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Silicon Photomultiplier Readout Solutions for Organic Scintillator Detector Assemblies

Steven Hammon, Gene Kallenbach, **Peter Marleau**, and Melinda Sweany

Sandia National Laboratories, Livermore, CA

Chris Allwork

Atomic Weapons Establishment, Aldermaston, UK

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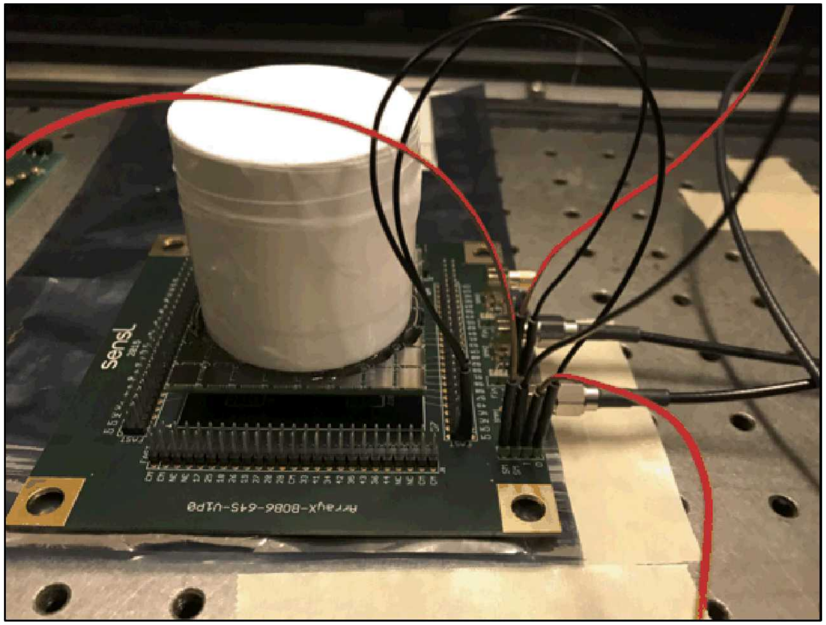
Overall Project Outline

Demonstrate PMT replacement

- Develop a SiPM summing board for coupling to SensL's 8x8 array and Hamamatsu MPPC
    - Passive sum on SOUT– SensL's ArrayX_BOB6_64S
    - Passive sum on SOUT – custom PCB with same footprint as the SiPM array.
- Determine PSD, timing, energy response characteristics compared with H1949-50 PMT
- Integrate into existing system
- Characterize overall system performance compared to PMT version

Demonstrate Pixelated Detector:

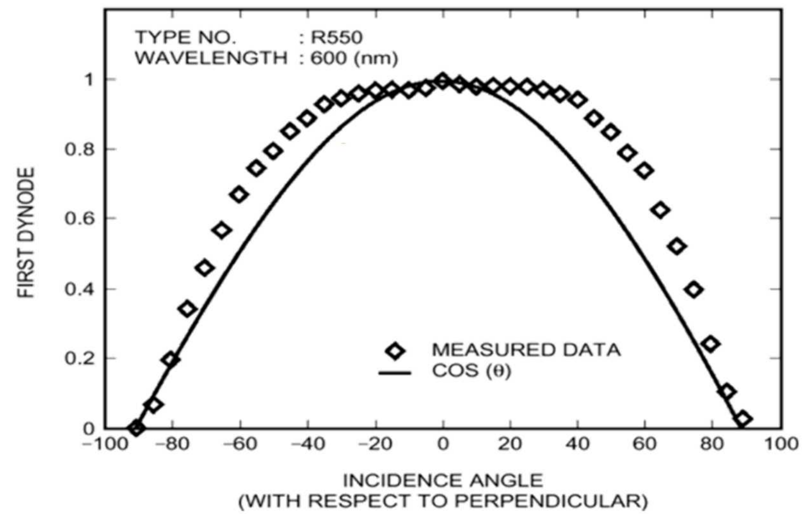
- Design and fabricate a 10x10 SiPM circuit board to interface with 10x10 – 1cmx1cm pixel block detector.
- Readout all 100 pixels to demonstrate benefits over PMT-based pixelated detectors.
- Design and fabricate breakout board and readout electronics for 8x8 SiPM arrays for compact pixelated neutron detectors.



