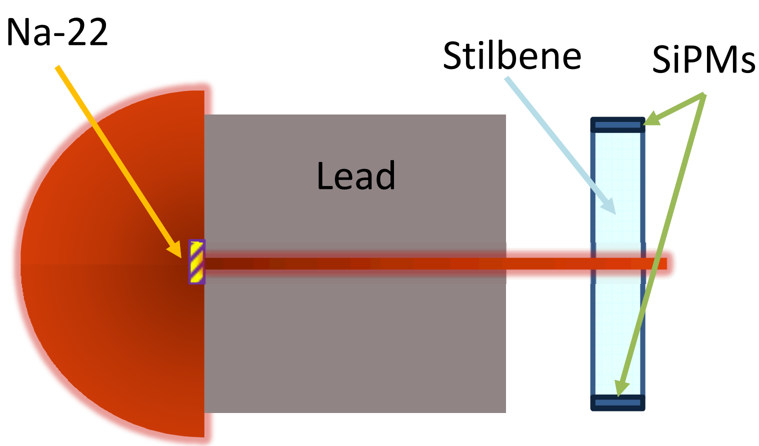
Position Within Bar

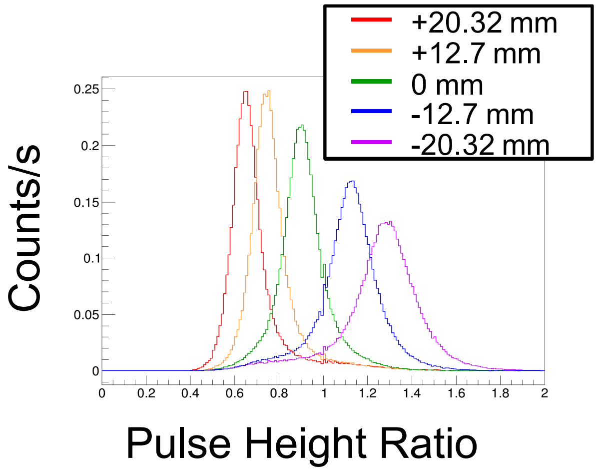
- Number of scintillation photons that reach a SiPM on either end of a bar of scintillator is a function of
  - Energy deposited
  - Scintillation efficiency (# photons/MeV)
  - Light collection efficiency
    - Function of position
  - Photo-detection efficiency
- When taking the ratio of scintillation photons at bottom to those at the top
  - Energy deposited cancels out
  - Scintillation efficiency cancels out
  - Light collection efficiency ratio a function of position
  - PDE ratio is constant
- Ratio varies with position, not energy

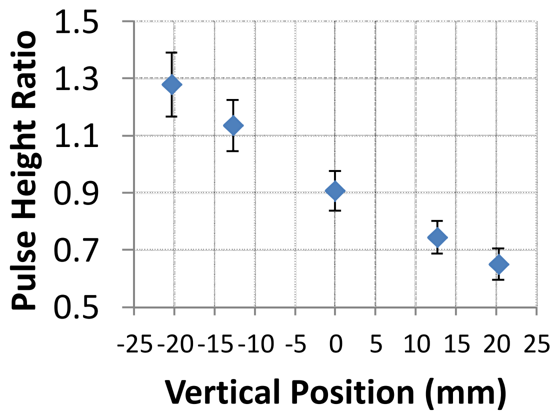


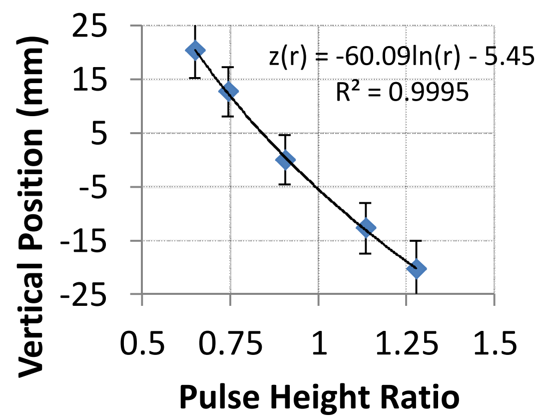
Measurement of Position Resolution

- Measured position sensitivity within a bar of stilbene with a SiPM on either end
  - 0.6 cm x 0.6 cm x 5.0 cm
- Collimated Na-22 source
- Measured at 5 positions along bar
- Position certainty of ± 0.5 cm



