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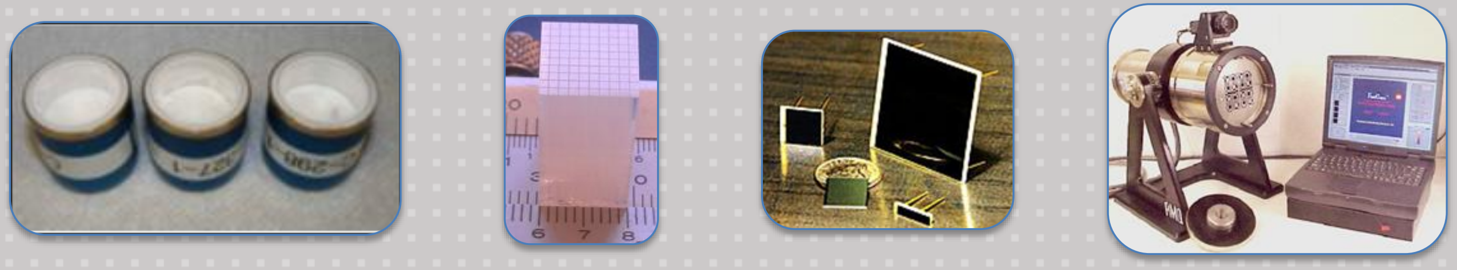
Solid-State Neutron Detectors with Integrated Electronics for Nuclear Physics - DE-SC0011280

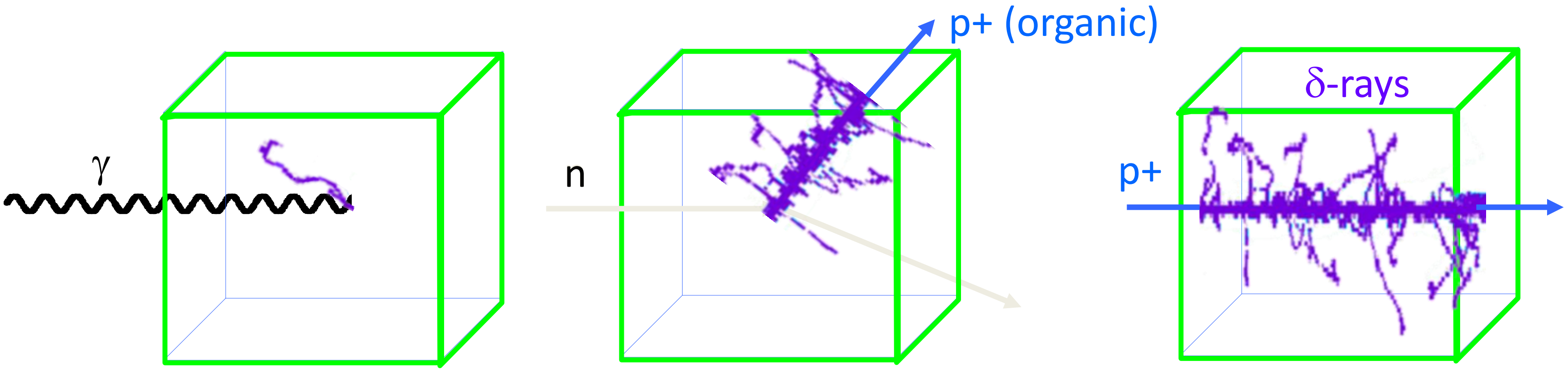
- Neutron Detection with Plastic Scintillators coupled to Solid-state Photomultiplier Detectors

James F. Christian, Ph.D., PI, Michael R. Squillante, Ph.D.

Aug. 2016



Plastic* Scintillation Interactions & Energy Deposition

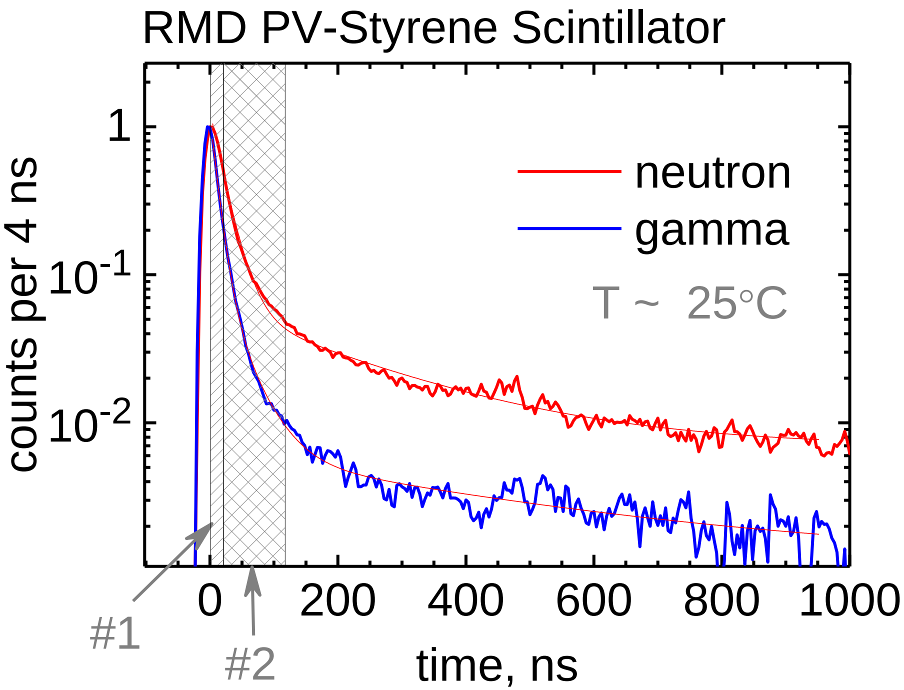


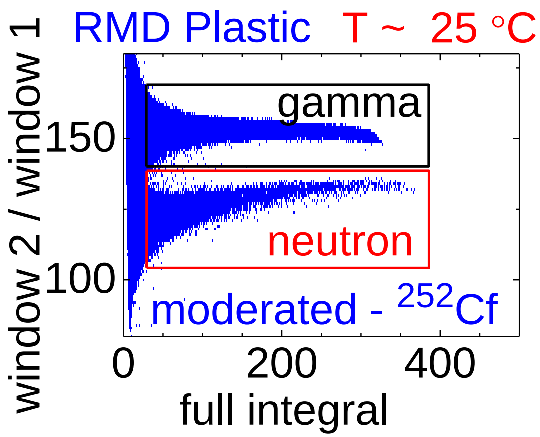
- Gammas produce Compton and photoelectrons: delta rays ~ beta
- n produce recoil protons (break bonds) and excited nuclear states (capture)
- Charged particles, β, p+ and α
  - Excitation by collision: Bethe Bloch (linear energy transfer, LET)→ionization
  - Cerenkov

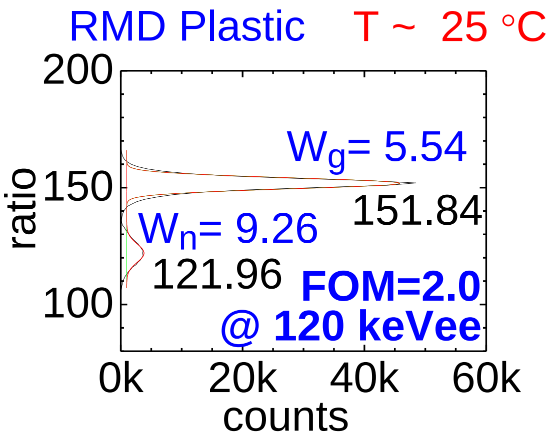
Extracting neutron energy is “convoluted”: Protons and LET

*“Plastic” - hydrocarbon

PSD distinguishes between gamma and neutron events







Pulse shape discrimination (PSD):
Collection of excited states
depends on LET

- Performance specifications: Light yield, **FOM**, and PSD threshold (depends on detector noise)

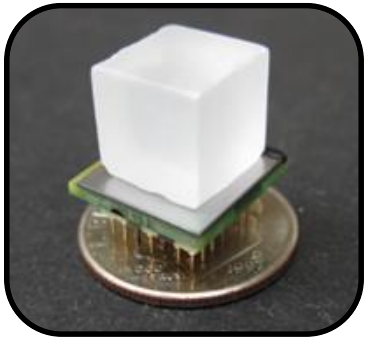
Plastic scintillation comparison

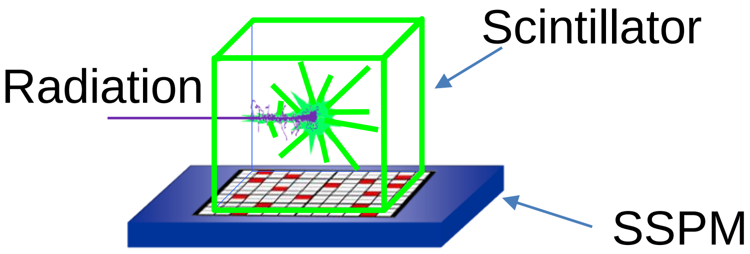
Table: Properties of fast neutron scintillators

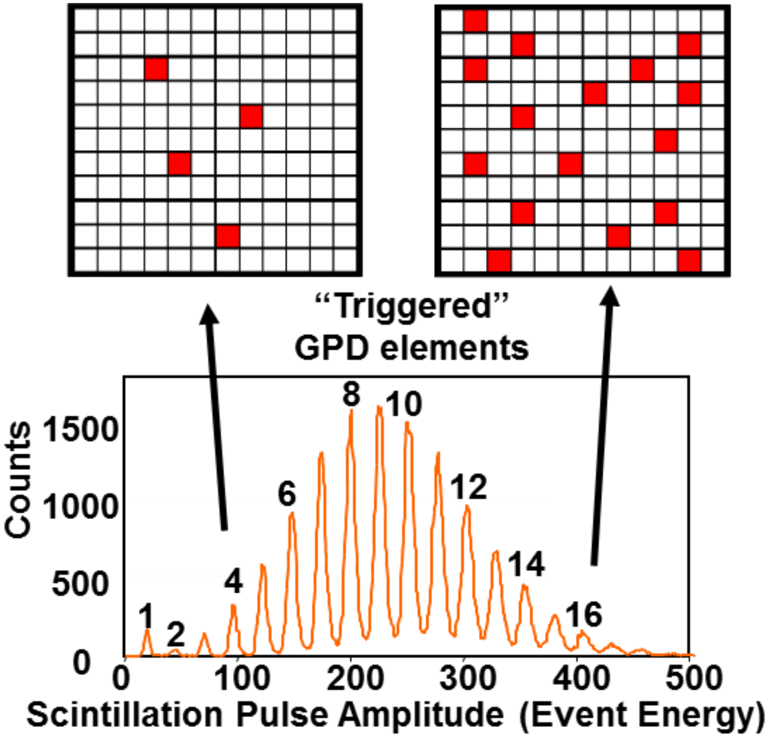
Scintillator	λ (nm)	Light yield (ph/MeV)	Decay time (ns)	Pulse shape discrimination
BC-408 plastic	425	12,800	2.1	poor
BC-501A liquid	425	15,600	3.2	Very good
Anthracene	445	20,000	30	poor
Stilbene	380	14,000	3.5	good
RMD plastic	440	13,000	5-10	Very good

- Emerging organic PSD materials exceeding Anthracene's Light Yield
- Plastic scintillation materials with emission-wavelength discrimination