Motivation – PMT replacements to enhance detection capabilities

Benefits of SiPMs over PMTs

- Portability
- Low voltage operation
- No susceptibility to magnetic fields
- Improved uniformity of response
- Excellent single photon resolution
- Mechanical robustness

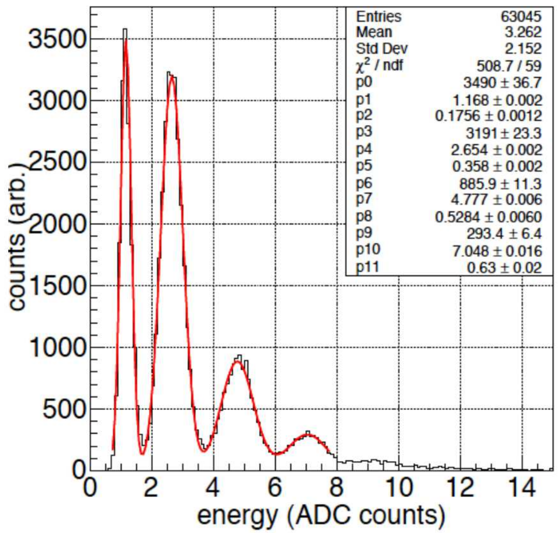


Characterization of a 6 × 6-mm² 75-µm cell MPPC suitable for the Cherenkov Telescope Array project

G. Romeo[a], G. Bonanno[a], S. Garozzo[a], A. Grillo[a], D. Marano[a], M. Munari[a], M.C. Timpanaro[a], O. Catalano[b], S. Giarrusso[b], D. Impiombato[b], G. La Rosa[b], G. Sottile[b]

Challenges:

- Gain variations due to temperature changes
- Preservation of pulse shape characteristics
  - Pulse shape must be preserved for gamma/neutron discrimination
- Preservation of interevent timing
  - Some applications require fast timing
- More dark noise per unit area
- Lower sensitive areas per unit channel

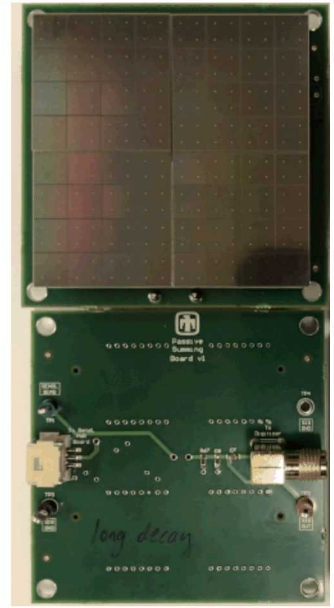


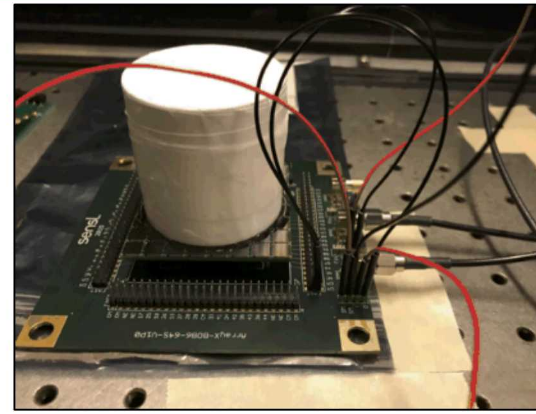
Offers better size, weight, and power

SiPM/PMT Comparison Testing

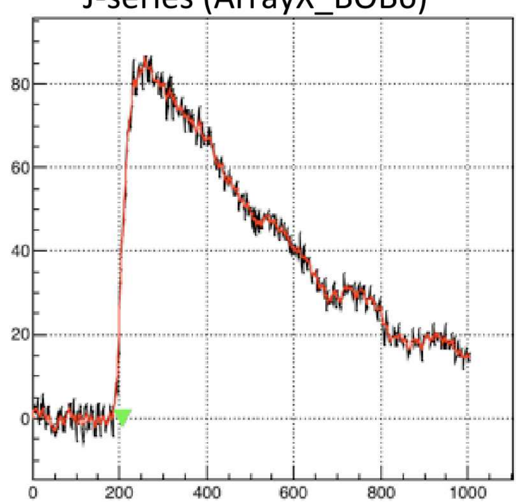
No viable commercial solution to summing SiPM arrays:

- SensL's ArrayX_BOB6_64S is not out-of-the box solution for field deployment
    - Large circuit board, lead wire circuits cause noise
- A passive summing board was designed and fabricated by SNL with AWE review
    - Can interface with SensL's C-series and J-series 8x8 arrays as well as the Hamamatsu MPPC.

