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# Simulation and Evaluation of a High Efficiency, Handheld Neutron Imager Design

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## Introduction and Motivation

- Neutron scatter cameras use the kinematics of elastic neutron-proton scattering to estimate the incoming direction of neutrons
- Neutrons must scatter twice in the scintillator volume to reconstruct incident neutron direction
- We need multiple parameters to back-project incident angle neutron cones:
  - Scintillation position along the pillar for first and second scatter
  - Proton recoil energy in first scatter
  - Time between neutron scatter events
- Evaluate best combination of scintillator, photodetector, and pillar size to estimate scintillation position, time, and brightness

## Design

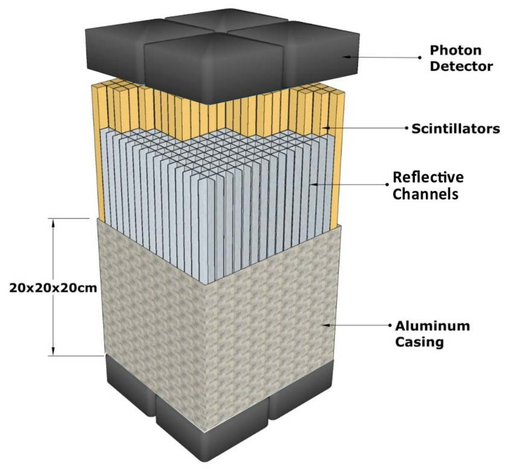


Figure 1: Instrument conceptual design using pillars of scintillator

- Instrument design uses a single, contiguous volume of organic liquid scintillator that is internally subdivided into optically isolated pillars (Figure 1)
- An air gap surrounds each scintillator pillar enabling total internal reflection
- Escaping light is reflected back into the pillar using a specular reflector lining the channel walls
- Photodetectors (PD) are affixed to opposing ends each pillar to collect scintillation light
- This design allows for an order-of-magnitude efficiency increase compared to a dual plane neutron scatter camera developed at Sandia National Laboratories

## Methods

- Position along pillar axis estimated using intensity vs. time history of charge carriers emitted by the photodetectors at each end of the pillar
- Tabulate nominal responses of scintillation photons to establish scintillation

$$R_{nom} = R_{scint}(t) * R_{chan}(t) * R_{TTS}(t) * R_{imp}(t)$$

- $*$ is the convolution operator
- $R_{nom}$ is the nominal response
- $R_{scint}$ is the scintillator time response
- $R_{chan}$ is the channel response
- $R_{TTS}$ is the transit time spread of the PD
- $R_{imp}$ is the impulse response of the PD

## Methods (cont.)

- Scintillation, transit time spread, and photodetector impulse responses obtained from their respective data sheets
- Channel response functions tabulated using Geant4 optical light simulation module by simulating $10^7$ optical photons in 0.5 cm increments
- Channel response functions estimate temporal spread of photons as they propagate throughout the pillar

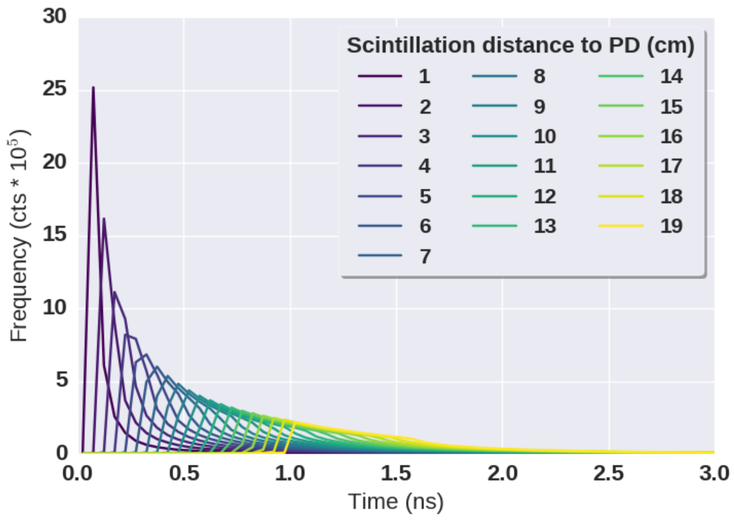


Figure 3: Channel response functions ($R_{chan}$). Demonstrates temporal spread of photon arrival times at ends of pillar.