SSPM Introduction: Array of Geiger Photodiode Elements





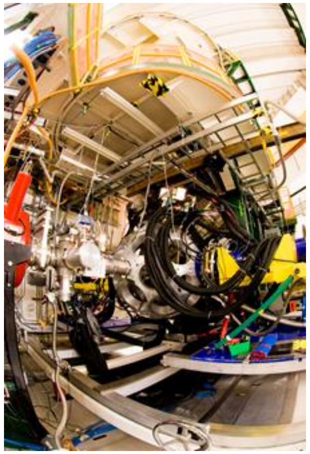


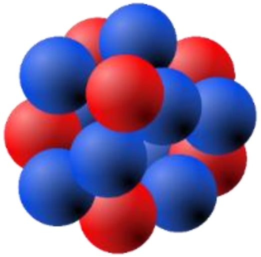
- SSPMs (SiPM – SSPM in Silicon
  - Gain >1,000,000
  - Very low noise
  - Robust
  - Digital (photon counting)
  - High DE
- Dark count rate has improved from a few MHz/mm^2 for early MRS devices to ~30 kHz/mm^2

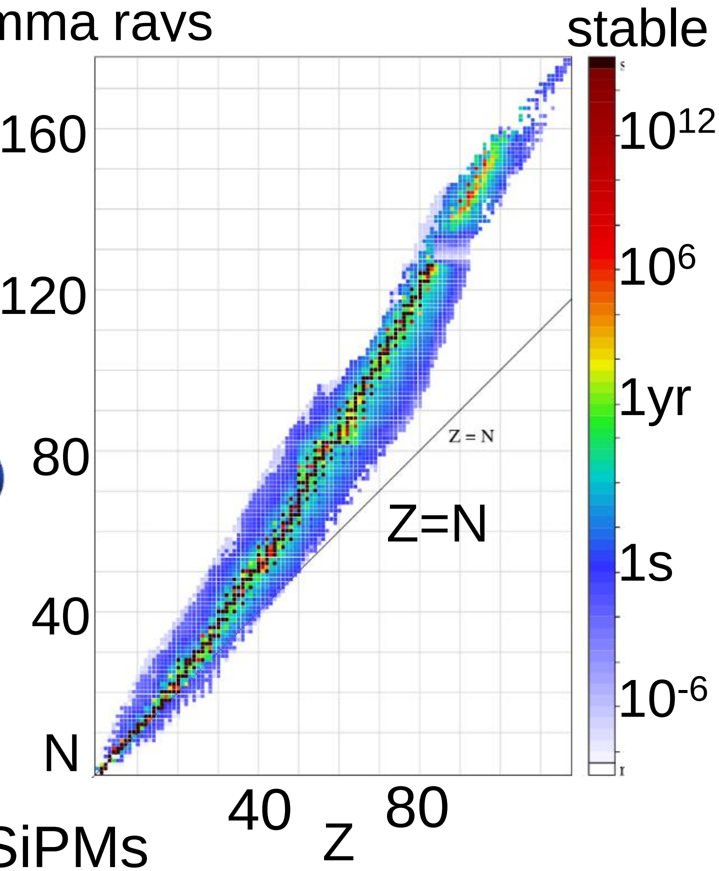
Program Goals

Enable experiments to explore very exotic nuclei systems, in particular with very large neutron excesses.

- Better discrimination for neutrons and gamma rays
- Improved spectroscopy for neutrons
- Ability to operate in magnetic field





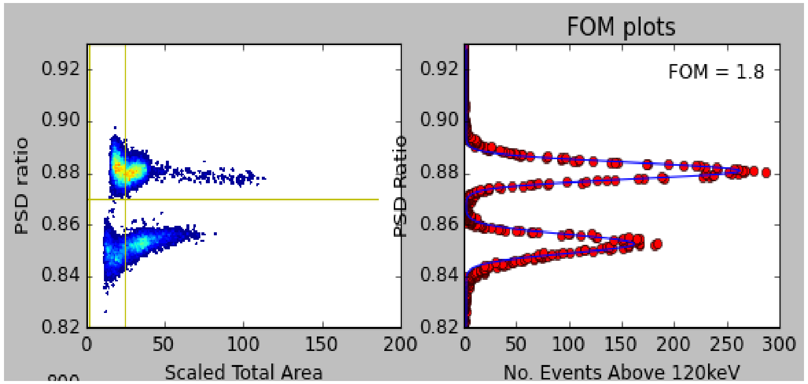


- Construct “large-volume” detector with SiPMs

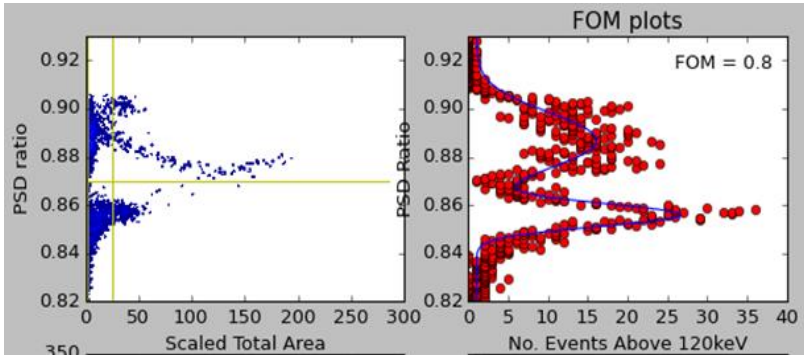
P1: Scintillator Composition and SiPM Mfgr.

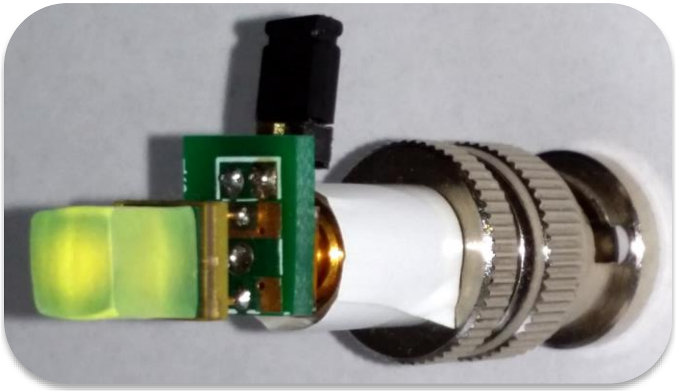
University of Kentucky Neutron Beam

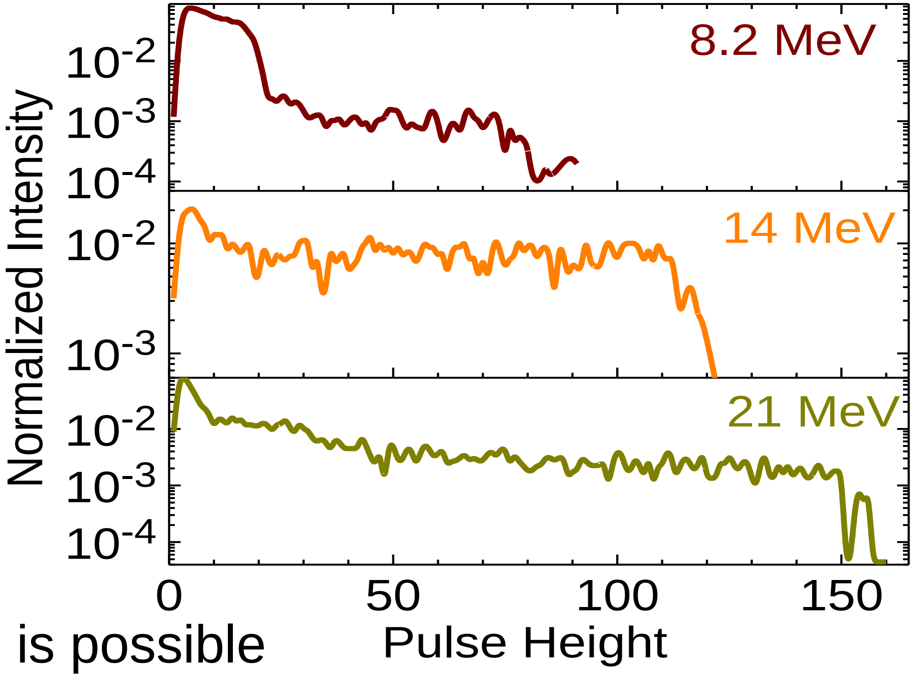
- 8.3 MeV neutrons: FR001



- 20.8 MeV neutrons: FR001







- Peak neutron energy determination is possible

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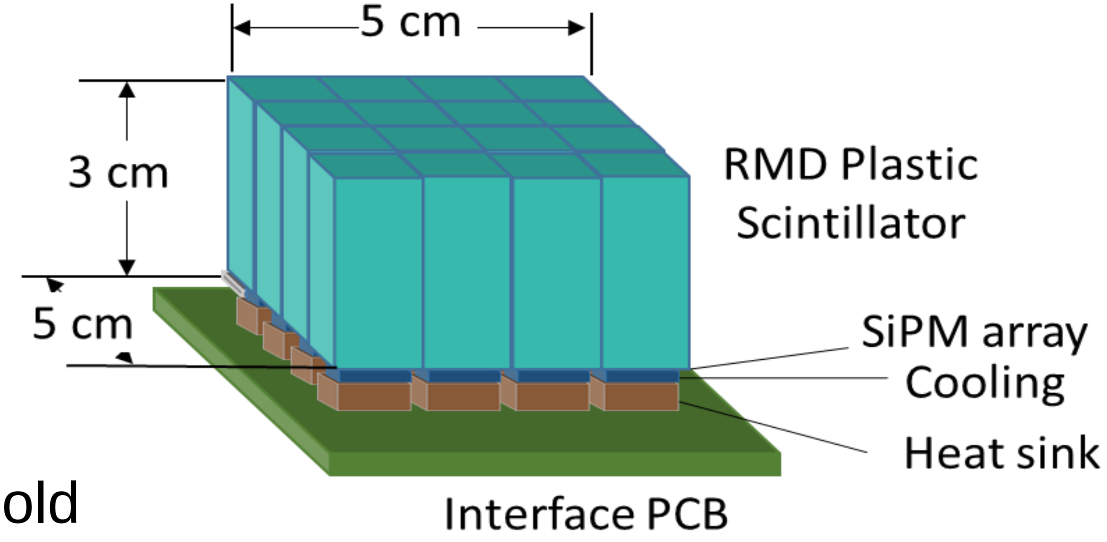
Phase-2 Objectives

- Scale up to large sizes of at least 3 cm × 5 cm × 5 cm.
- Optimize optical readout platform including cooled detectors to improve low-energy threshold
- Improve low-energy threshold (<200 keVgee)
- Demonstrate full experiment scale detector modules at NSCL.