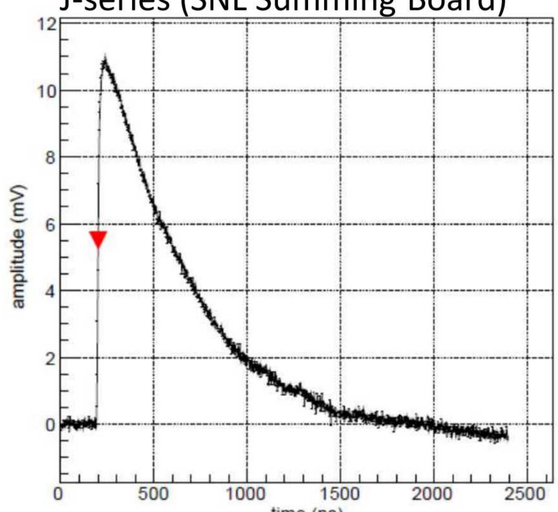




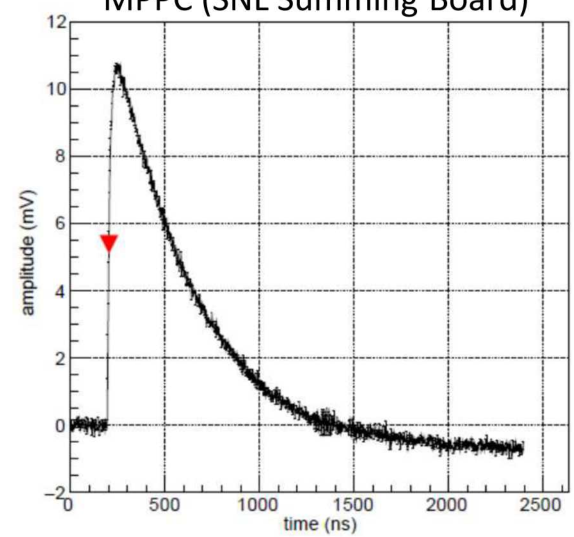
J-series (ArrayX_BOB6)



J-series (SNL Summing Board)



MPPC (SNL Summing Board)

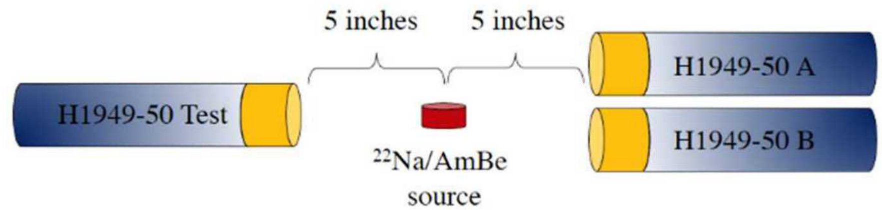


Timing resolution

SNL passive summing board coupled to 2”dia x 2” Stilbene crystal

- Coincident timing resolution,
  - 471 ± 50 ps (C-series)
  - 277 ± 68 ps (J-series)
  - 420 ± 64 ps (MPPC)
  - 481 ± 49 ps (H1949-50)

