Proof of Principle Simulation of a Handheld Dual Particle Imager

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Consortium for Verification Technology (CVT)

Introduction

Motivation

Human-portable systems are needed to locate special nuclear material (SNM) and identify warheads and for:

- Safeguards
- Treaty verification
- Emergency response

Nuclear weapons contain unique shapes of SNM that distinguish them from less dangerous items. SNM emits neutrons and gamma rays spontaneously or when interrogated.

A handheld dual particle imager (H²DPI) can exploit these two signatures to identify nuclear warheads.

Scatter Camera Operation

Neutron Scatter Camera

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

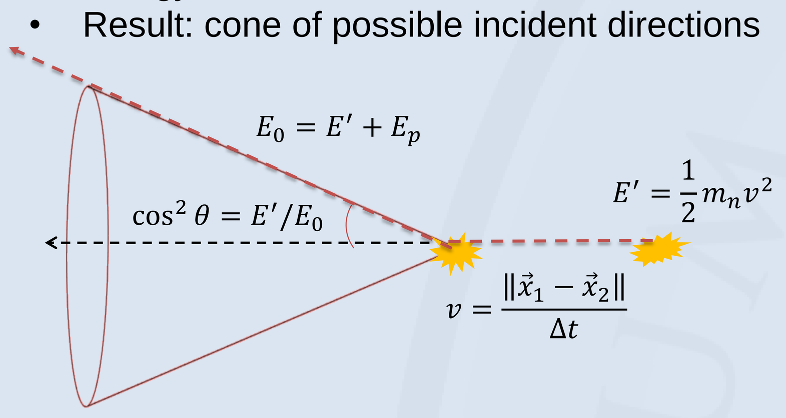

Figure 1: Diagram of neutron scattering kinematics.

Compton Scatter Camera

- Photon Compton scatters twice in low-Z material
- Energy of inter-scatter photon is approximated by empirical function of energy deposited in second scatter
- Incident photon energy approximated by adding inter-scatter energy to energy deposited in first scatter
- Scatter angle determined from Compton equation, follows from conservation of energy and momentum
- Result: cone of possible incident directions

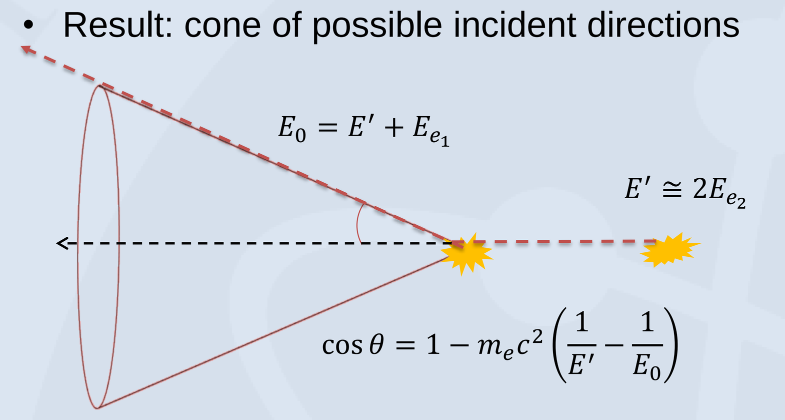

Figure 2: Diagram of photon scattering kinematics.

Handheld Dual Particle Imager (H²DPI) Design

- Exploits recent advances in silicon photomultiplier (SiPM) technology to achieve compact form factor
- Utilizes the crystalline organic scintillator, stilbene, for sensitivity to, and discrimination between, neutrons and gamma rays
- Closely-packed multiple-pillar design enabled by previously measured stilbene/SiPM performance:
  - 0.5 cm position resolution along the length of 5 cm bar
  - Coincidence timing resolution less than 0.5 ns

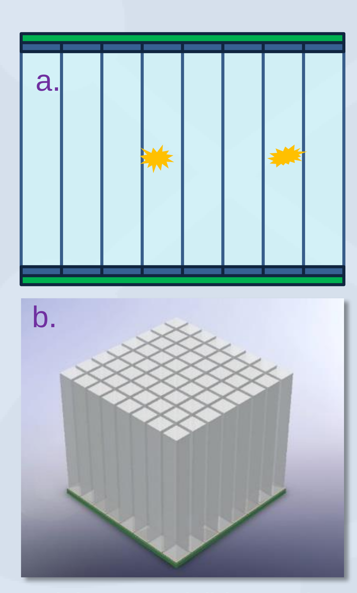

Figure 3: (a) 2D and (b) 3D sketches of proposed H²DPI design.