- Convolve channel response functions with scintillator response to randomly sample charge carrier arrival times in the photodetector

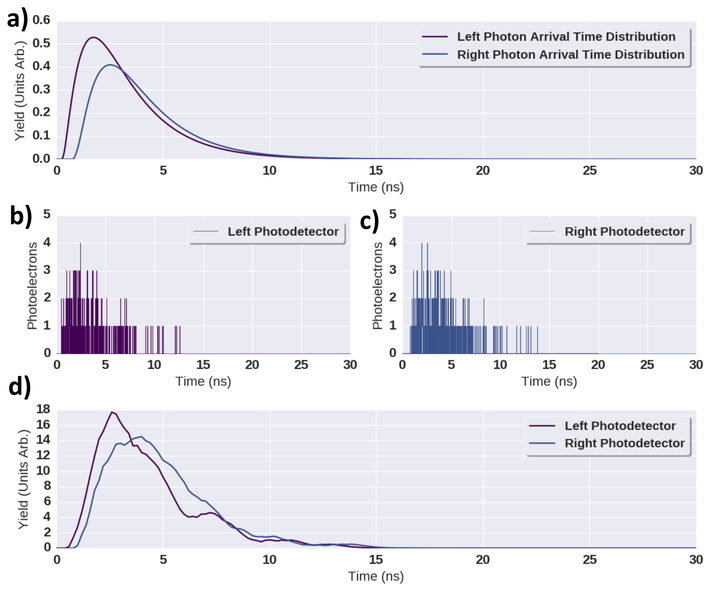


Figure 4: **a)** Pair of channel responses convolved with scintillator time response at true scintillation position. **b,c**) Randomly sampled charge carrier arrival times in photodetector using a). **d**) Convolve with charge carrier arrival time with transit time spread and photodetector impulse response

- We compared the observed responses (Figure 4d) to nominal responses (Figure 5) using Broyden-Fletcher-Goldfarb-Shanno minimization method and a negative log Poisson likelihood objective function

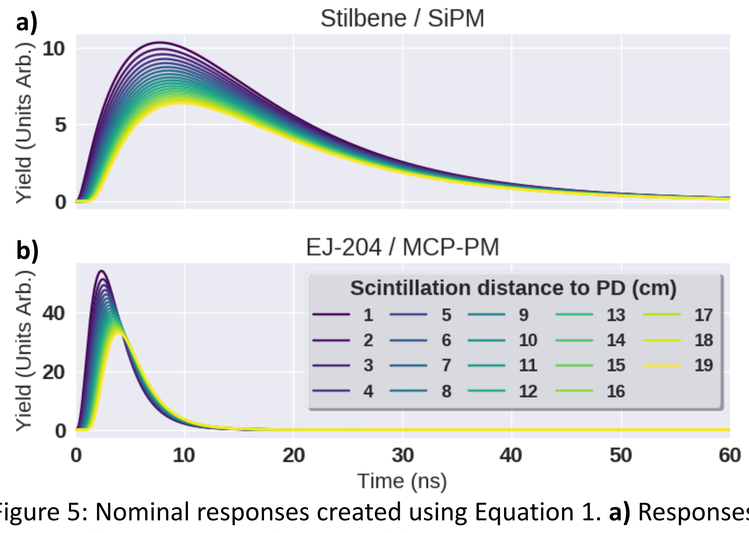


Figure 5: Nominal responses created using Equation 1. **a)** Responses using stilbene/SiPM combination. **b)** Responses using EJ-204/MCP-PM combination