$$\sigma_t = \sqrt{\sigma_{A-T} + \sigma_{B-T} - \sigma_{A-B}}$$



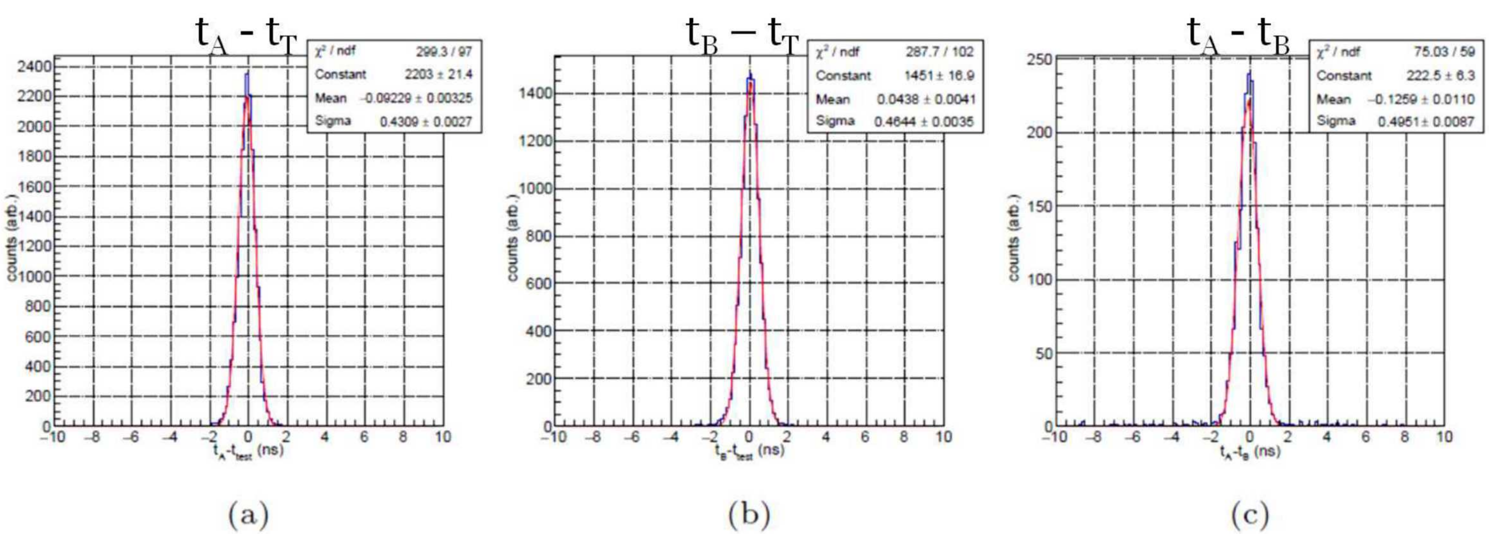


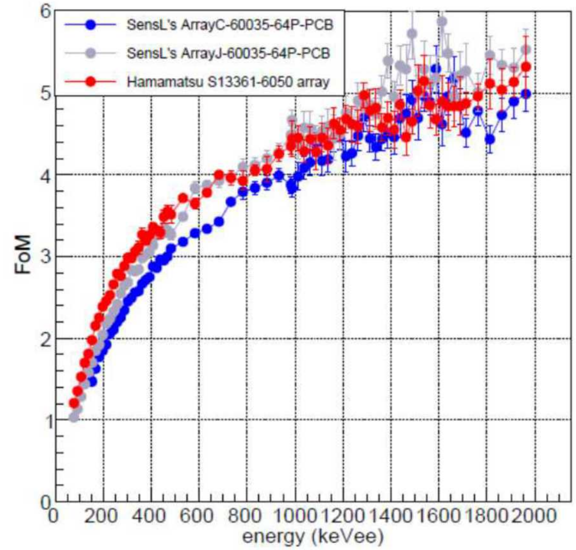
Figure 8: The timing distributions and fits for the ArrayJ-60035-64P-PCB: (a) $t_A - t_T$, (b) $t_B - t_T$, and (c) $t_A - t_B$.