Prototype Concept



Readout

Phase-II Tasks

- ✓ 1. Kickoff meeting and preliminary design review
- ✓ 2. Finalize scintillator properties (fabrication)
- ✓ 3. Select optical detector unit and test small scintillation samples
- ● 4. Critical design review
- 5. Build processing electronics
- ✓ 6. Design, build and test module
- 7. Build expanded module for field use experiments

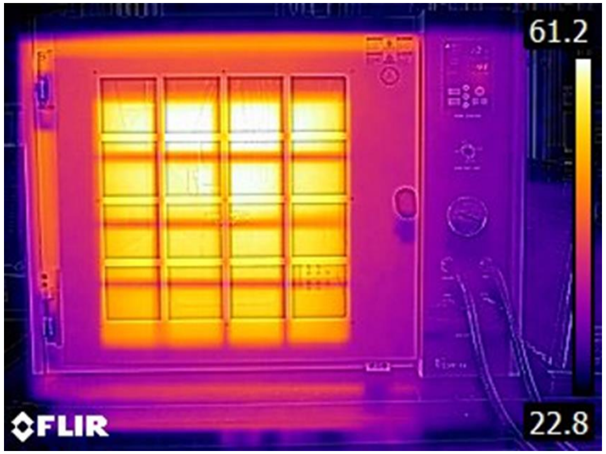
Improve Scintillator Fabrication

Materials

- Styrene
- Diphenyloxazole (PPO)
- Activated alumina
- Acetone
- Argon/Nitrogen

Materials purification

High temperature oven



Box furnace – IR image of uniform temperature

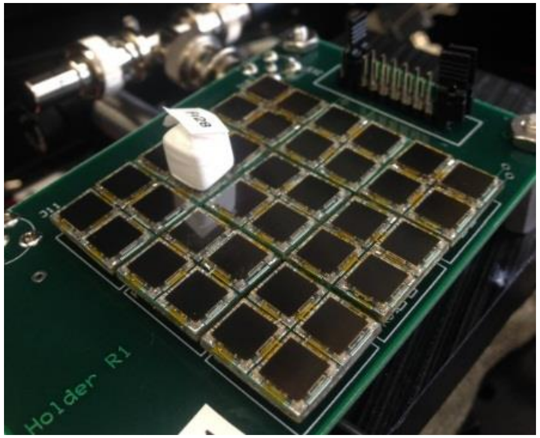
Polymerized samples in ampoules

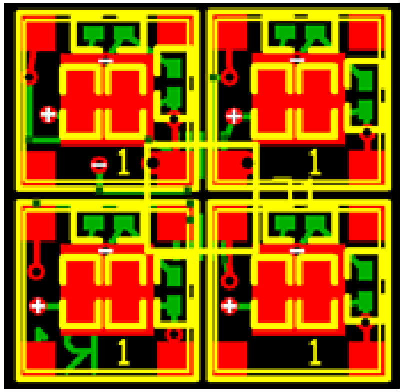
Grinding and polishing

Cast Scintillator: omit cut and polish process

Modular Design

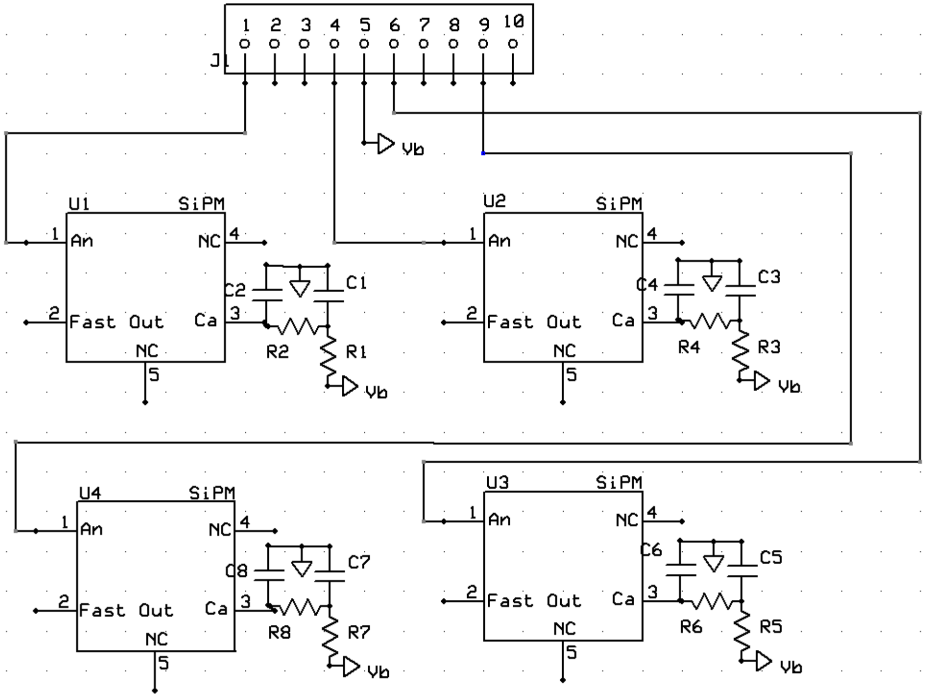
- 2 x 2 arrays for substitution and assembly
- Individual Bias filter on each





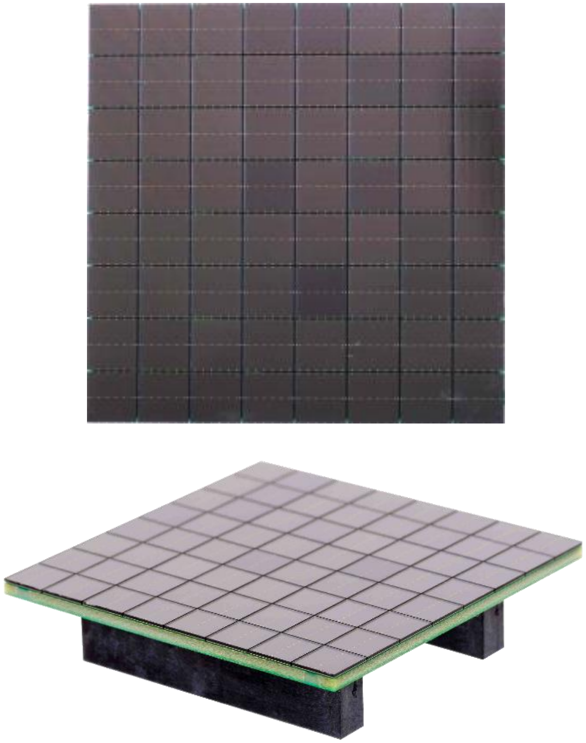
2×2 Array

Device connections

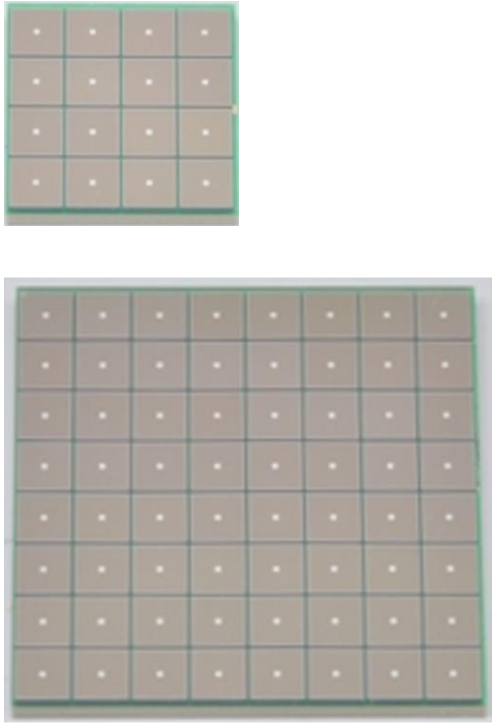


Additional Options

SensL



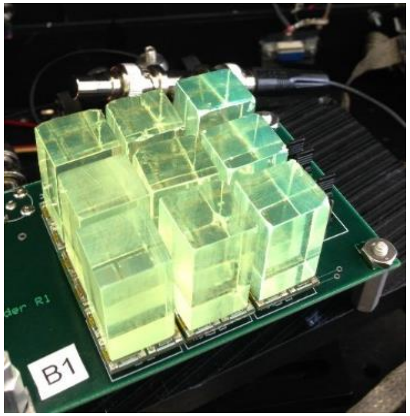
Hamamatsu

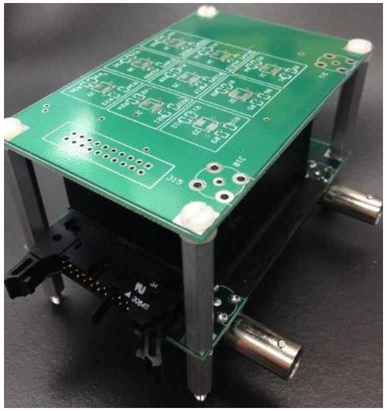


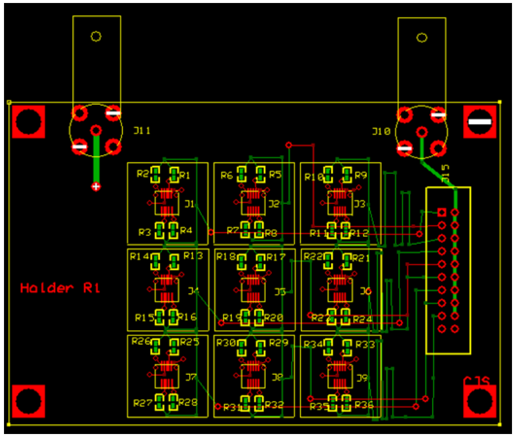
- Commercially available 2×2, 4×4, and 8×8 arrays

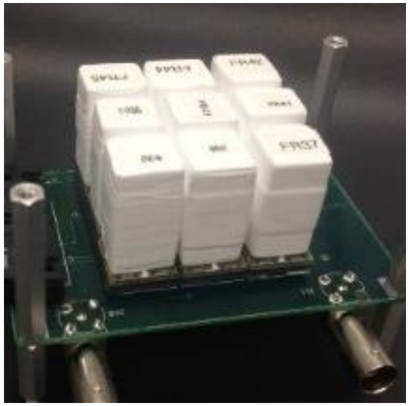
Large-volume Prototype Detector Development

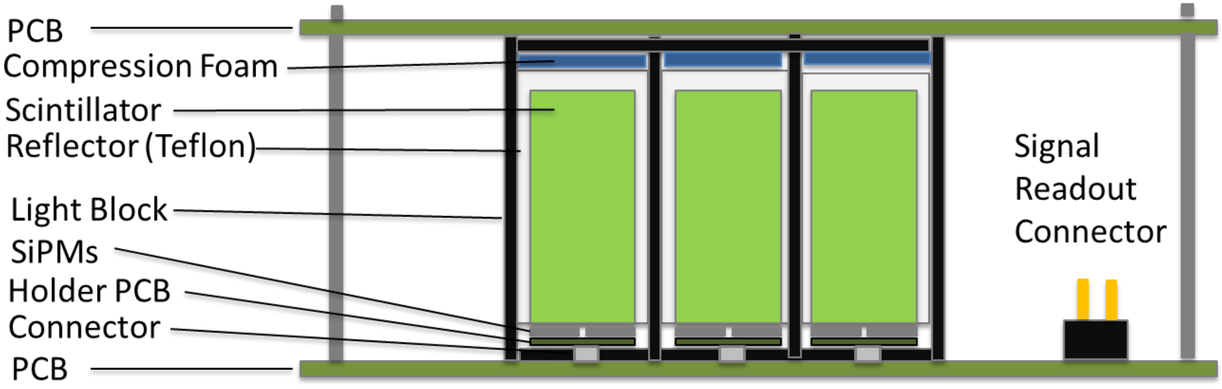
- Compression padding to hold individual scintillators in place
- Teflon tape for prototype reflective coatings, must optimize process for mechanical fit and minimal non sensitive detector mass