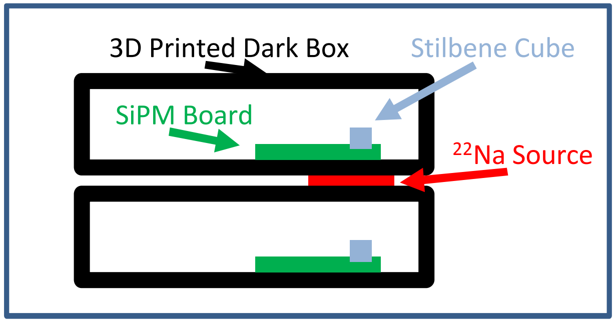


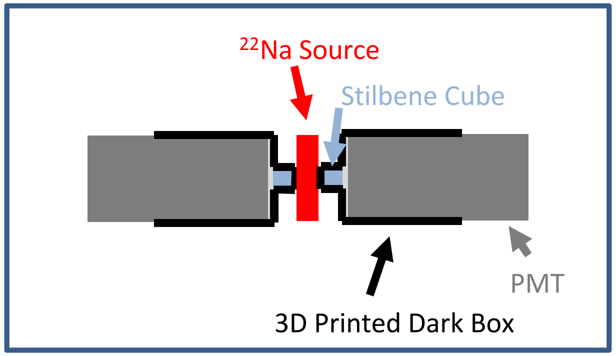


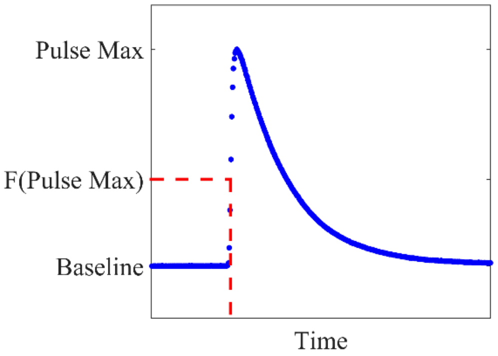


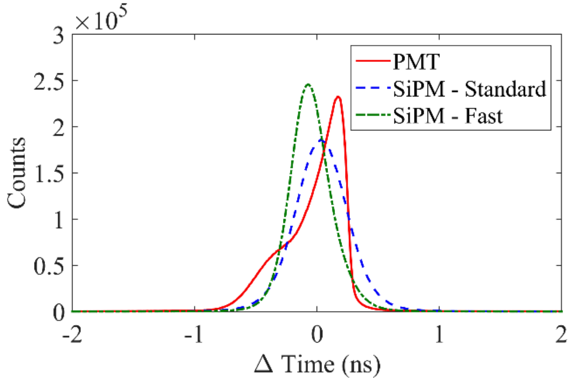
Measurement of Timing Resolution

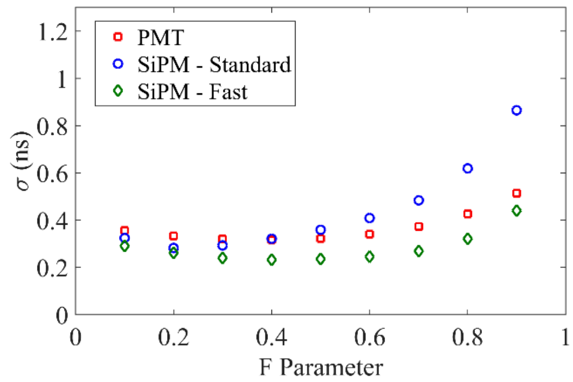
- Measured timing of stilbene/SiPM system using coincident Na-22 annihilation photons
- CAEN DT5730 digitizer (500 MS/s)
- SensL C-Series SiPM
- Hamamatsu H10580 PMT Assembly
- SiPM standard output: 0.28 ns σ
- SiPM fast output: 0.23 ns σ
- Fast PMT: 0.32 ns σ







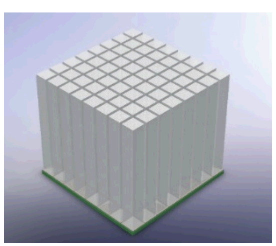


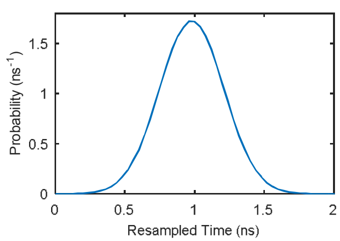


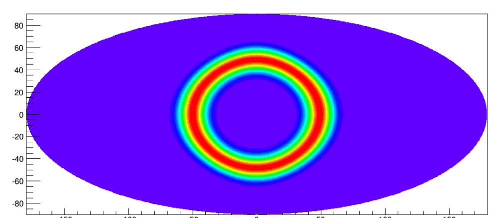
Simulation of the Handheld Neutron Scatter Camera

Particle Transport	Detector Response	Coincidence Pairing	Cone Projections	List Mode MLEM Image

• MCNPX-PoliMi
• Cf-252 spontaneous fission source at 1m from imager
• Collect neutron collisions in imager active volume
	• Energy deposited to light
	• Centering of X, Y position
	• Gaussian broadening of
	  • Light
	  • Time
	  • Z position
		• Match pulses coincident in time
		• Both above threshold
		• Reject within same crystal
		• Reject adjacent crystals
			• Back project cone onto sphere
			• Uncertainty in measured quantities propagated into cone width
				• Produce response matrix from cone projections
				• Observation matrix is vector of ones
				• Iterate, increasing likelihood of source image with each step