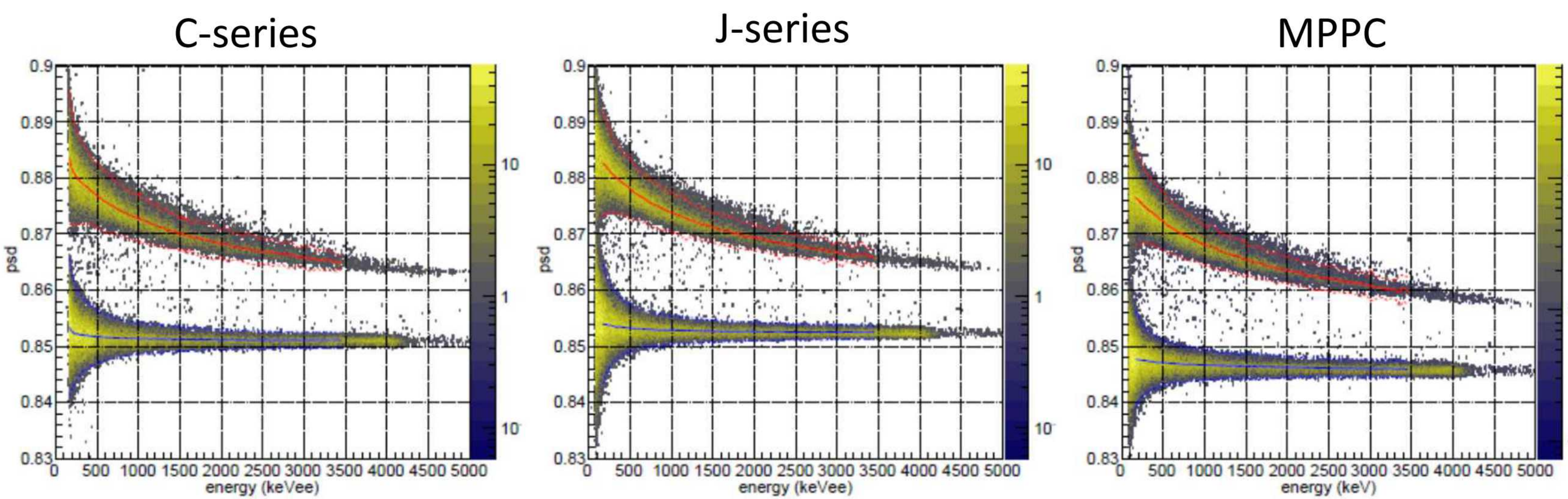
Pulse Shape Discrimination

SNL passive summing board (2” Stilbene)

- Figure of Merit (240 – 260 keV),
    - 2.11 ± 0.03 (C-series)
    - 2.33 ± 0.03 (J-series)
    - 2.66± 0.05 (MPPC)

$$FoM = \frac{\mu_n - \mu_\gamma}{2.355(\sigma_n + \sigma_\gamma)}.$$





SiPM array summing summary

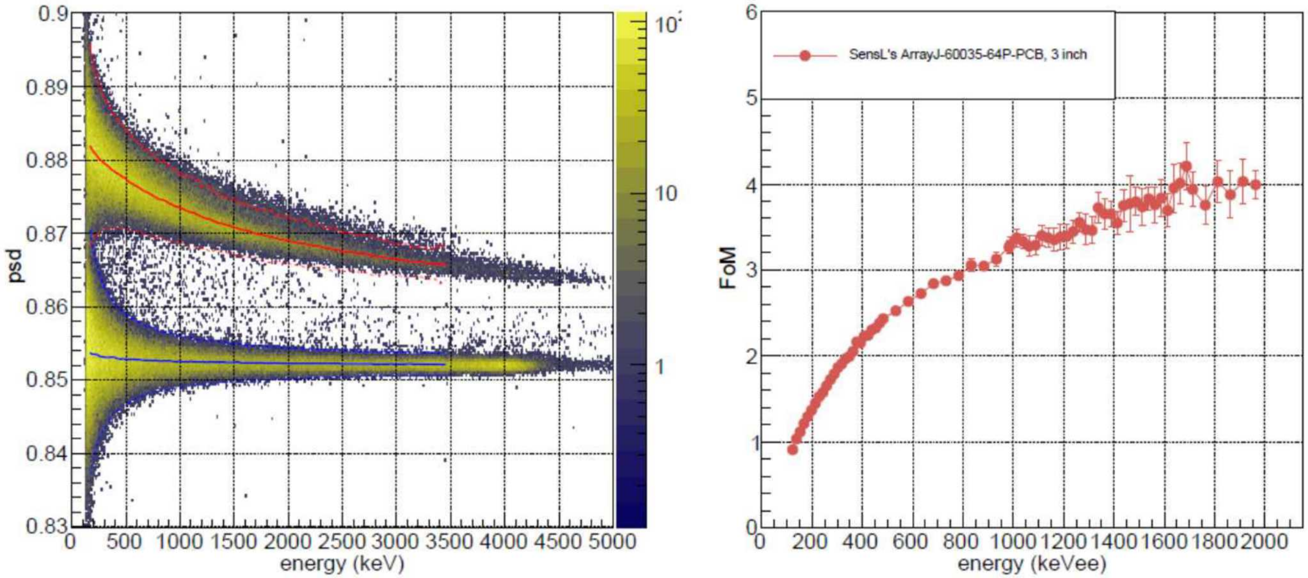
Summary

- If your application can tolerate longer pulse widths and higher dark noise, then passively summed SiPM arrays can equal or exceed the performance of PMTs
    - Efficiency
    - Gain
    - Single photoelectron resolution
    - Timing
    - PSD

Future

- Temperature compensation for bias voltage
- Dealing with noise (if necessary)
    - Preamplification
    - Diodes ahead of the sum