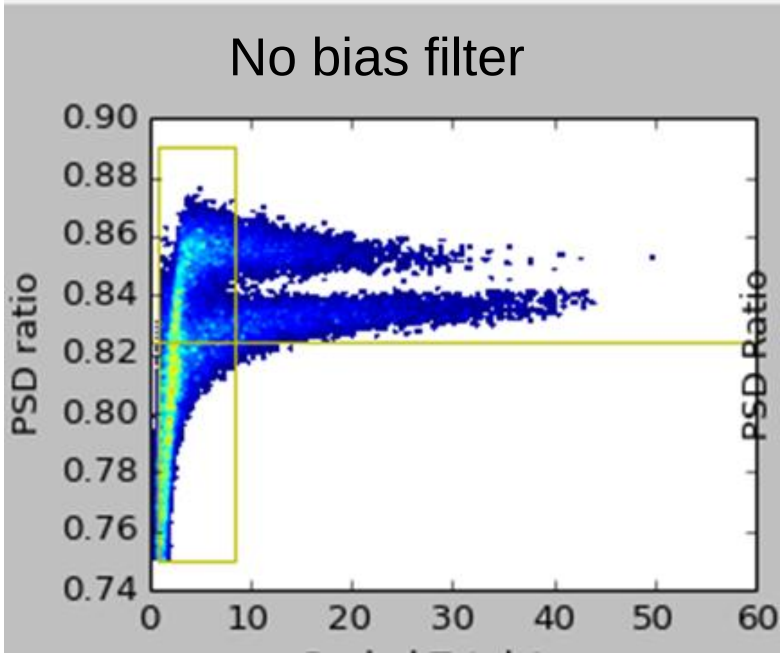


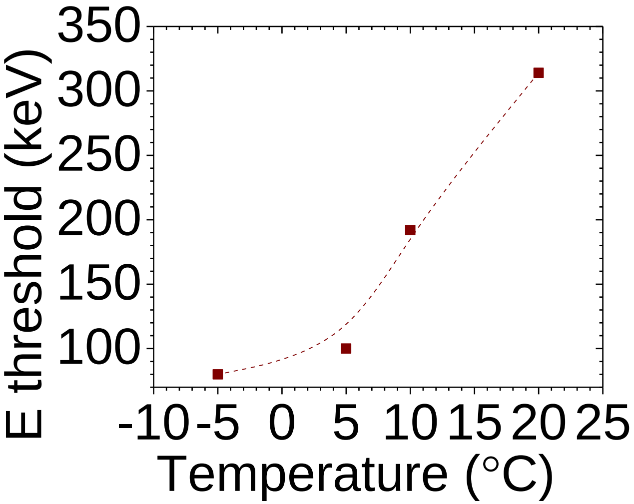


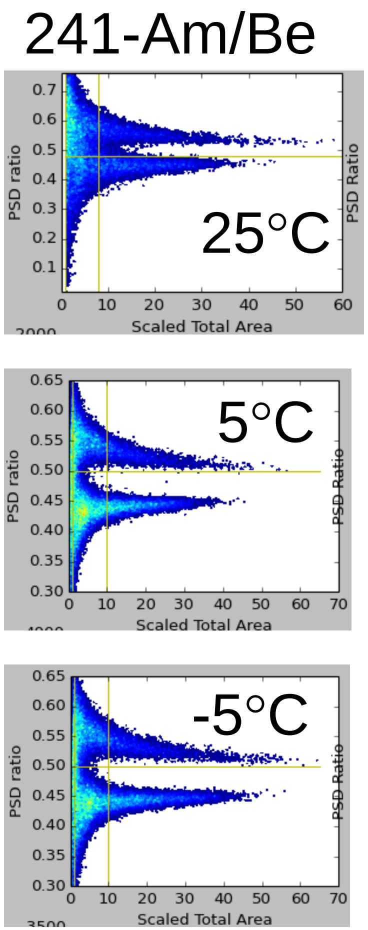
3×3 tile of 2×2 SiPMs

QC, Temperature and Bias Filter

- QC: good module uniformity
- Temperature: Dark count rate
- Need bias filter

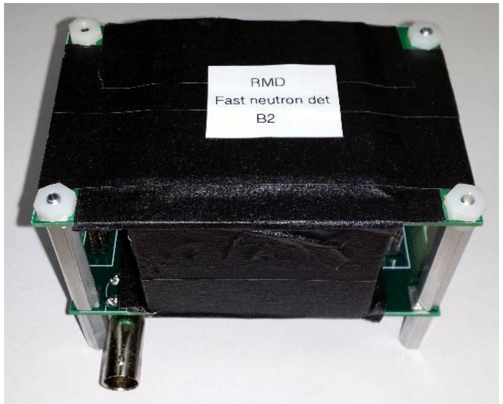






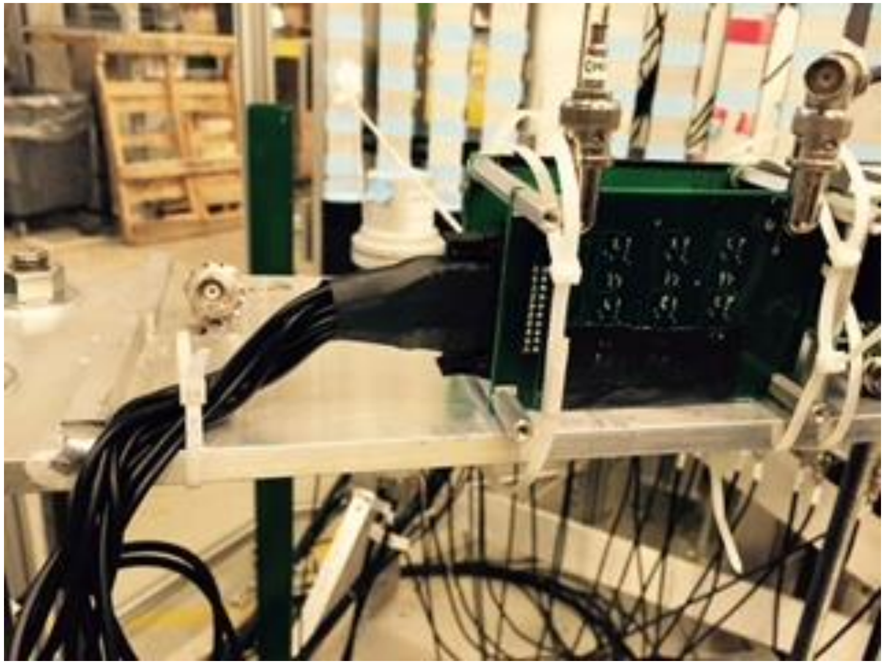
Measurements at NSCL

RMD Prototype



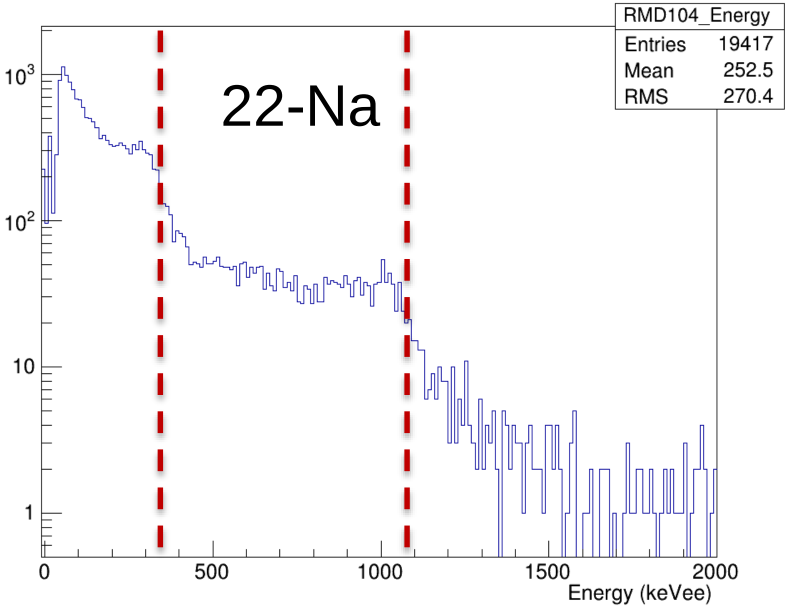
Measurements by C. Stapels, J. Pereira, R. Zegers

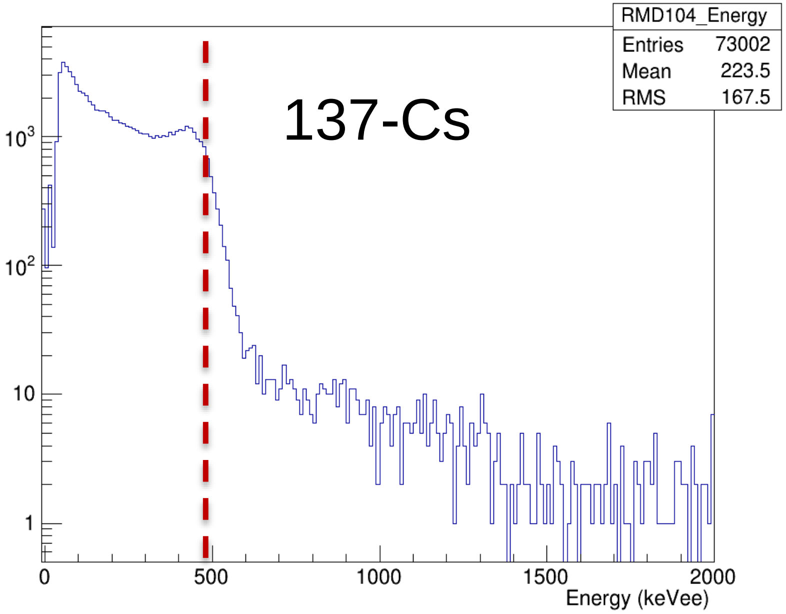
Prototype at the National Superconducting Cyclotron Laboratory (NSCL)



- Compare performance to LENDA (Low Energy Neutron Detector Array) detector (bar) using LENDA Digital Data-Acquisition System (DDAS)