Previous Experimental Results

- 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

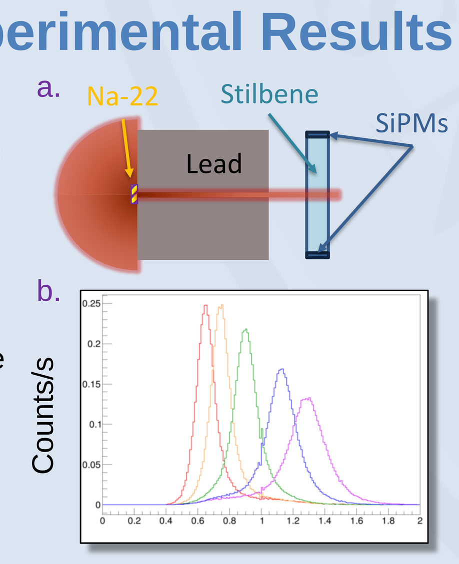

Figure 4: (a) Setup and (b) results for position resolution experiment.

- Measured time resolution of stilbene/SiPM system
- Coincident annihilation photons Na-22 source
- CAEN DT5730 digitizer (500 MS/s)
- SensL C-Series SiPM
- SiPM standard output: 0.28 ns σ
- SiPM fast output: 0.23 ns σ
- Fast PMT: 0.32 ns σ

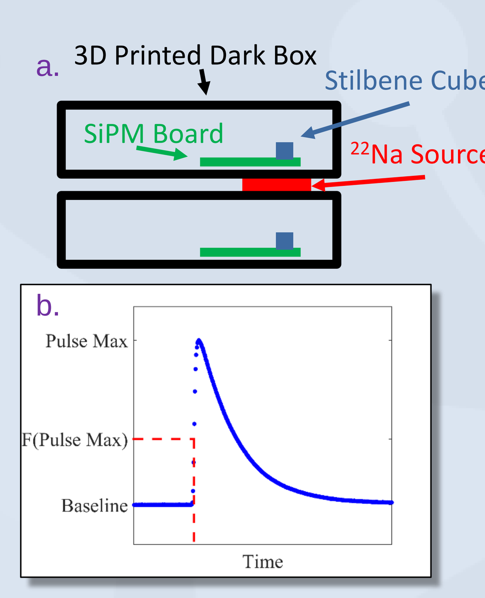

Figure 5: (a) Setup and (b) algorithm depiction for time resolution experiment.

Method

Simulation Technique

Particle Transport

- MCNPX-PoliMi
- Cf-252 spontaneous fission source
- Collect neutron and photon collisions in imager active volume

Detector Response

- Convert energy deposited to electron equivalent energy (linearly proportional to light output)
- Center X, Y position above SiPM
- Gaussian broaden (mean FWHM)
  - Light (7.7%)
  - Time (0.5 ns)
  - Z position (1.2 cm)

Coincidence Pairing

- Match coincident pulses
- Require both pulses above threshold (40 keVee)
- Require interactions in different crystals
- Reject interactions in adjacent crystals for improved image quality

Cone Projections

- Back project cone onto sphere
- Propagate uncertainties in measured quantities into cone width

List Mode MLEM

- Produce response matrix using cone projections as probability distribution functions
- Observation matrix is a vector of ones
- Iterate, increasing likelihood of source image with each step

Results

Simulation Setup

- Cf-252 placed 1m in front of system
- 4×10⁸ fissions simulated
- Equivalent to 67 min of 10⁵ fission/s source

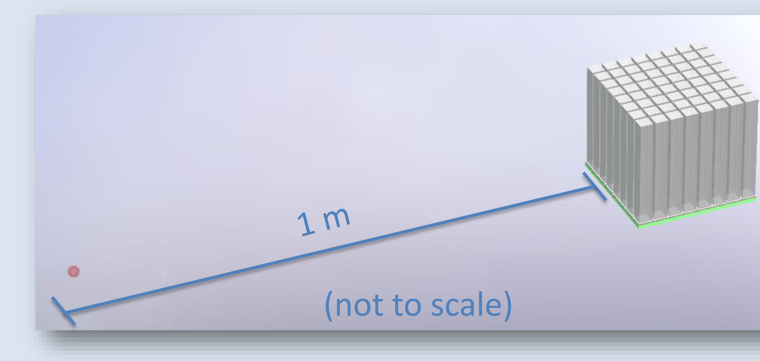

Figure 6. Diagram of source location simulations.