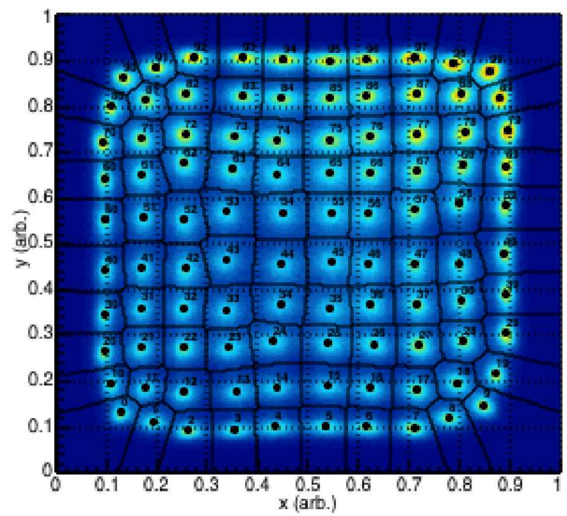
Summed SensL J-series 8x8 array on a 3” Stilbene crystal

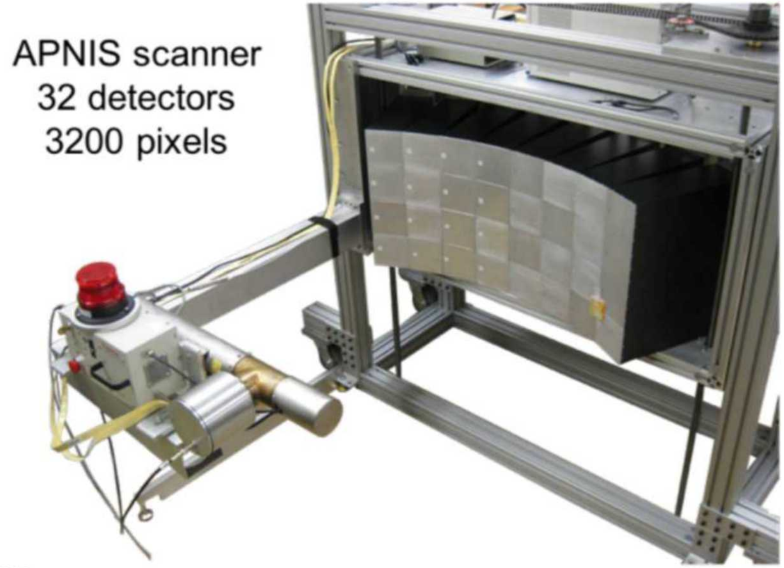


Motivation – SiPM readout for pixelated detectors

Seed development for more portable and fieldable fast neutron imaging

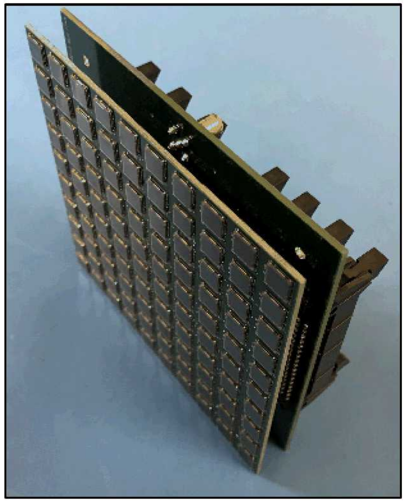
- Current state of the art is the block detector:
  - Scintillation from optically separated 1x1 cm pixels propagate through light guide to four PMTs
  - Gamma/neutron discrimination with EJ-299-34, performed on combination of four PMTs
  - Algorithm creates a Look-up Table (LUT) that maps x and y centroids to pixel numbers
- Applications include:
  - Fast neutron transmission imaging (APNIS)
  - Passive fast neutron imaging (coded aperture)





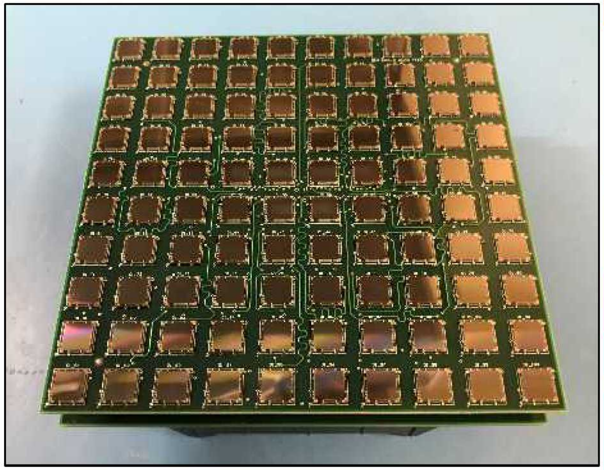
McConchie, et al, "Transportable, Low-Does Active Fast-neutron Imaging, ORNL/TM-2017/187