Energy calibration and noise floor uniformity

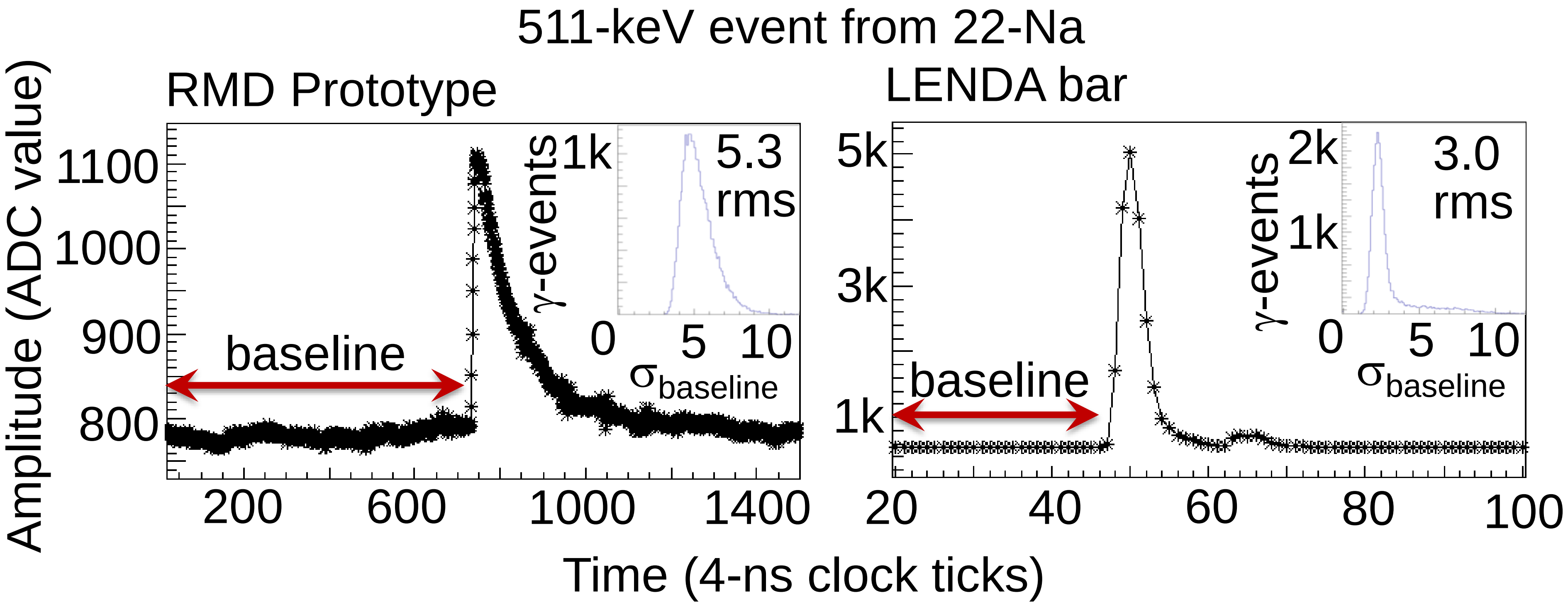




Segment	Noise (keVee)	Segment	Noise (keVee)	Segment	Noise (keVee)
RMD101	45	RMD104	45	RMD107	55
RMD102	64	RMD105	75	RMD108	65
RMD103	45	RMD106	65	RMD109	55

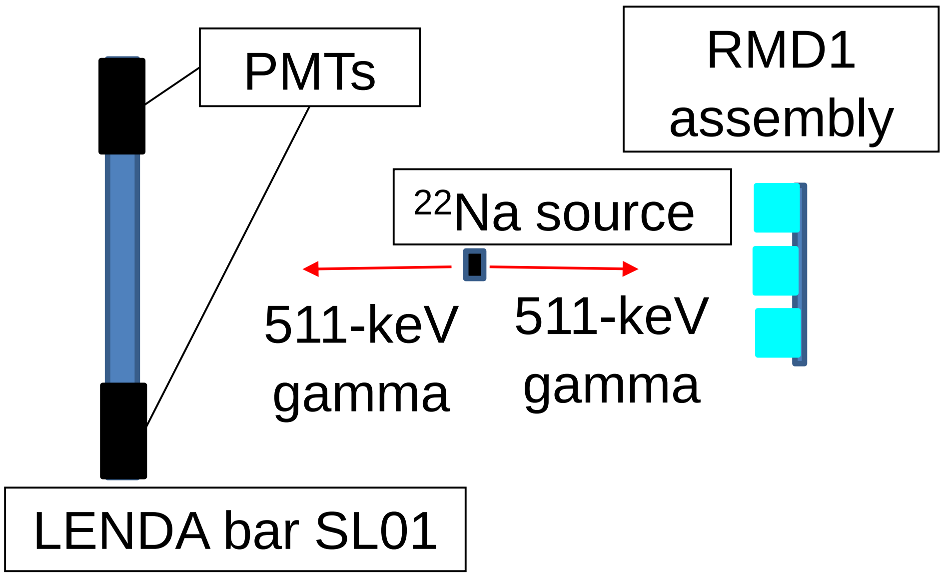
- Noise floor defined with respect to 137-Cs Compton counts

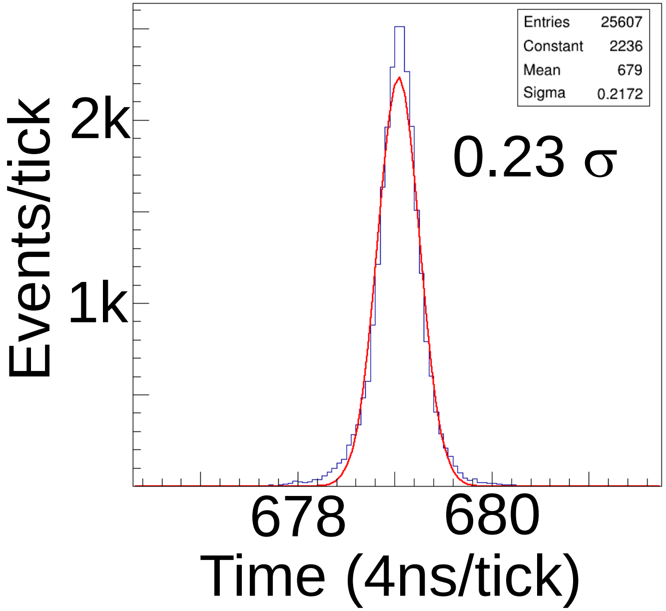
Waveform Comparison



- Baseline noise in RMD Prototype likely due to SiPM dark current (2×2-6mm×6mm SiPM array)
- The average signal-to-baseline-noise ratio is 53 and 1,300 for the RMD prototype and LENDA bar, respectively (lower due to longer/slower pulse)

Timing Characterization

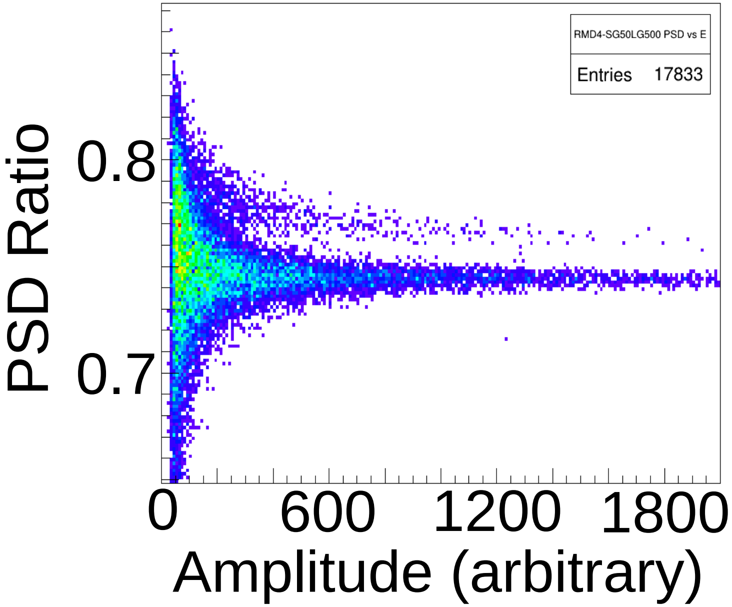


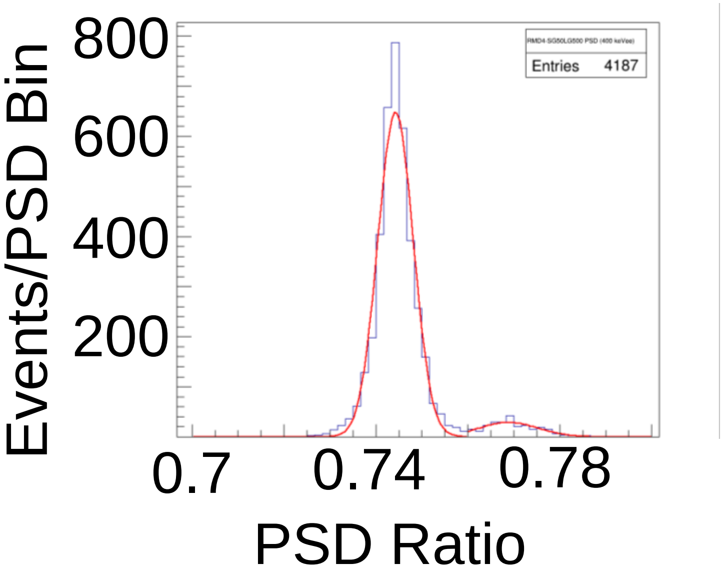


Segment	Timing (ns FWHM)	Segment	Timing (ns FWHM)	Segment	Timing (ns FWHM)
RMD101	2.05	RMD104	1.98	RMD107	2.06
RMD102	2.50	RMD105	2.33	RMD108	2.29
RMD103	2.91	RMD106	3.02	RMD109	3.29

- Timing improves to ~500 ps with ~300-keV noise threshold
- Timing depends on SNR

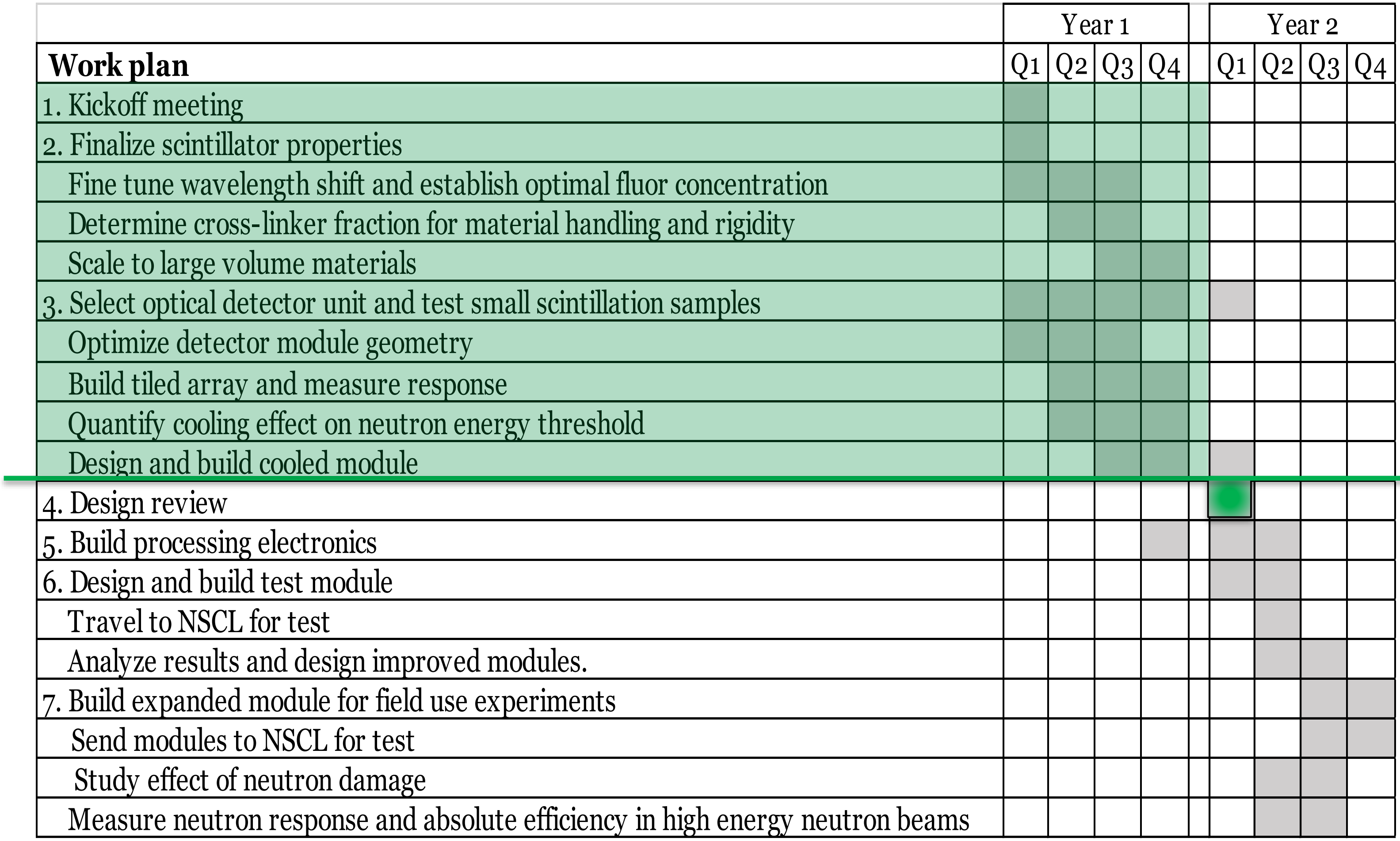
PSD and FOM (for events above an energy threshold)