Cone from Single Event

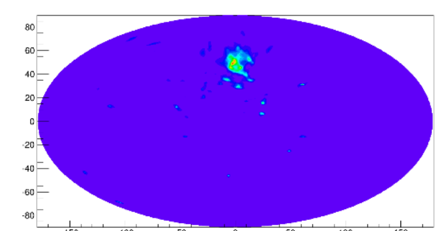


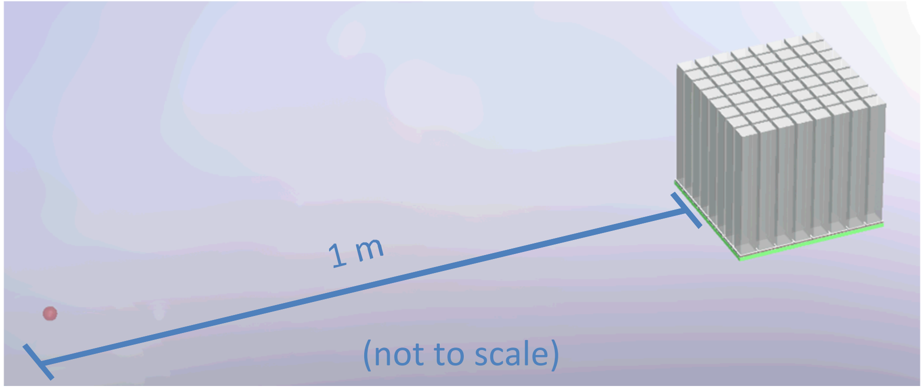
Image from Many Events

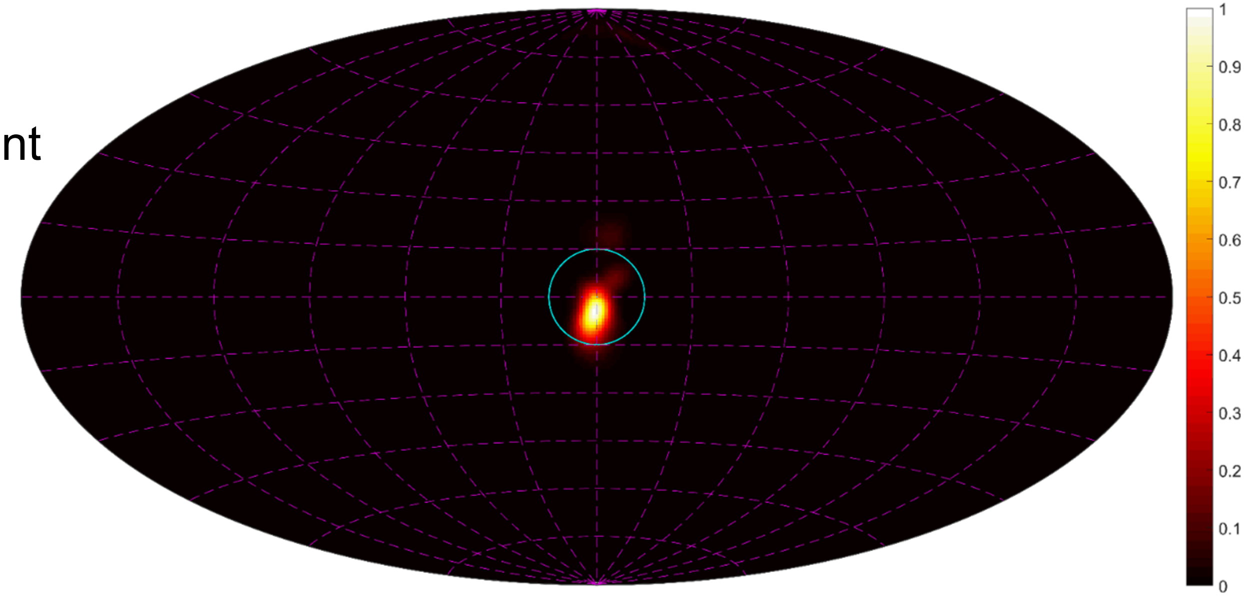
Results

- 30 minute simulated measurement
- 20,000 n/s Cf-252 source

- 64 correlated events
- 0.657% (±0.001%) of incident fission neutrons produce a correlated event
- 0.18 cm^2 effective area

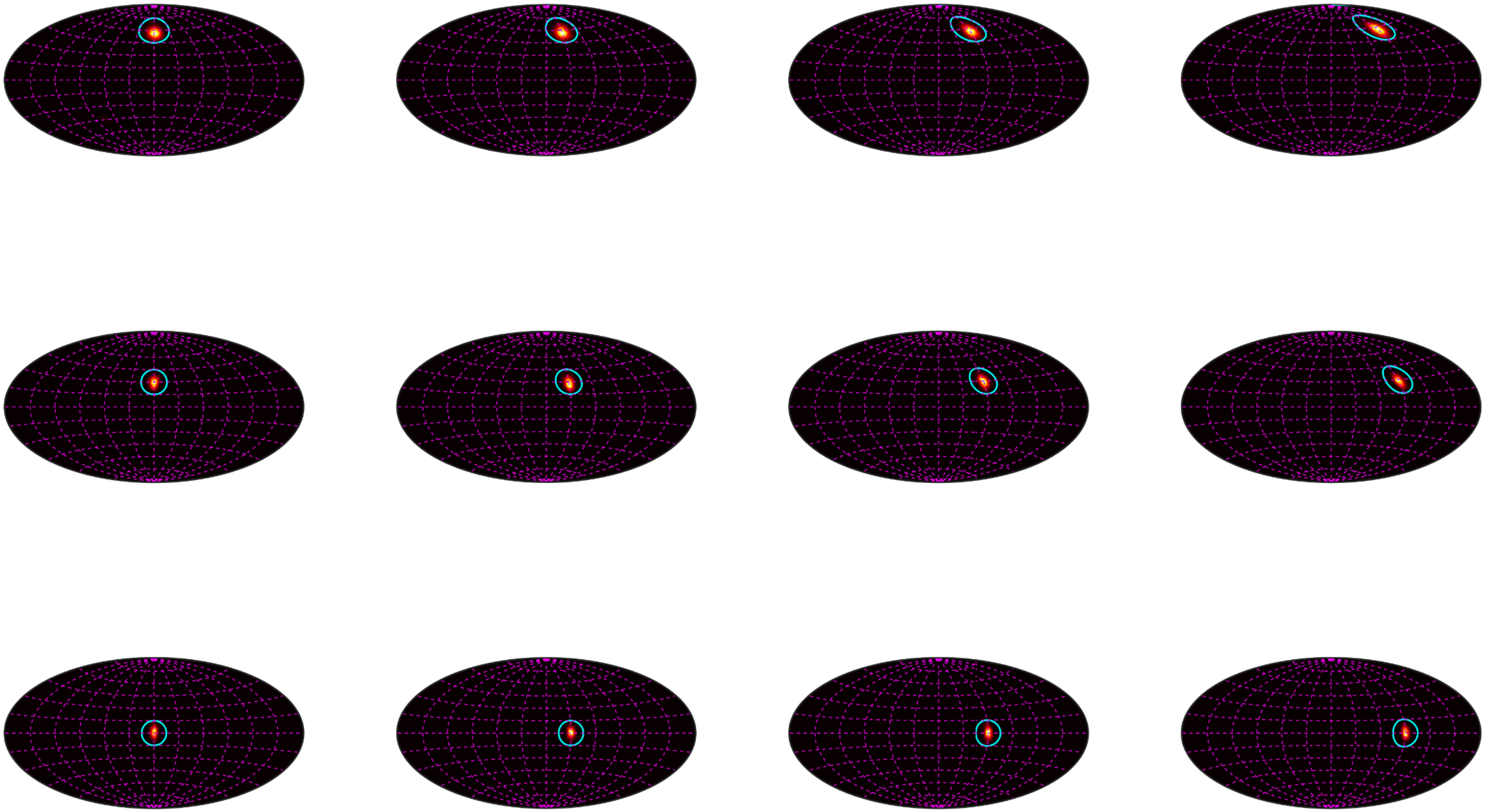
- Blue circle for reference:
  - 15° radius