Pixelated fast neutron detection



Key to imaging ~~capabilities~~ limitations is the base detection unit:

- Gamma/neutron discrimination with EJ-299-34, performed on combination of four PMTs
    - For certain pixels, this imposes greater threshold than if all the light were read out by a single photodetector
- Scintillation from optically separated 1x1 cm pixels propagate through light guide to four PMTs
    - Are they truly isolated? If not, how does this effect position reconstruction?

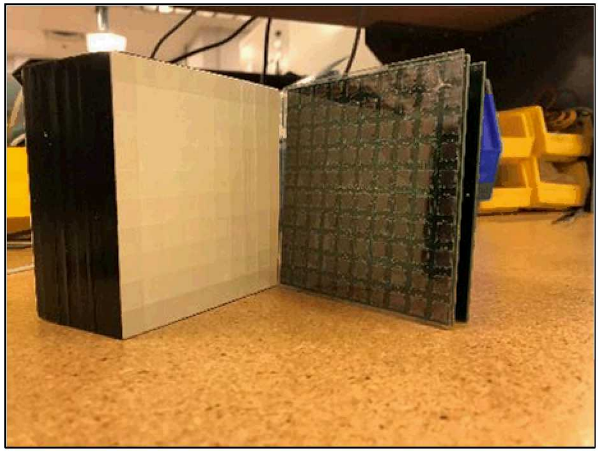


- Normalized sum of two orthogonal PMTs yield pixel responses in x and y
    - These are distributions with significant overlap in response
    - About 20-30% of interactions occur in more than one pixel, with no way of separating. This causes image artifacts that don’t improve with statistics.

Current and future work – Pixelated detectors

Laboratory studies and readout board development

- Developed 100 channel SiPM and readout board
  - Lessons learned with University of Michigan (CVT) 8 channel board
  - Design reviewed by AWE collaborators
- Like-to-like comparison to pixelated block detector (PMT)
  - Multiple scatter/timing characterization
  - PSD characterization
  - Relative efficiency
  - Optical cross talk
- Performance testing underway
  - 100-channel breakout board
  - 10x10 pixelated scintillator block
  - Seven 16-channel 250 MHz 14-bit CAEN digitizers + VME crate
  - Acquisition software for synchronized readout (not as easy as it sounds)