- FOM exhibits strong dependence on threshold (1.03 for events > 400 keV compared to 0.88 for events > 300 keV)

Milestones



	Year 1					Year 2			
Work plan	Q1	Q2	Q3	Q4		Q1	Q2	Q3	Q4
1. Kickoff meeting	🟩								
2. Finalize scintillator properties	🟩								
Fine tune wavelength shift and establish optimal fluor concentration	🟩	🟩	🟩						
Determine cross-linker fraction for material handling and rigidity		🟩	🟩						
Scale to large volume materials			🟩	🟩					
3. Select optical detector unit and test small scintillation samples	🟩	🟩	🟩	🟩		▒			
Optimize detector module geometry	🟩	🟩	🟩						
Build tiled array and measure response		🟩	🟩	🟩					
Quantify cooling effect on neutron energy threshold		🟩	🟩	🟩					
Design and build cooled module			🟩	🟩		▒			
4. Design review						●			
5. Build processing electronics				▒		▒	▒		
6. Design and build test module						▒	▒		
Travel to NSCL for test							▒		
Analyze results and design improved modules.							▒	▒	
7. Build expanded module for field use experiments								▒	▒
Send modules to NSCL for test								▒	▒
Study effect of neutron damage							▒	▒	
Measure neutron response and absolute efficiency in high energy neutron beams							▒	▒	

Spring 2017 Send modules

Summary

- First prototype fabricated and tested
  - Critical Design Review to optimize performance
- Trade between segmentation and SNR performance
  - Manufacturability
- Silicon SSPMs work well for small, 1 cubic inch, scintillators
- SNR performance determines timing and PSD FOM

Extra Slides

Outline

Introduction
- Plastic Scintillation
- SSPMs
- Objective

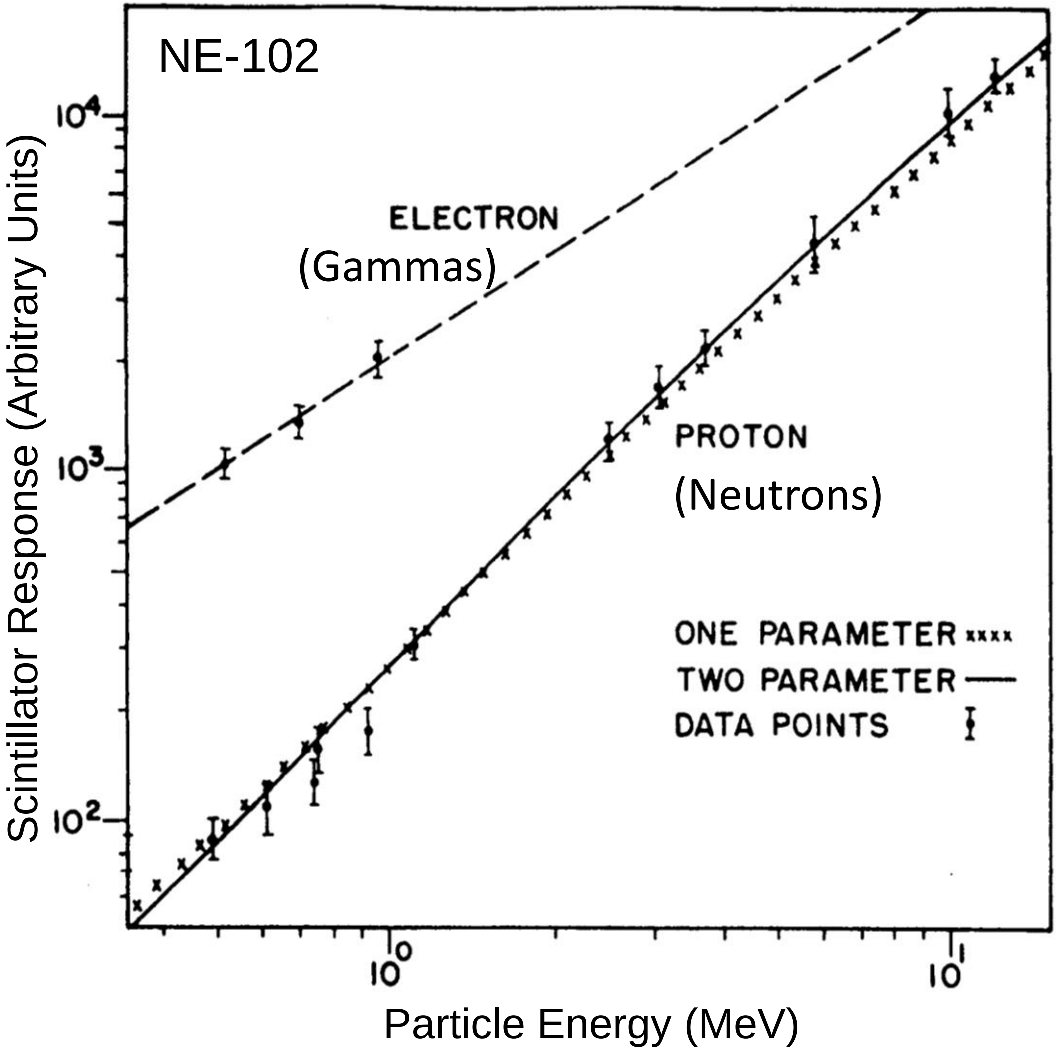
Overview of Phase-1 Results

Phase-2 Objectives

Phase-2 Tasks
- Progress
- Measurements at National Superconducting Cyclotron Laboratory (NSCL)

Summary

Light yield in plastic scintillation materials

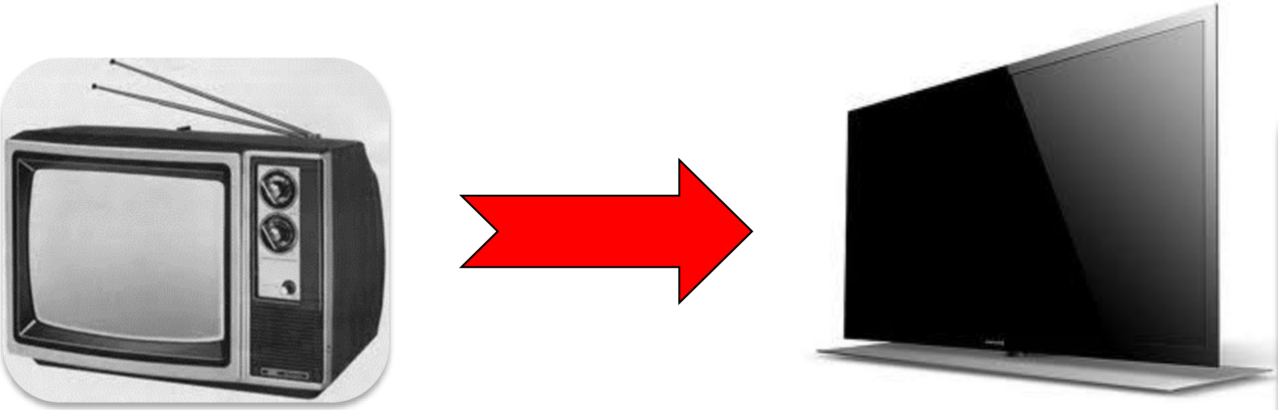


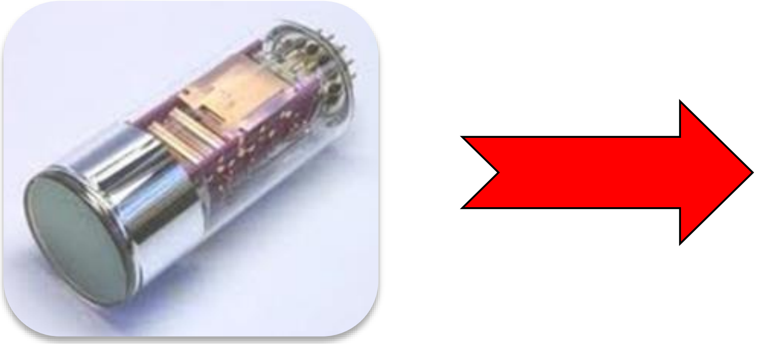
- Birk's equation relates light yield (dL/dx) to dE/dx (LET)
  - – "S" term: photoelectron yield
  - – "kB" (quenching) polyvinyl styrene: 9.0E-3 compared to 11.6E-3 g/(cm^2·MeV) for PVT
- Neutron produces a distribution of recoil proton energies (impact parameters)
- Mono-energetic recoil protons produce a distribution of light amplitudes from the distribution of path lengths

Plastic scintillation performance specifications for neutron detection often in gamma-equivalent energy

Solid-state Photodetectors: Replacing Vacuum Tubes

- Typically read out scintillators using photomultiplier tubes.





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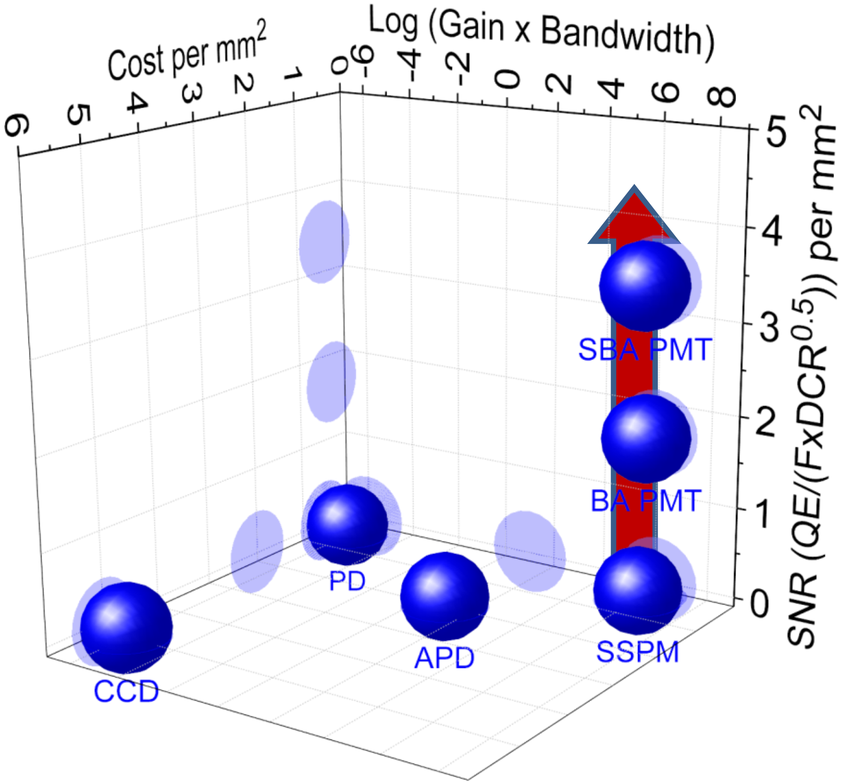
Scintillators are radiation sensitive materials that produces a characteristic flash of light when a radiation event interacts with the scintillator.