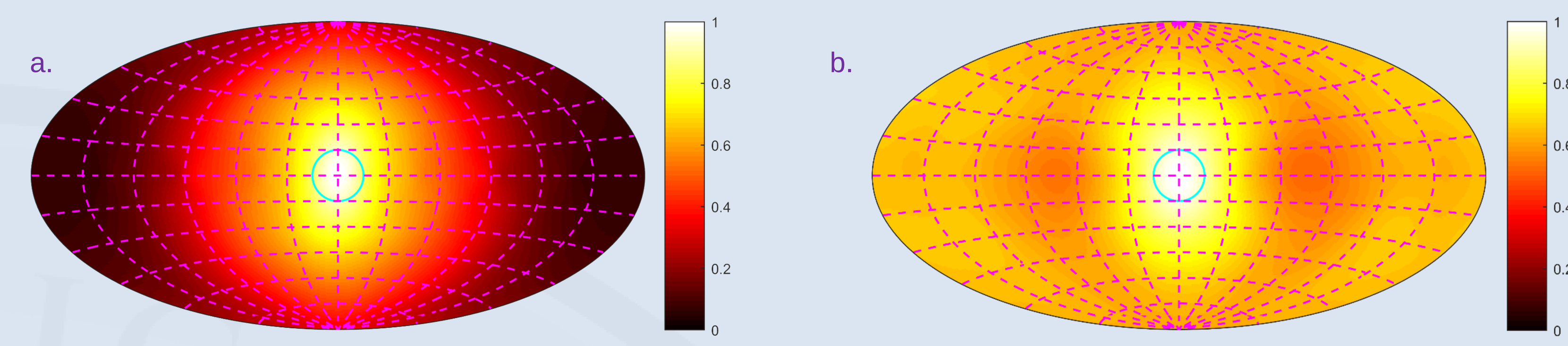

Figure 7. Back projection image of (a) neutrons and (b) photons from Cf-252 source at 1 m.

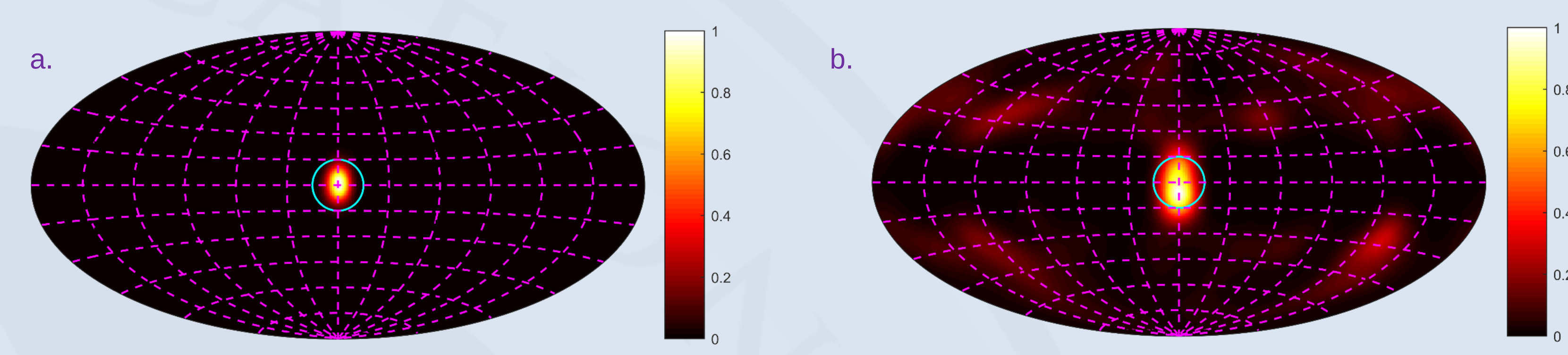

Figure 8. MLEM image of (a) neutrons and (b) photons from Cf-252 source at 1 m.