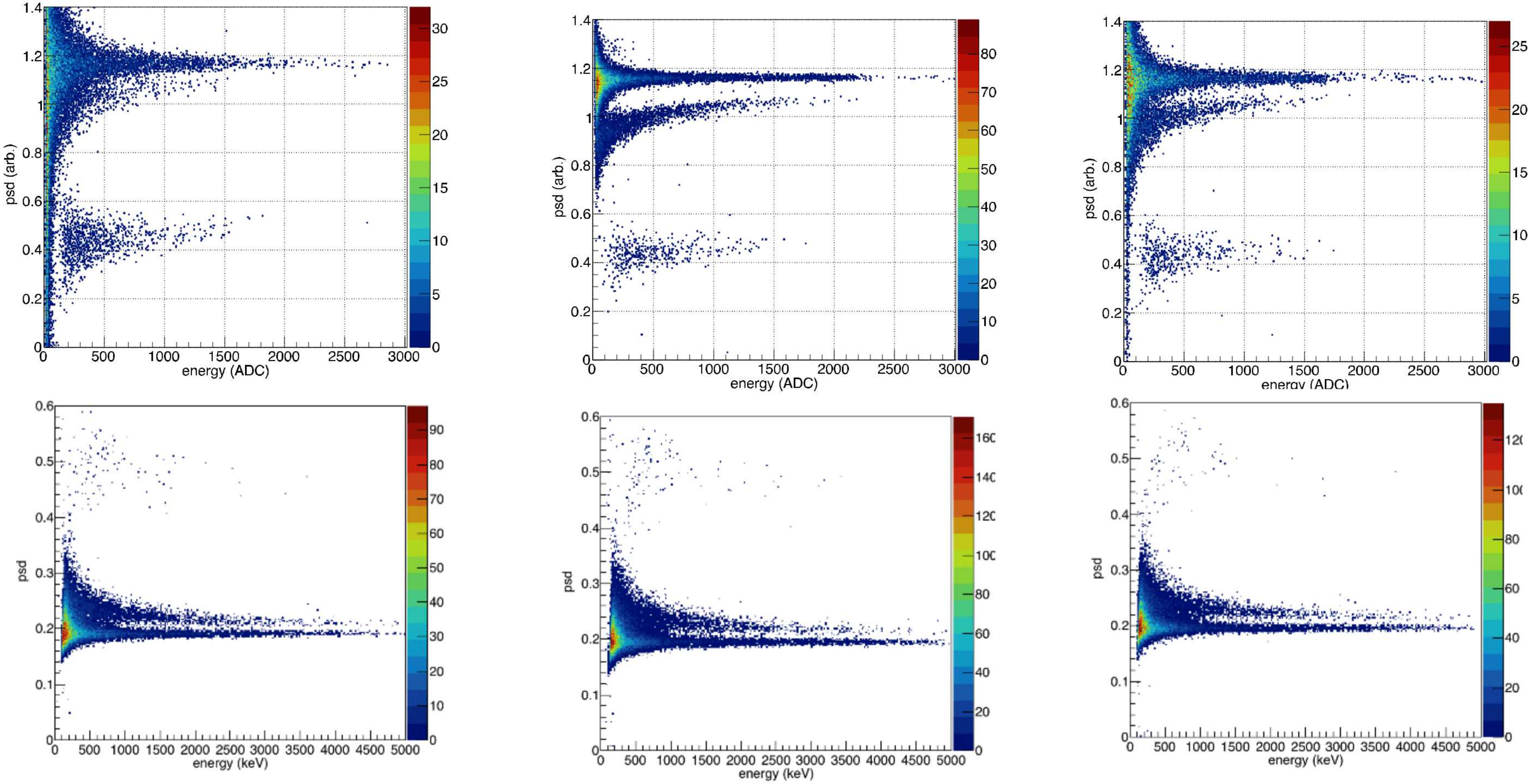
Detector characterization

PSD performance is between best/worst of PMT readout

Pixel 0 - corner | Pixel 44 - center | Pixel 49 - edge

Anger logic

SiPM readout



Current and future work - electronics

You may have noticed…

- Under component list:
  - Seven 16-channel 250 MHz 14-bit CAEN digitizers+crate
  - Acquisition software for synchronized readout
- We've exchanged calibration simplicity and potentially improved response for complexity in digitization!!

How is this an improvement in portability?

- We're taking a phased approach towards portability:
  - First demonstrate the efficiency and image quality improvements with individual pixel readout.
  - Then revisit readout
- Planning ahead:
  - Evaluating commercial solutions: TOFPET2 ASIC from PETsys.
  - Working with UC Davis through NSSC to develop scalable 8-channel readout solution that preserves timing, pulse shape, and energy

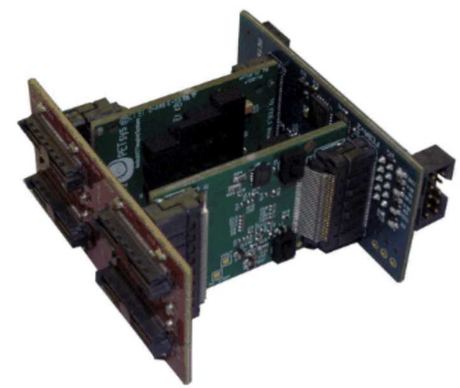


Figure 1: The FEM128 module has two ASICs, and has connectors accepting a Hamamatsu S13361-3050Ax-08 MPPC 8x8 array, or a KETEK PA3325-WB-0808 array.

Di Francesco et al. (2016) *JINST* 11 C03042

Future work

Building blocks of the future

- 6mm x 6mm is the maximum size that is currently available
- 64 bars of 6x6x30 mm scintillator pixels
  - Will improve light collection and PSD
- Fabricate pixelated block with no optical cross-talk
  - What reflector? ESR is semi-transparent
  - Diffuse reflector with air gap?
  - Can we cast in place glass-based scintillator with diffuse reflector mold?
  - Tranloc?
- Data reduction – onboard digitization (look to medical imaging?)
  - Need fast timing O(100 ps)
  - Syncronization
  - PSD
  - Dynamic range
  - Scalable
  - Trigger logic