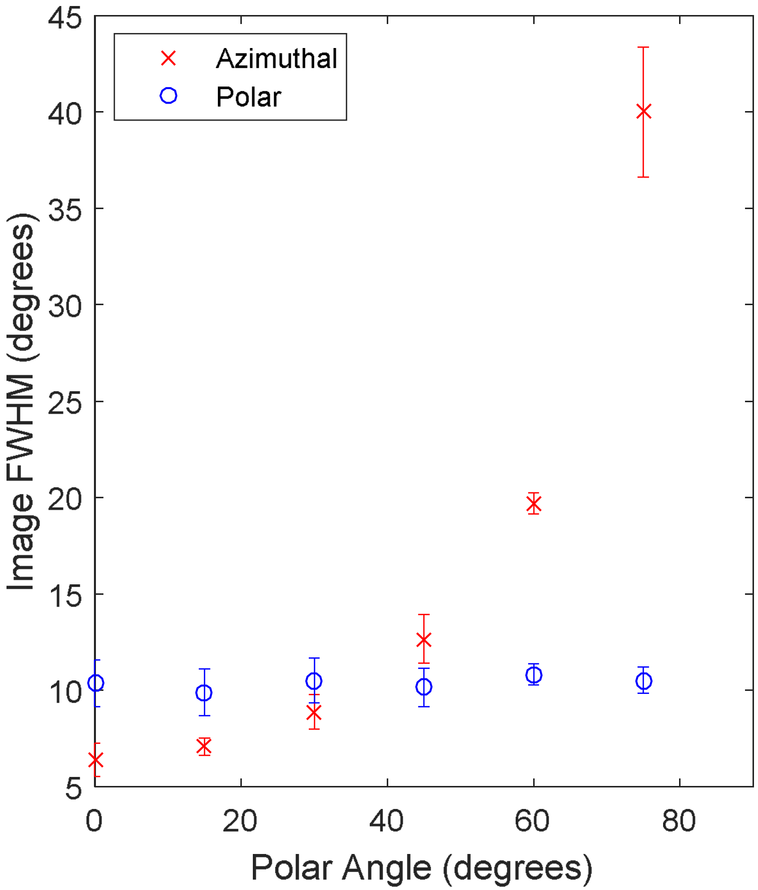


List Mode MLEM Image of Full 4π Field of View

Accurate Location Determination



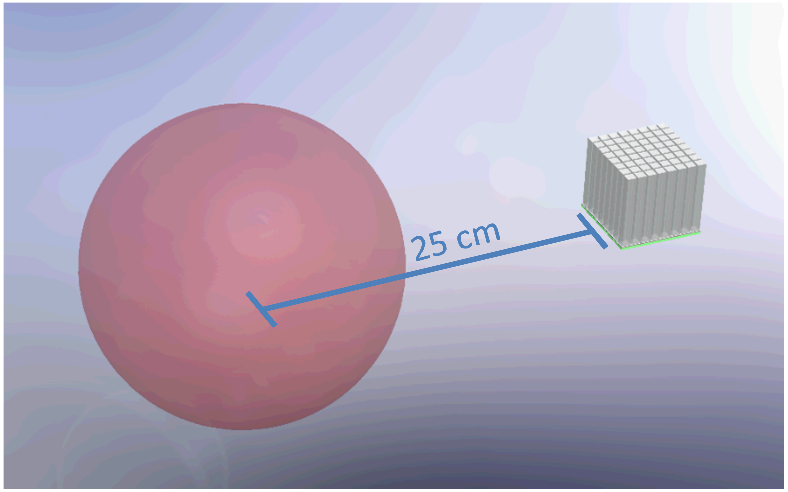
Angular Resolution

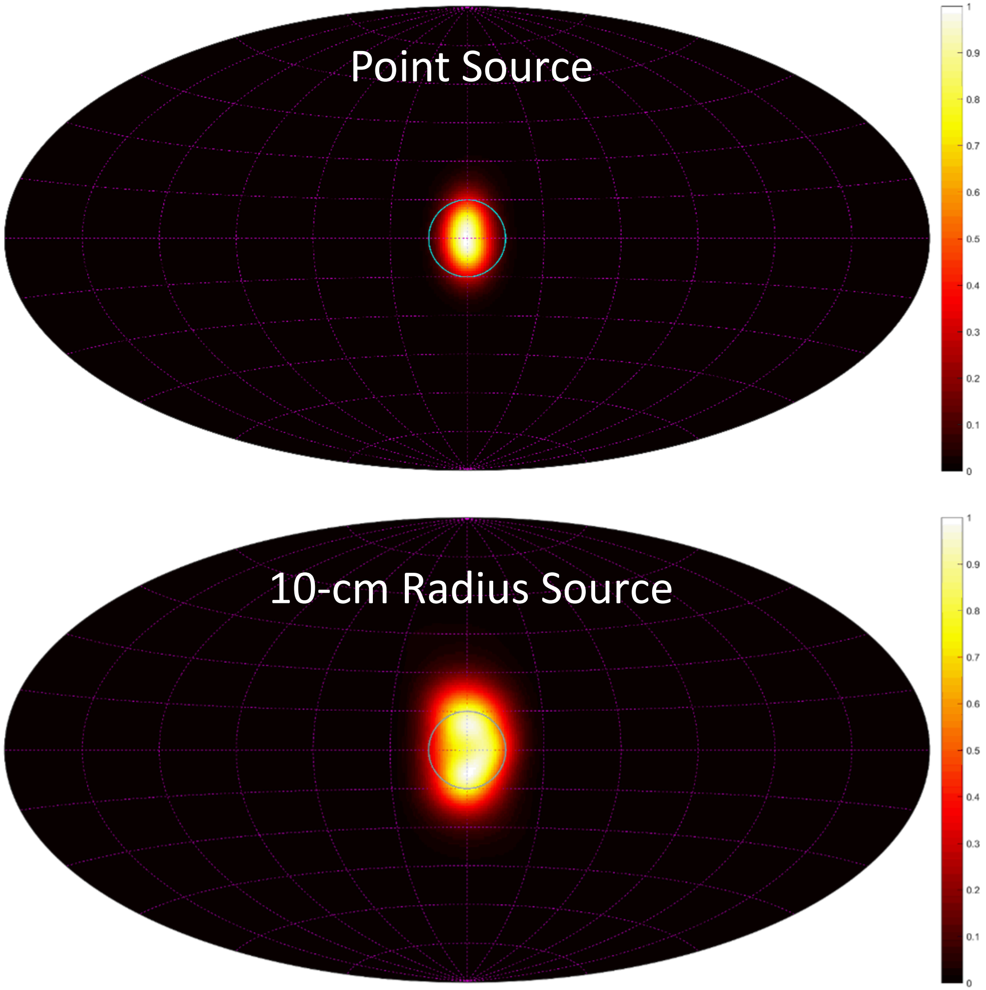


- Angular resolution calculated along lines of latitude and longitude through source location
- Technique not apples-to-apples along different lines of latitude
- Mean polar angle FWHM: 10.37° ± 0.98°
- Approximate angular standard deviation: 4.4° ± 0.4°