- Solid-state Photo-Multiplier Detectors: viable alternative to the vacuum tube based photomultiplier tubes (PMTs).

SiPMs Compared to Other Photodetectors



Photodetectors

PD: photodiode

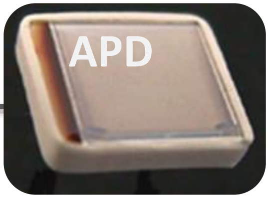
APD: avalanche photodiode

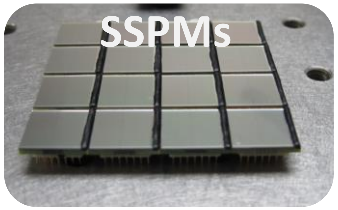
SSPM: solid-state photomultiplier

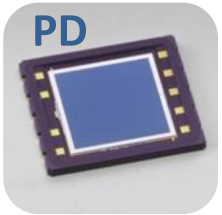
CCD: charge-coupled device

BA PMT: bialkali PMT

SBA PMT: super-bialkali PMT







- Dark count rate has improved from a few MHz/mm^2 for early MRS devices to ~30 kHz/mm^2

Photomultiplier tube (PMT)

Phase-1 (P1) Overview

Objectives

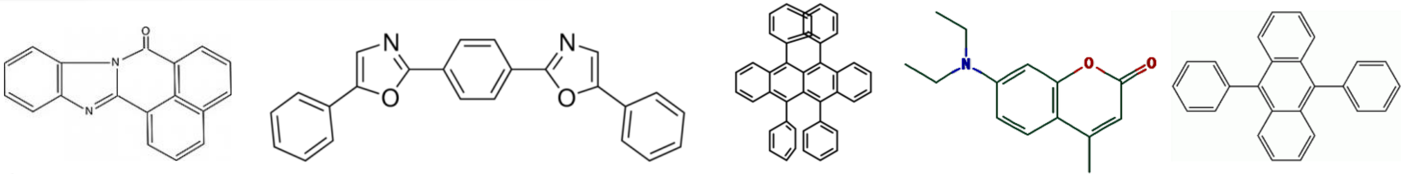
- ✓ Fabricate plastic scintillators with PSD
- ✓ Measure Scintillation properties
- ✓ Demonstrate Solid-State Optical Readout and Investigate Component Integration

Met all of its objectives

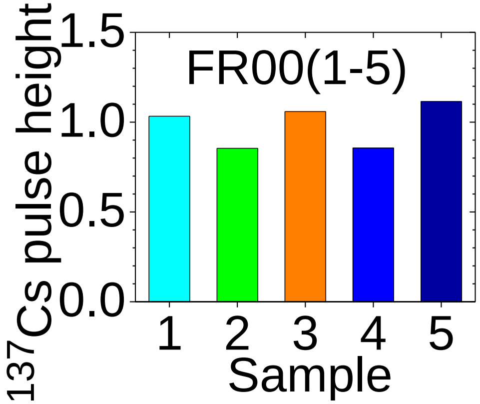
Successfully demonstrated the capabilities of a solid-state detectors and modules for neutron detection with PSD plastic scintillators

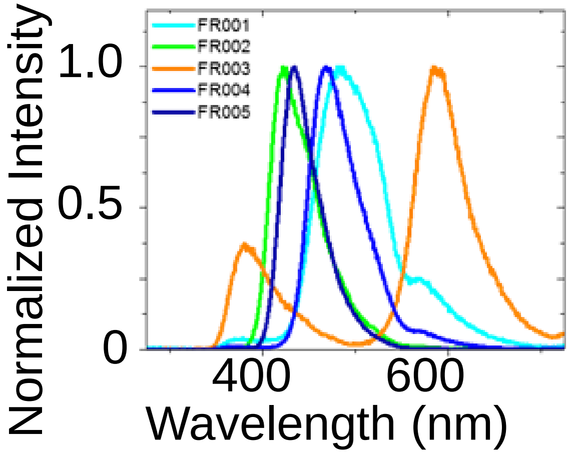
P1 results: Flours

5 Flours:



- Match QE of SSPM
- Improve pulse shape discrimination
- Create intermediate states with different lifetimes mid-band gap.

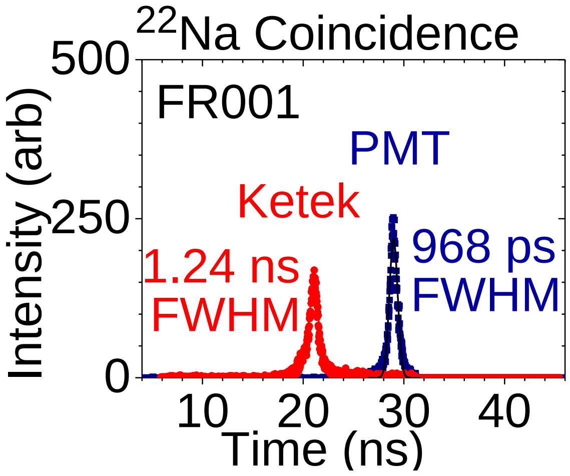


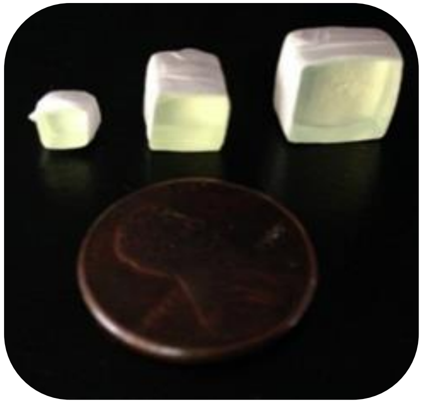


Fluor Abbreviation	Chemical name	Plastic sample name	Peak emission wavelength
BBQ	7H-benzimidazo[2,1-a]benz[de]isoquinoline-7-one	FR001	~480
POPOP	1,4-bis(5-phenyloxazol-2-yl)benzene	FR002	~410
Rubrene	5,6,11,12-tetraphenyltetracene	FR003	~600, ~380
Coumarin	7-(diethylamino)-4-methyl-2H-1-benzopyran-2-one	FR004	~460
DPA	Diphenylanthracene	FR005	~420

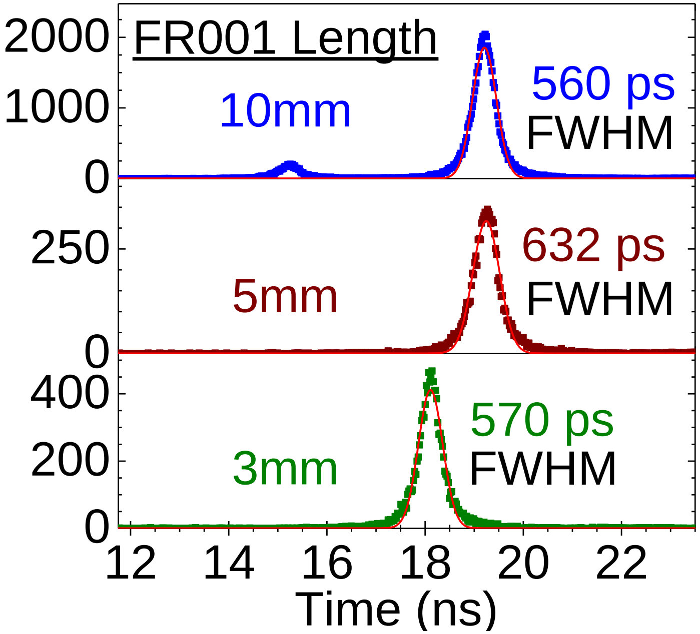
Phase-I results: timing

- Timing measurements with multiple devices indicate adequate time response.
- Electronics are a limitation
- Interested in direct calculation of time resolution from ADC (Caen) data





3 sq. mm, 5 sq. mm, and 10 sq. cm. FR001



P1-results: SiPM Device Comparisons

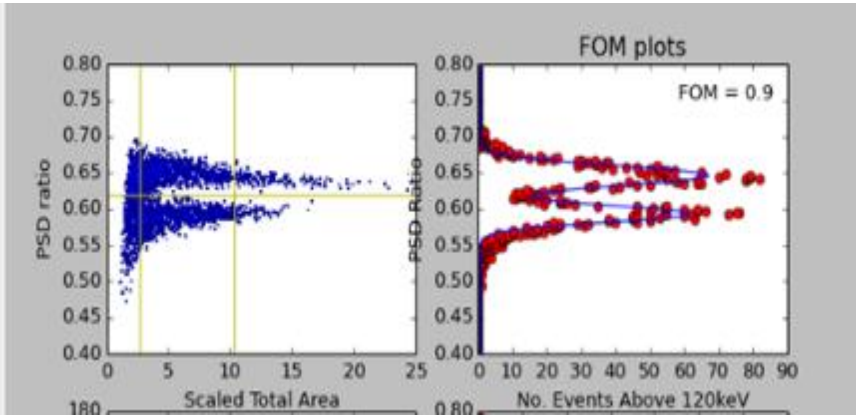
Excellent pulse separation on multiple devices