Accurate Location Determination

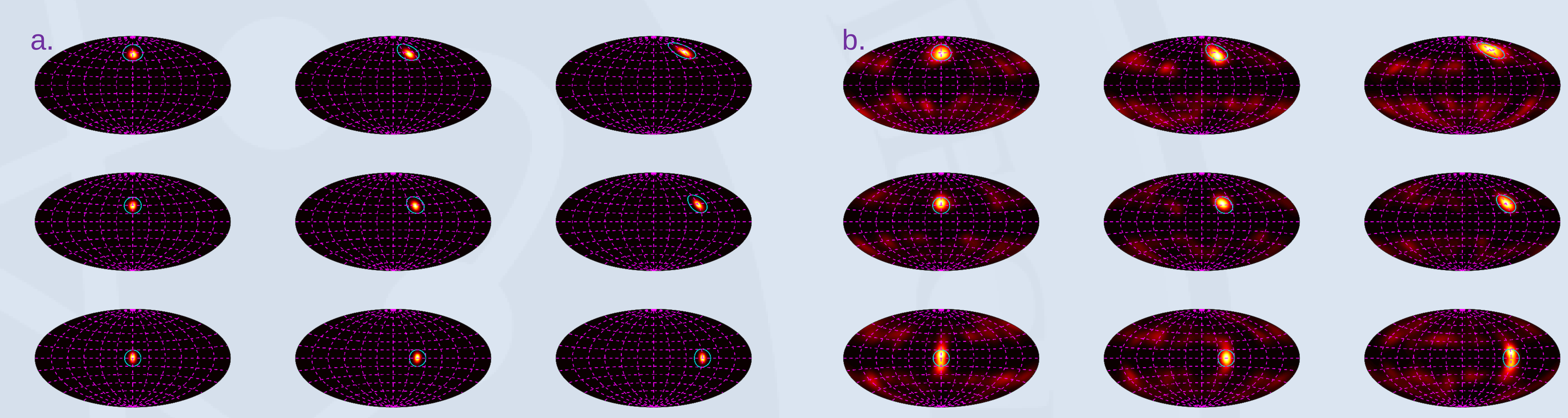

Figure 9. MLEM image of (a) neutrons and (b) photons from Cf-252 source at different angles at 1 m.

Size Estimation using Neutron Imaging

- Simulated sphere sources of Cf-252
- Source 25 cm in front of system
- Varied source radius from 0 to 12 cm
- Sources more than 4 cm in radius have >3σ larger FWHM than sources that are less than 3 cm in radius
- Significance: 1 IAEA significant quantity of plutonium is equivalent to a metal sphere that is 4.6 cm in radius

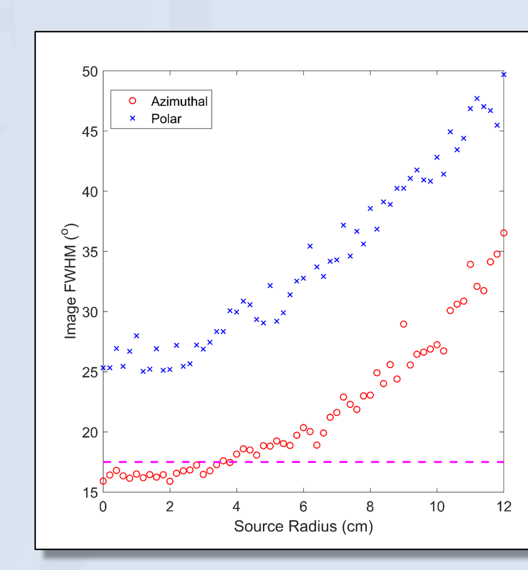

Figure 10. MLEM image (FHM) as a function of source diameter.

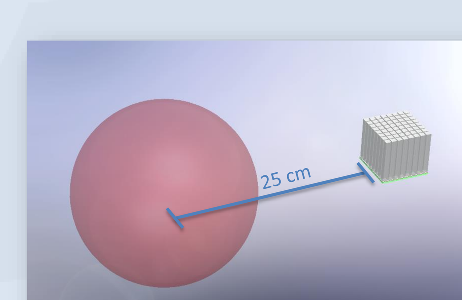

Figure 11. Diagram of source size estimation simulations.

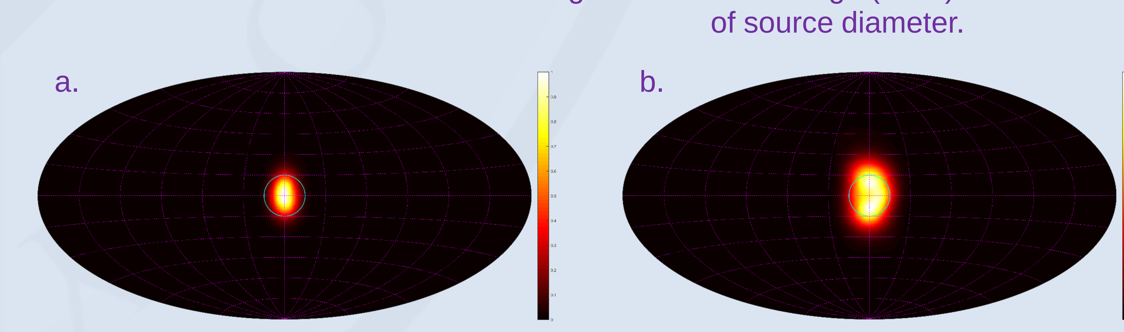

Figure 12. MLEM image (FHM) of a Cf-252 (a) point source and (b) 10-cm radius sphere source.

Conclusions

- Design allows accurate location determination using either neutrons or photons
- Imaging intrinsic efficiency for fission neutrons: 0.66%
- Neutron angular resolution: 10° FWHM
- Minimum distinguishable sphere radius using neutrons @ 25 cm: 4 cm

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