Measuring Distributed Sources

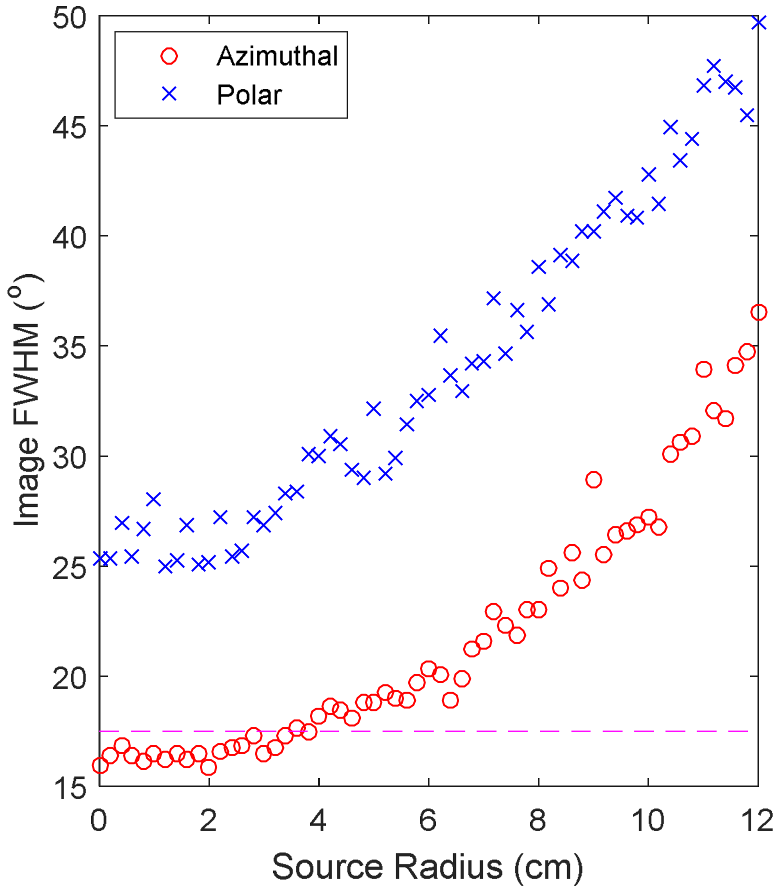
- 10^8 fissions simulated
  - Equivalent of 16.7 minutes at 10^5 neutrons/s source
- 25 cm source-imager distance
- Reference blue circle: 15° radius





Volume Source Size Estimation

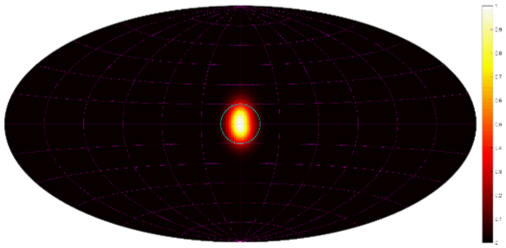
- Simulated spheres emitting Cf-252 fission neutrons
- 10^8 fissions
  - Equivalent to 16.7 minutes with 10^5 neutrons/s source
- Source-imager distance: 25 cm
- Magenta line is 3σ above mean of data points below 3 cm
- All spheres at or in excess of 4 cm in radius exceed this confidence line
  - 1 IAEA significant quantity of Pu metal (8 kg) is equivalent to a sphere with a radius of ~4.6 cm

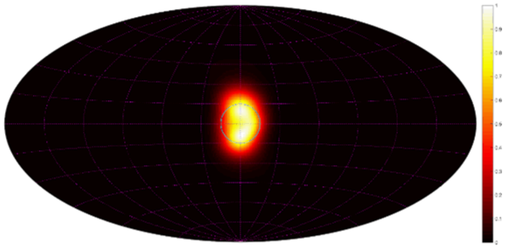


Conclusions

- Previously demonstrated stilbene/SiPM performance is adequate to create a compact neutron scatter camera based on a multi-pillar design
  - Position sensitivity within 5 cm bar of stilbene: 0.5 cm σ
  - Timing performance: 0.23 ns σ

- Simulation results show the design's ability to accurately locate and determine information on the spatial distribution of a fission source
  - Imaging intrinsic efficiency: 0.66%
  - Angular resolution: 10° FWHM
  - Minimum distinguishable sphere radius @ 25 cm: 4 cm





- Work in progress: prototype under construction
  - Recently awarded DTRA funding for Handheld Dual Particle Imager (H^2DPI)