## Results

- Photodetectors modeled
  - Microchannel plate photomultiplier (MCP-PM)
  - Silicon photomultiplier (SiPM)
- Scintillators modeled
  - EJ-204, EJ-232Q, stilbene
- Pillar geometry
  - 10 cm and 20 cm lengths
  - 0.5 cm and 1.0 cm side widths

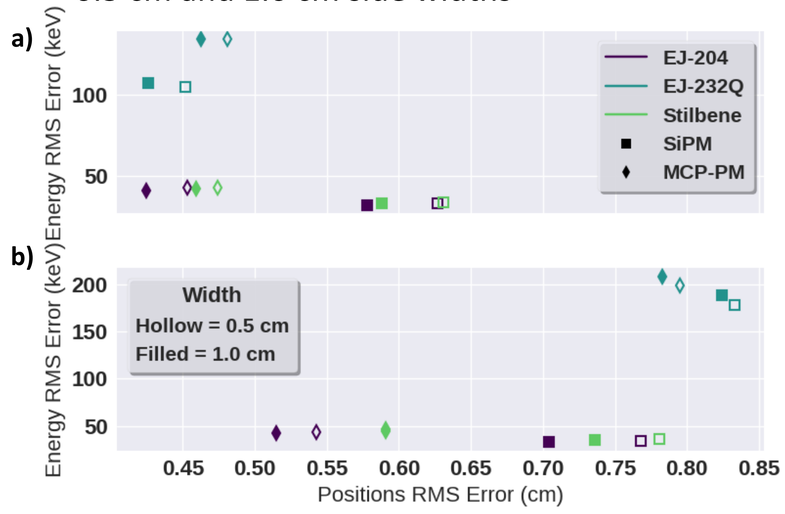


Figure 6: Scintillation position and proton recoil energy reconstruction results using a 2 MeV proton recoil. **a)** Results for a 10 cm pillar. **b)** Results for a 20 cm pillar

- Overall, best combination observed was EJ-204/MCP-PM
  - Compact charge carrier time distribution in photodetector allows for best position precision
  - Luminosity and quantum efficiency dictate proton recoil energy reconstruction precision
- Short self-attenuation length of EJ-232Q (8 cm) substantially reduces position precision for 20 cm pillar
- Proton recoil energy RMS error stays constant at 50 keV for proton recoil energies between 0.2 – 3 MeV
- Combination reconstruction ability did not change relative to each other for a 1 MeV proton recoil energy
  - A decrease in reconstruction precision observed due to reduced photostatistics

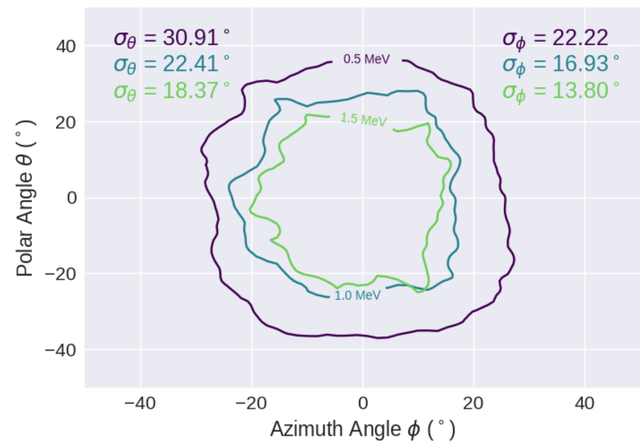


Figure 7: Detector resolution using 0.5, 1 and 1.5 MeV thresholds for neutron double scatter events. Simulated using a Cf-252 source 1 m away from center of imaging device using MCNPX-PoliMi.

- Better precision of scintillation position for higher proton recoil energies
  - Cone back-projection more accurate
- Discriminate on double scatter events where both interactions have proton recoil energy estimates above threshold
- Improved back-projected image resolution for higher energy thresholds
  - At the cost of fewer double scatter events passing threshold criteria

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