PSD
scatter plot

PSD FOM
120 keVee threshold

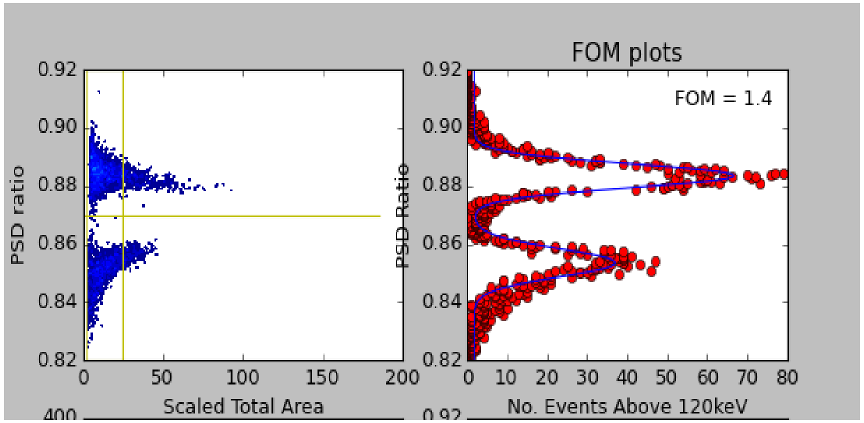
- RMD’s Rambler CMOS SSPM device

  ^{241}Am/Be neutrons, FR001



- Ketek SiPM

  ^{241}Am/Be neutrons, FR001



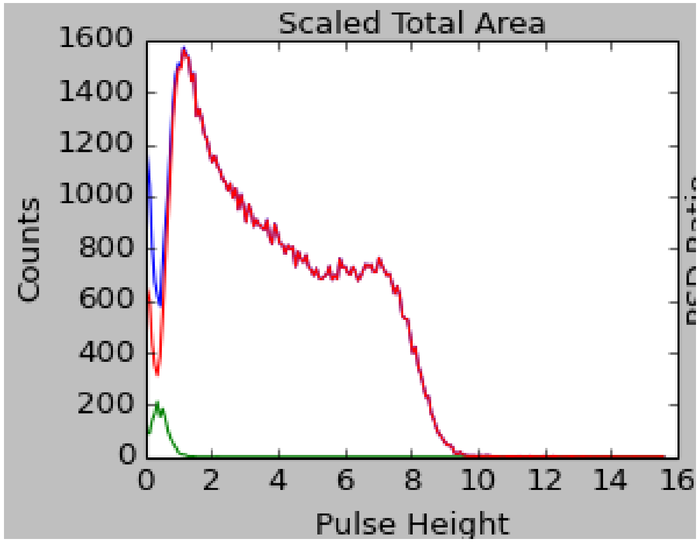
- Other work, but some obsolete: advances in SiPMs (new products)

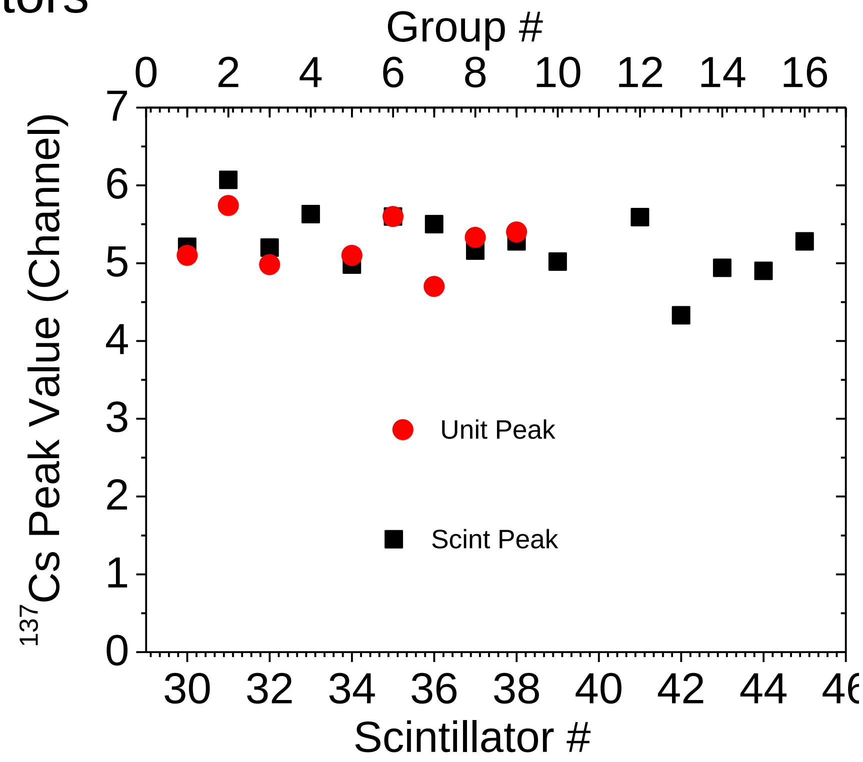
Commercialization considerations

- Define performance goals/specifications
- Fabricate and test “first article” units
    - Set up production area
    - Establish QC procedures
- Evaluate cost ladder
- Deliver first article units
- Scale up for delivery of units per month for 2 years to NSCL

Quality Control

- Measured 9 scintillators on 9 devices, and 9 scintillators on one device
- Estimates of Compton edge location by eye
- Unit performance tracks scintillator performance, showing variation is due to scintillators, not optical detectors



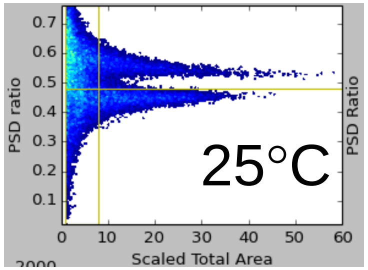


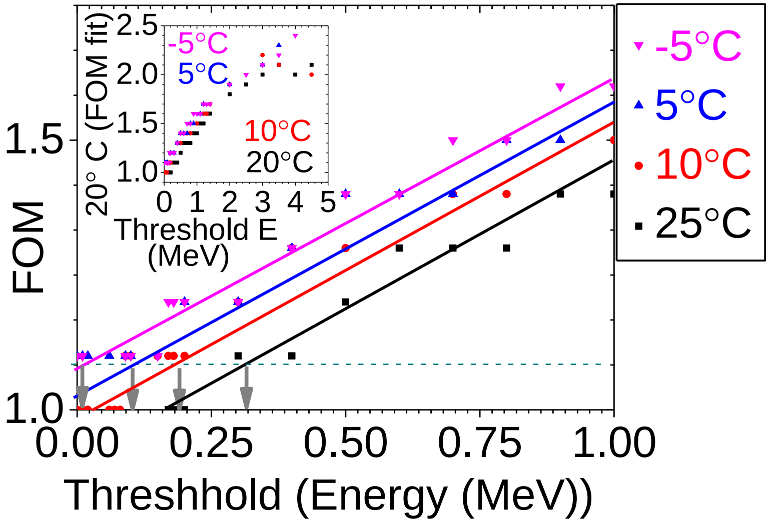
- Good module yield

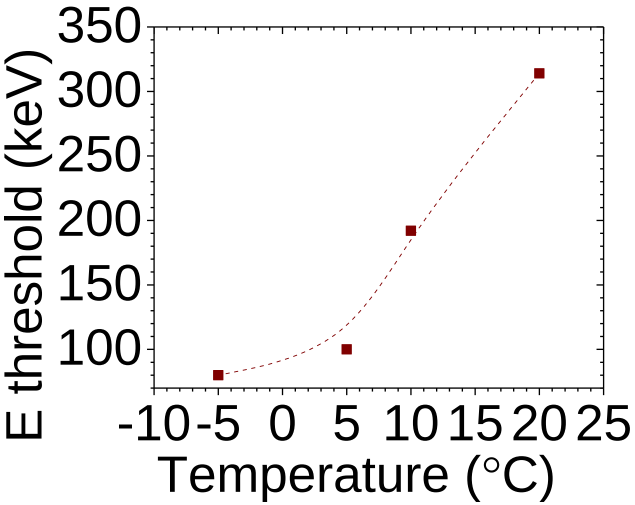
Detector Temperature Effects

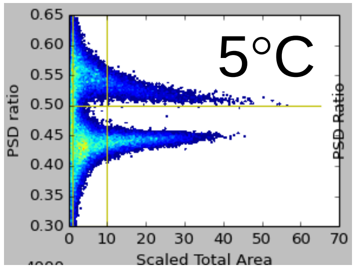
- SensL C-Series (6mm) SiPMs coupled to FR001 were chosen as final detector components.
- Neutron energy threshold goal < 200 keVee
- Temperature cycle neutron measurements show greater PSD at lower temperatures
  - SiPM bias adjusted to keep constant gain

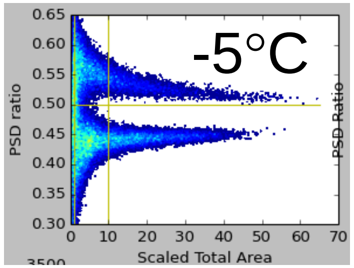
241-Am/Be





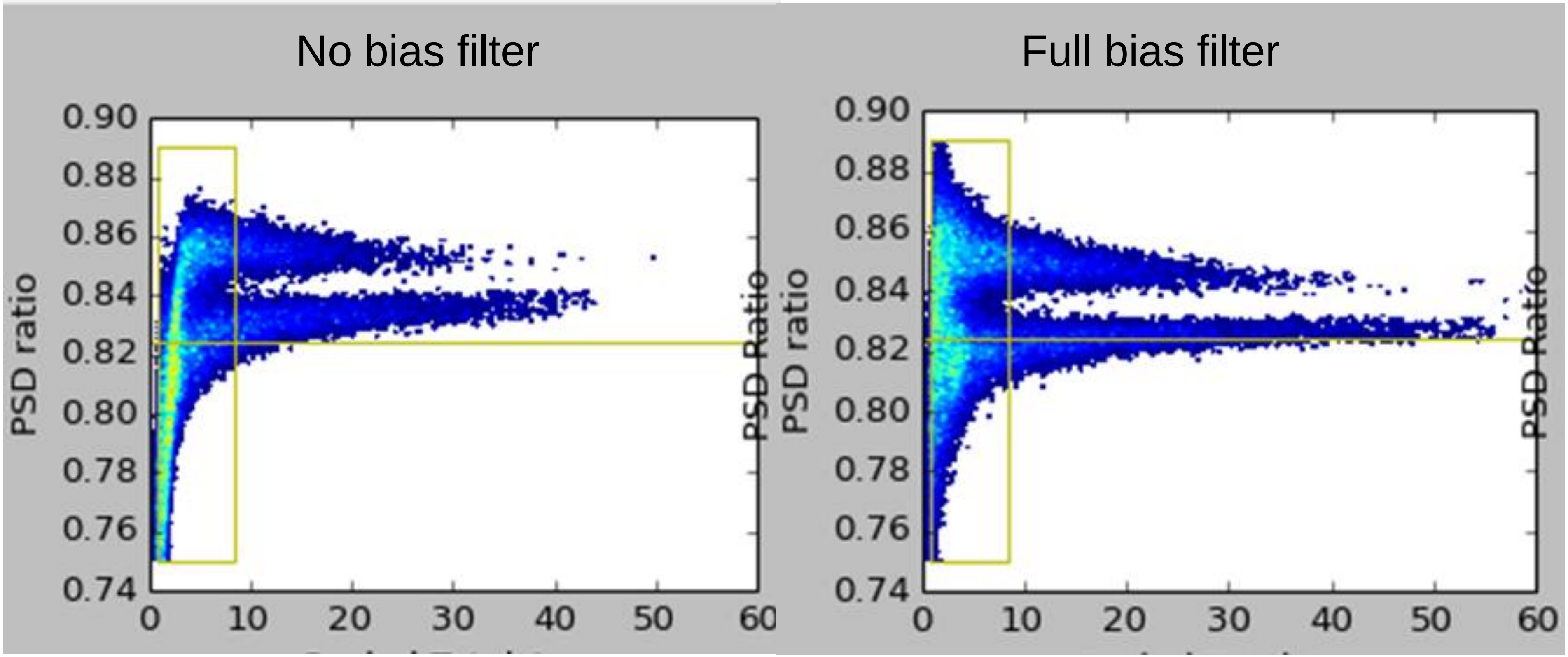






(Left) PSD Figure of Merit as a function of threshold energy.
(Right) Threshold Energy for FOM > 1.1 as a function of temperature.

Effect of bias filter on PSD histogram



- “Low” energy/amplitude events susceptible to distortion