Acknowledgements

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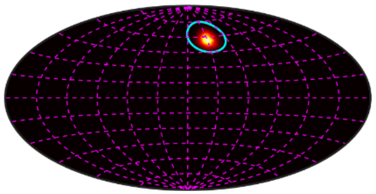
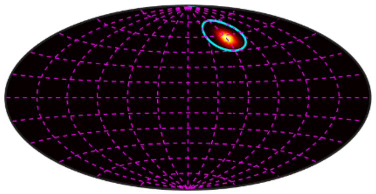
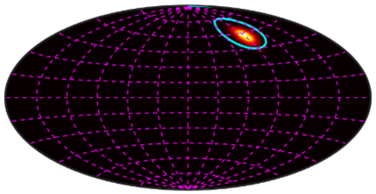
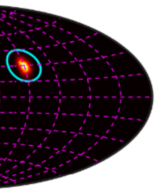
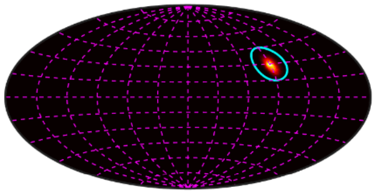
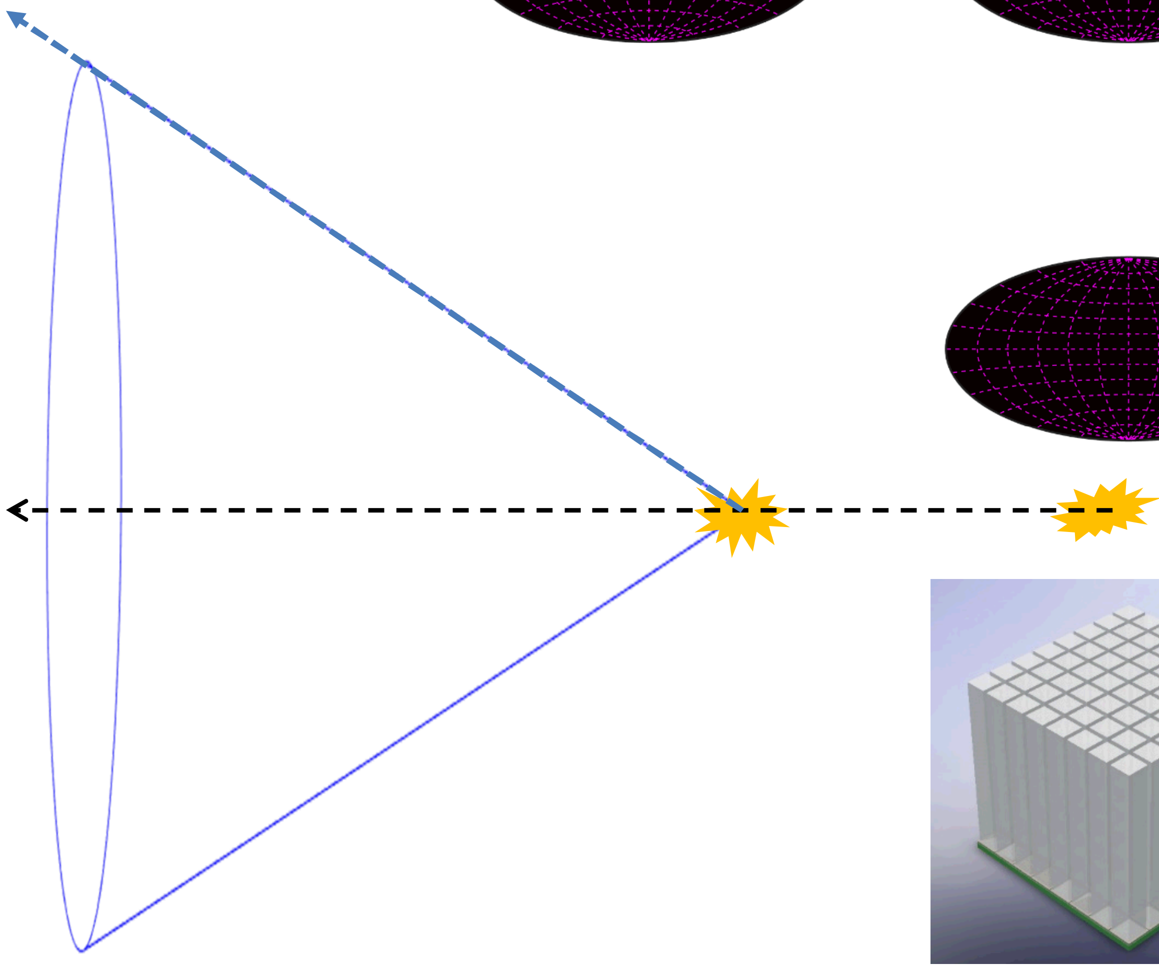
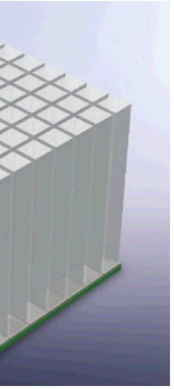
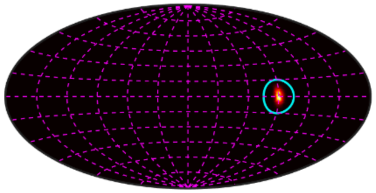
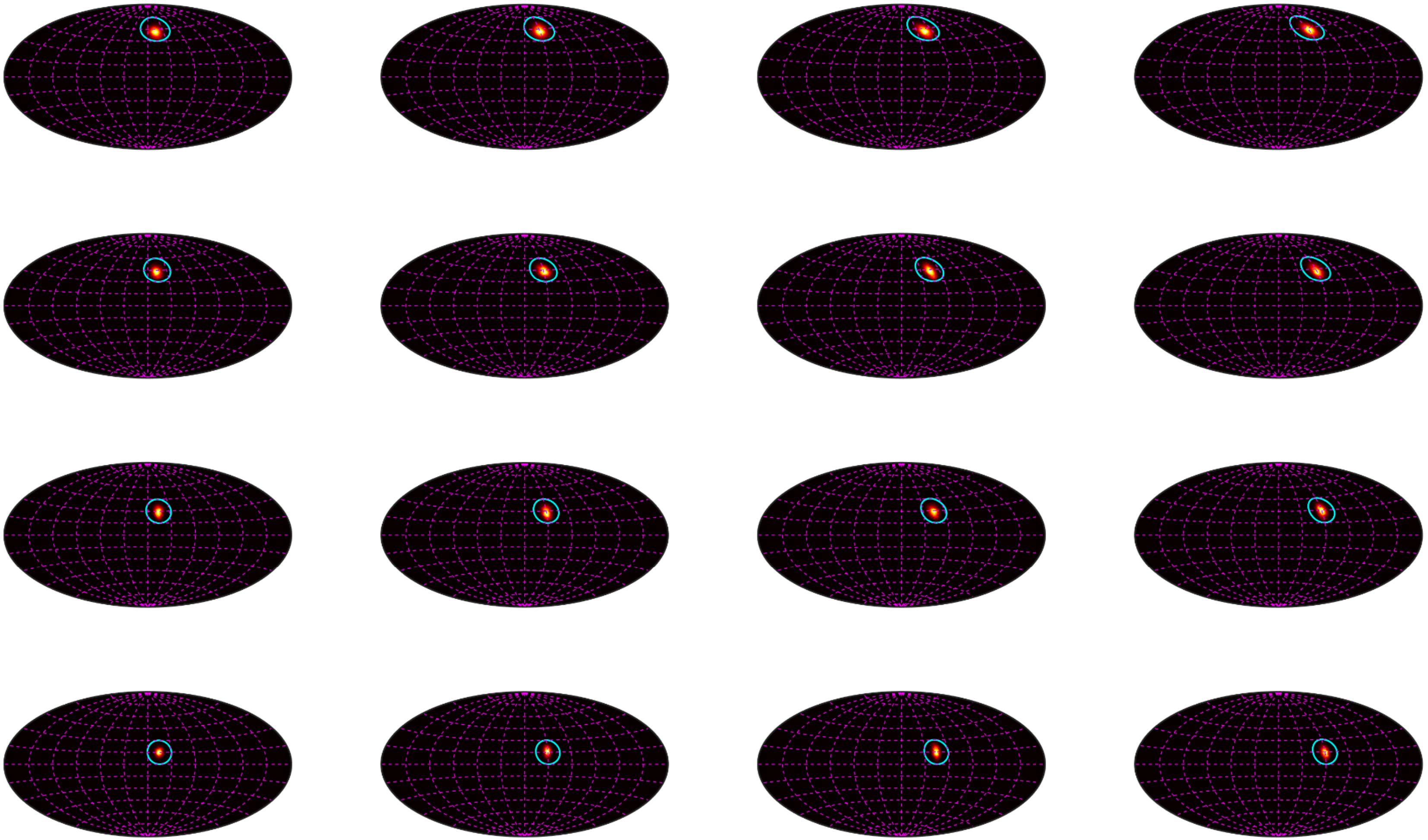
Questions

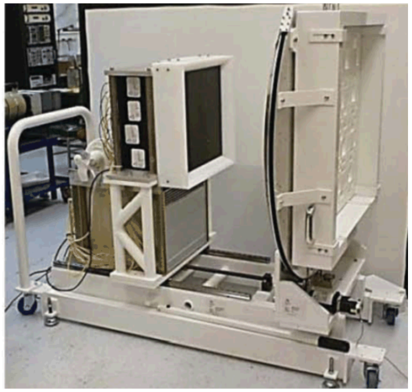
BACKUP SLIDES

Accurate Location Determination

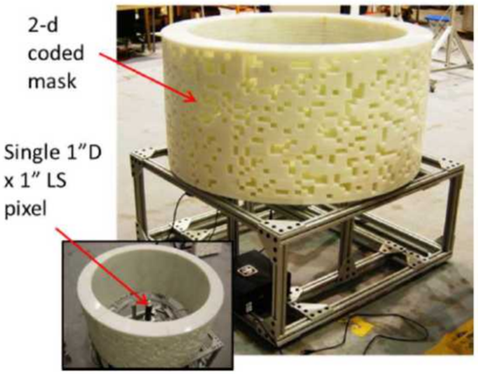


Neutron Scatter Cameras
High Potential for Compactness

- Aperture-based imagers
  - Resolution scales with number of elements
  - **Require large amounts of shielding to make aperture/mask**
- Time encoded approaches
  - **Require enough material to modulate signal**
  - **Large mechanical system**
- Neutron scatter cameras
  - Lower spatial resolution than coded-aperture technique
  - Requires double-scatter for imaging events
  - Gives spectral information
  - **Potential to make very compact while still effective**



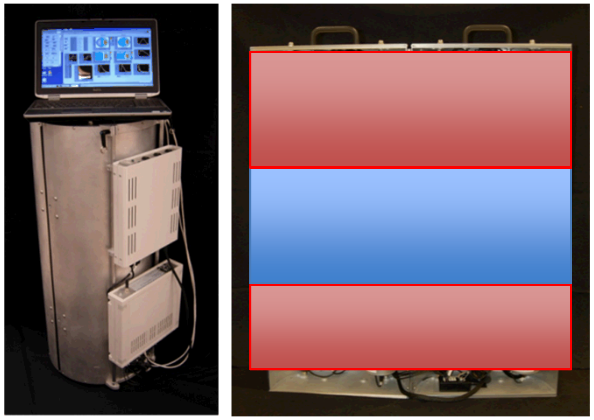
Hausladen et. al., "Fast-Neutron Coded-Aperature Imaging of Special Nuclear Material Configurations," 2012.



Marleau et. al., "Time-Encoded Imagers," 2014.

PMTs in Neutron Scatter Cameras

- Traditionally, photomultiplier tubes (PMTs) have been used to sense light from organic scintillators, being the only option that combines
  - Good resolution
  - Fast timing
  - Preservation of time profile
  - Relatively good price
- Bulky and fragile vacuum tubes
- Require high voltage
- Highly sensitive to magnetic fields
  - Earth's magnetic field is enough to impact performance
  - Require mu metal shielding
- **Take up the majority of neutron scatter camera volume**



Photos curtesy of John Goldsmith

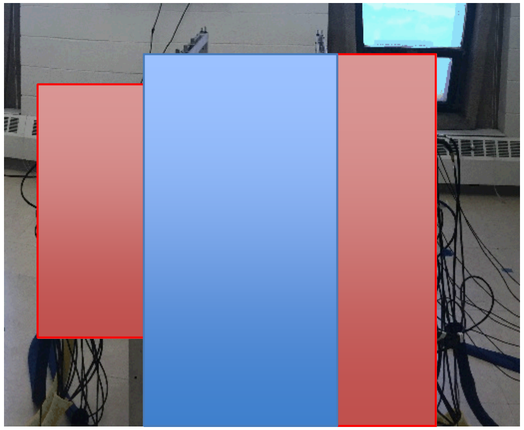
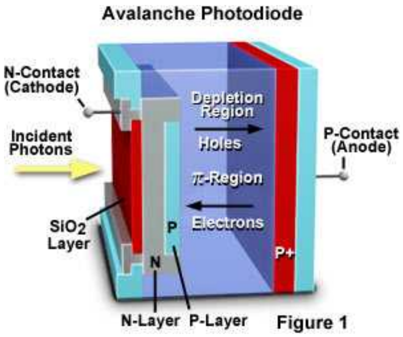


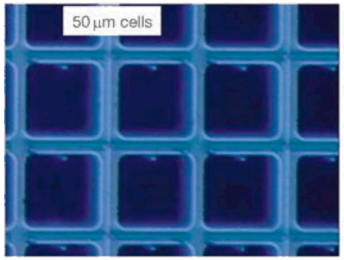
Photo curtesy of Kyle Polack

Silicon Photomultipliers (SiPMs)

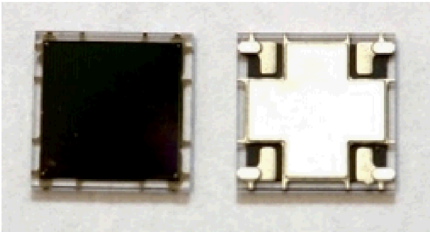
- Single photon avalanche diode (SPAD) invented in 1960s
- Metal-resistor-semiconductor (MRS) avalanche photodiodes (APDs) invented in 1990s
- Multi-cell devices produced shortly thereafter
- Composed of many avalanche photodiodes
- Operate at low voltage (<100V)
- Insensitive to magnetic fields
- **Small packaging**
- Cost comparable to PMTs
- Gain comparable to PMTs
- Time resolution comparable to fast PMTs
- Up until recently, plagued by
  - High dark count rates
    - Greatly reduced by improved silicon handling
  - Optical Crosstalk
    - Substantially reduced by optical trenches



http://micro.magnet.fsu.edu/primer/digitalimaging/concepts/avalanche.html



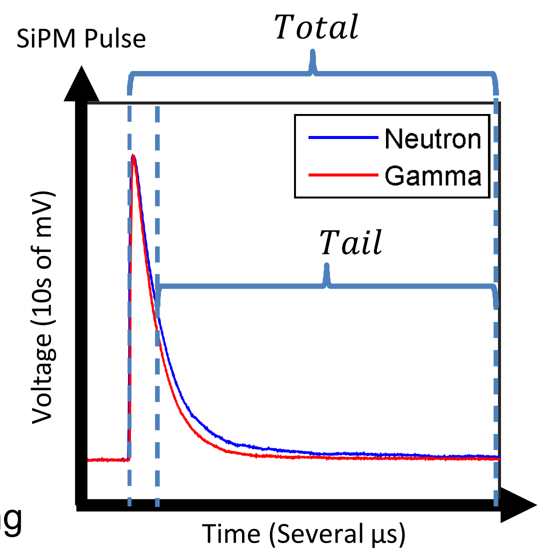
From E. Garutti, 8.21 - Silicon Photomultipliers, In Comprehensive Biomedical Physics, Oxford, (2014)

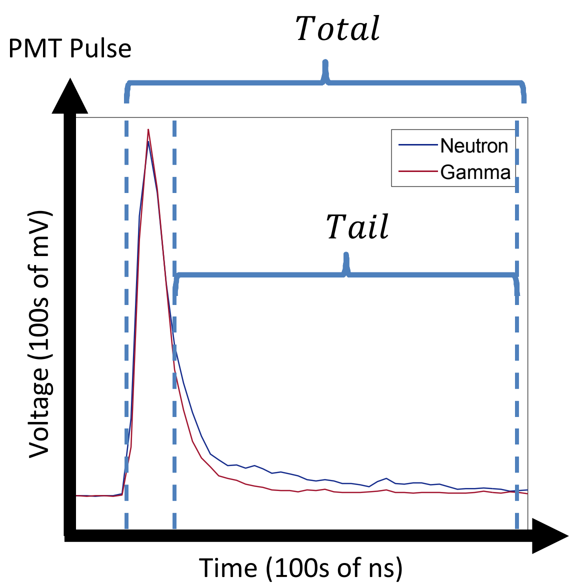


http://sensl.com/estore/microfc-60035-smt/

Pulse Shape Discrimination

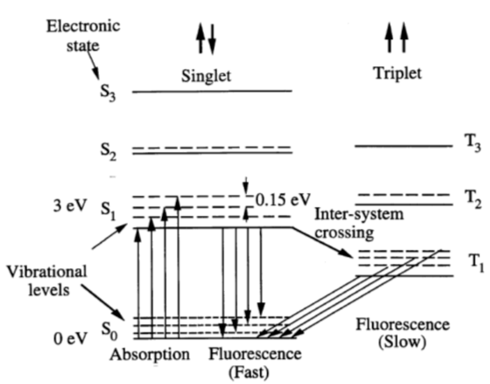
- Gamma rays scatter off of electrons
  - Lower stopping power ($\frac{dE}{dx}$)
- Neutrons scatter off of protons
  - Higher $\frac{dE}{dx}$
  - Larger density of ionization and excitations results in more quenching
- Singlet-singlet quenching reduces prompt component
- Triplet-triplet annihilation increases slow component
- Ratio of delayed light to total light indicates particle type

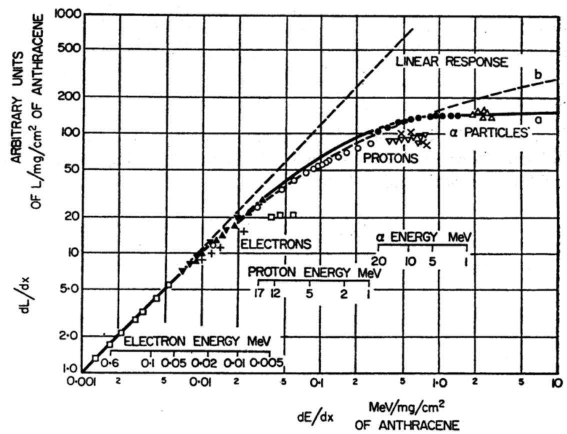




$$R = \frac{Tail}{Total}$$

Typical energy levels
(from Birks, as redrawn by Derenzo)



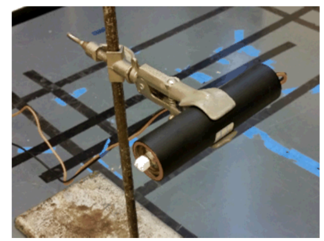


(Brooks, from Birks)

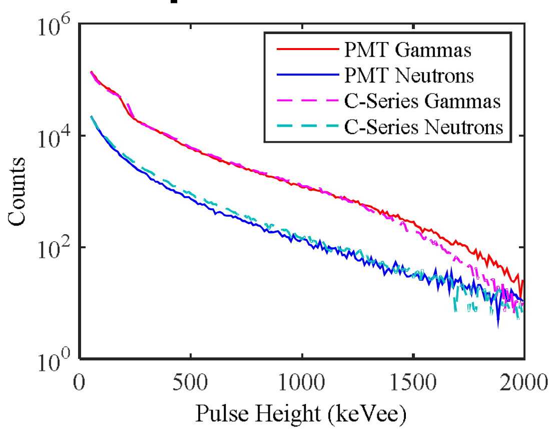
Measurement of Pulse Shape Discrimination

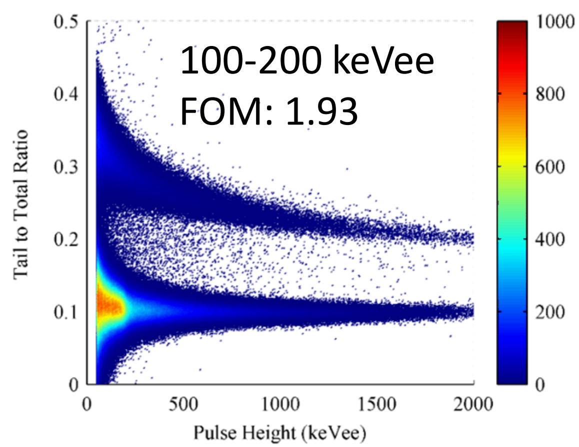
- Performed measurements with fast PMT and C-Series SiPM
  - Each coupled to stilbene
- Calibrated with Cs-137 source
- Measured Cf-252 fissions
- CAEN DT5730 digitizer (500 MHz)
- Optimized PSD integral ranges
- **First results showing SiPM PSD comparable to PMT**

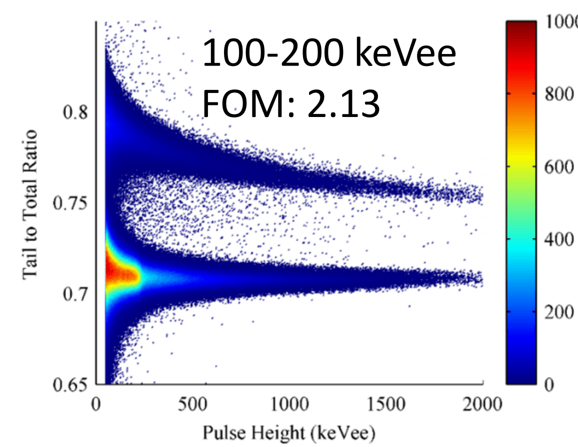
PMT



C-Series SiPM







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